

Metabolomic Profiling of Bioactive Seaweeds of Chosen South Indian Peninsular Coast.

B. Robert Bruce^{1,3}, B. Xavier Innocent¹ and Ezhilmozhil Sophia²

¹Department of Zoology, St. Xavier College, Palayamkottai, Tirunelveli- 627002

²Department of Zoology, St. John's College, Palayamkottai, Tirunelveli- 627002

³Affiliated to Manonmaniam Sundaranar University, Tirunelveli-627012

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ABSTRACT

Seaweeds (marine macroalgae) from the South Indian peninsular coast represent a rich and underexplored source of bioactive metabolites with significant ecological and biotechnological importance. Coastal regions such as the Gulf of Mannar and Palk Bay provide favorable environmental conditions that support diverse seaweed flora, including red, brown, and green algae. This study focuses on the metabolomic profiling of selected seaweeds to identify and characterize their primary and secondary metabolites using advanced analytical techniques such as GC-MS, LC-MS, FTIR, and NMR spectroscopy. The profiling revealed the presence of various bioactive compounds, including phenolics, flavonoids, fatty acids, terpenoids, pigments, and sulfated polysaccharides. These metabolites are associated with a wide range of biological activities, including antioxidant, antimicrobial, antidiabetic, anti-inflammatory, and anticancer properties. Multivariate statistical analyses further enabled the differentiation of species based on their metabolite composition and bioactivity. The findings highlight the immense potential of South Indian seaweeds as sources of novel compounds for pharmaceutical, nutraceutical, industrial, and environmental applications. Overall, metabolomic approaches provide a comprehensive platform for understanding the chemical diversity and functional significance of marine macroalgae, supporting their sustainable utilization and conservation.

Keywords: Seaweeds, Metabolomic profiling, Bioactive compounds, Antioxidant activity, Marine natural products, Nutraceuticals

INTRODUCTION

Marine macroalgae, commonly known as seaweeds, are an ecologically and economically significant group of photosynthetic organisms distributed widely along coastal ecosystems. The South Indian peninsular coast, encompassing regions such as Gulf of Mannar, Palk Bay, and the Arabian Sea coastline of Kerala and Karnataka, represents one of the richest marine biodiversity zones in India. These coastal environments provide optimal conditions for the growth of diverse seaweed flora, including members of Rhodophyta (red algae), Phaeophyceae (brown algae), and Chlorophyta (green algae). Seaweeds from these regions have gained considerable attention due to their high content of structurally diverse bioactive compounds, which hold immense potential for applications in pharmaceuticals, nutraceuticals, agriculture, and environmental management [1].

In recent years, there has been a growing interest in understanding the chemical diversity of marine organisms through advanced analytical approaches. Among these, metabolomics has emerged as a powerful tool for the comprehensive profiling of small molecular weight compounds present within biological systems. Metabolomics, a branch of systems biology, involves the qualitative and quantitative analysis of metabolites in a given organism under specific environmental conditions. In the context of seaweeds, metabolomic profiling provides valuable insights into the biochemical composition, metabolic pathways, and adaptive responses of these organisms to their dynamic marine environment [2,3]. This approach is particularly important for identifying novel bioactive compounds that may contribute to drug discovery and development.

Seaweeds are known to produce a wide array of primary and secondary metabolites. Primary metabolites such as carbohydrates, proteins, amino acids, and lipids are essential for growth and development, whereas secondary metabolites including phenolics, flavonoids, terpenoids, alkaloids, and sterols play crucial roles in defense mechanisms against herbivory, UV radiation, and environmental stress. The unique physicochemical conditions of the South Indian coastal waters, including variations in salinity, temperature, light intensity, and nutrient availability, significantly influence the metabolic profiles of seaweeds. As a result, seaweeds from these regions often exhibit distinct metabolomic signatures compared to those from other parts of the world.

Among the various groups of seaweeds, brown algae such as *Sargassum wightii* and *Turbinaria ornata* are particularly rich in polyphenols, especially phlorotannins, which exhibit strong antioxidant and antimicrobial properties. Red algae such as *Gracilaria edulis* and *Gelidiella acerosa* are well-known for their high content of sulfated polysaccharides like agar and carrageenan, which have antiviral, anticoagulant, and immunomodulatory activities. Green algae such as *Caulerpa racemosa* and *Ulva lactuca* are also important sources of bioactive compounds, including chlorophyll derivatives, carotenoids, and essential fatty acids [4]. These metabolites not only contribute to the ecological fitness of seaweeds but also enhance their value as functional food ingredients and therapeutic agents.

The application of advanced analytical techniques has significantly improved the resolution and accuracy of metabolomic studies in seaweeds. Techniques such as gas chromatography-mass spectrometry (GC-MS), liquid chromatography-mass spectrometry (LC-MS), nuclear magnetic resonance (NMR) spectroscopy, and Fourier transform infrared (FTIR) spectroscopy are commonly employed for metabolite identification and characterization. GC-MS is particularly useful for analyzing volatile and semi-volatile compounds, including fatty acids and hydrocarbons, whereas LC-MS is more suitable for detecting non-volatile and thermally unstable compounds such as phenolics and peptides. NMR spectroscopy provides detailed structural information about metabolites, while FTIR is used for functional group analysis. The integration of these techniques with bioinformatics tools and multivariate statistical analysis enables a more comprehensive understanding of the metabolome. The importance of metabolomic profiling lies not only in identifying individual compounds but also in understanding the complex interactions between metabolites and their biological functions. For instance, the antioxidant activity of seaweeds is often attributed to the synergistic effects of multiple compounds, including phenolics, flavonoids, and pigments such as carotenoids and chlorophylls [5,6]. Similarly, antimicrobial and anticancer activities are associated with a combination of fatty acids, terpenoids, and sulfated polysaccharides. Therefore, a holistic metabolomic approach is essential for elucidating the functional properties of seaweeds and their potential applications in various industries. In the context of the South Indian peninsular coast, several studies have reported the presence of bioactive compounds with significant pharmacological properties. Seaweeds from the Gulf of Mannar, a designated biosphere reserve, have been extensively studied for their rich metabolite diversity and bioactivity. These studies have demonstrated strong antioxidant, antimicrobial, anti-inflammatory, antidiabetic, and anticancer activities in various seaweed species. Such findings underscore the importance of conserving marine biodiversity and promoting sustainable utilization of seaweed resources.

Furthermore, metabolomic profiling also plays a crucial role in quality control, standardization, and authentication of seaweed-based products. With the increasing commercialization of seaweed-derived products, there is a need to ensure their safety, efficacy, and consistency. Metabolomics can help in identifying biomarkers for specific species, detecting adulteration, and monitoring changes in chemical composition due to environmental or processing factors.

Despite the significant progress in this field, there are still several challenges associated with metabolomic studies of seaweeds. These include the complexity of marine matrices, variability in metabolite composition due to environmental factors, and limitations in metabolite databases for marine organisms. Addressing these challenges requires the development of standardized protocols, expansion of spectral libraries, and integration of metabolomics with other omics approaches such as genomics and proteomics. By providing a comprehensive understanding of the chemical diversity and functional properties of seaweeds, metabolomics paves the way for the discovery of novel bioactive compounds and their application in medicine, nutrition, and environmental sustainability. Continued research in this field will not only enhance our knowledge of marine natural products but also contribute to the sustainable development of coastal resources.

Study Areas

The South Indian peninsular coast is one of the most biologically productive marine regions, supporting diverse seaweed populations. The major study areas for metabolomic profiling of bioactive seaweeds include the following:

1. Gulf of Mannar

The Gulf of Mannar, located along the southeast coast of Tamil Nadu, is a designated biosphere reserve and one of the richest marine biodiversity hotspots in India. It consists of 21 islands and extensive coral reef ecosystems. The region provides ideal conditions such as warm tropical climate, high salinity, and nutrient-rich waters for the growth of diverse seaweed species like *Sargassum*, *Gracilaria*, and *Gelidiella*. Due to its high species diversity and ecological significance, it is a primary site for studying bioactive metabolites, especially antioxidants, polysaccharides, and phenolic compounds.

2. Palk Bay

Palk Bay lies between India and Sri Lanka and is characterized by shallow waters, sandy substrates, and seagrass meadows. The calm and sheltered nature of this region supports abundant growth of green and red algae, particularly *Caulerpa* and *Ulva* species. Seasonal variations and anthropogenic influences make this area important for studying environmental effects on metabolite composition. Seaweeds from Palk Bay are often investigated for their lipid profiles and antimicrobial properties.

3. Rameswaram Coastal Region

The coastal waters around Rameswaram form part of the Gulf of Mannar ecosystem and are well known for large-scale seaweed harvesting. Rocky substrates and intertidal zones favor the growth of commercially important seaweeds. This region

is frequently selected for metabolomic studies due to easy accessibility and high biomass availability. It is particularly significant for analyzing industrially valuable compounds such as agar and alginates.

4. Kerala Coast (Arabian Sea)

The Kerala coastline along the Arabian Sea exhibits different ecological conditions compared to the southeast coast, including higher wave action and monsoonal influence. Seaweeds such as *Ulva*, *Enteromorpha*, and *Padina* are commonly found here. The variation in environmental stressors contributes to unique metabolomic profiles, especially in terms of stress-induced secondary metabolites like terpenoids and flavonoids.

5. Karnataka Coast

The Karnataka coast is less explored but ecologically significant, with rocky shores and estuarine regions supporting diverse macroalgal communities. Seaweeds in this region are adapted to fluctuating salinity and tidal conditions, making them valuable for studying adaptive metabolites. Research from this area often focuses on antioxidant and antimicrobial compounds.

Methodology for Metabolomic Profiling of Bioactive Seaweeds

Metabolomic profiling of bioactive seaweeds involves a systematic and integrated approach that includes sample collection, preparation, extraction, analytical characterization, and data analysis. Seaweed samples are typically collected from coastal regions such as the Gulf of Mannar and Palk Bay during low tide, ensuring that healthy and mature thalli are selected. The collected samples are carefully washed with seawater followed by distilled water to remove salts, sand, and epiphytic organisms. They are then shade-dried or freeze-dried to preserve sensitive metabolites, ground into fine powder, and stored under controlled conditions to prevent degradation [7].

Extraction of metabolites is carried out using a range of solvents such as methanol, ethanol, acetone, ethyl acetate, and hexane, depending on the polarity of the target compounds. Techniques like cold maceration, Soxhlet extraction, or ultrasonication are commonly employed to maximize extraction efficiency. The extracts are then filtered and concentrated using a rotary evaporator, resulting in crude extracts that contain a mixture of primary and secondary metabolites. These extracts are subjected to advanced analytical techniques for detailed characterization. Gas chromatography-mass spectrometry (GC-MS) is used to identify volatile and semi-volatile compounds such as fatty acids and hydrocarbons, while liquid chromatography-mass spectrometry (LC-MS) is employed for non-volatile compounds including phenolics, flavonoids, and alkaloids. Fourier transform infrared (FTIR) spectroscopy helps identify functional groups, and nuclear magnetic resonance (NMR) spectroscopy provides detailed structural information about the metabolites. High-performance liquid chromatography (HPLC) is further used for the separation and quantification of specific bioactive compounds [8,9].

The data generated from these analytical platforms are processed using specialized software and compared with spectral libraries such as NIST and METLIN for compound identification. Multivariate statistical tools, including principal component analysis (PCA) and cluster analysis, are applied to interpret complex datasets, differentiate species, and identify potential biomarker compounds. Finally, the identified metabolites are correlated with biological activities through assays such as antioxidant, antimicrobial, and enzyme inhibition studies. This comprehensive methodology enables a deeper understanding of the chemical diversity and functional potential of seaweeds, supporting their application in pharmaceutical, nutraceutical, and environmental fields.

Case Studies from South India

Several studies conducted along the South Indian peninsular coast highlight the metabolomic diversity and bioactive potential of different seaweed species. Key case studies are summarized below:

1. Brown Algae – *Sargassum* spp. (Southeast Coast of India)

Seaweeds belonging to the genus *Sargassum*, collected from regions such as the Gulf of Mannar, have been extensively studied for their metabolomic composition. Using GC-MS and LC-MS techniques, researchers have identified a wide range of metabolites including fatty acids, aldehydes, and amino acid derivatives. A recent metabolomic study reported the identification of over 150 compounds, highlighting the chemical complexity of *Sargassum* species. These metabolites contribute to strong antioxidant and cytotoxic activities, indicating their potential in pharmaceutical applications. Additionally, these seaweeds are rich in proteins, carbohydrates, and phenolic compounds, making them suitable for nutraceutical use.

2. Red Algae – *Grateloupia indica* and *Gracilaria corticata*

Red seaweeds from the Indian coastline, particularly from Tamil Nadu regions, have shown remarkable bioactive properties. A recent metabolomic profiling study revealed that *Grateloupia indica* exhibited very high antioxidant activity (up to 94%) along with elevated phenolic and flavonoid content. GC-MS analysis identified bioactive compounds such as palmitic acid and other secondary metabolites associated with antimicrobial and anticancer activities. Similarly, *Gracilaria corticata* has been investigated for its anticancer potential. Methanolic extracts analyzed through GC-MS revealed various bioactive constituents, supporting its role as a promising natural source for cancer therapeutics.

3. Green Algae – *Ulva lactuca* and Related Species

Green seaweeds such as *Ulva lactuca*, commonly found along both southeast and southwest coasts of India, have been studied for their biochemical and metabolomic composition. These species are rich in lipids and essential fatty acids, which are important for energy metabolism and therapeutic applications. Comparative studies show that Chlorophyta (green algae) generally have higher lipid content than red algae, making them valuable for nutraceutical and biofuel-related research. Metabolomic analyses also reveal the presence of pigments, sterols, and antioxidant compounds that contribute to their antimicrobial and anti-inflammatory properties.

4. Multi-Species Study – Indian Coastal Seaweeds

A comprehensive metabolomic and antioxidant profiling study conducted on multiple seaweed species from the Indian coastline demonstrated significant variation in metabolite composition among species. The study identified key compounds such as xylitol, palmitic acid, and myristic acid through GC-MS analysis. Among the species studied, red algae showed higher phenolic content, while brown algae exhibited a balanced composition of primary and secondary metabolites. Multivariate analysis further helped in distinguishing species based on their chemical profiles and biological activities.

Biological Activities Linked

Seaweeds from the South Indian peninsular coast, particularly regions like the Gulf of Mannar and Palk Bay, are rich in diverse metabolites that exhibit a wide range of biological activities. These activities are primarily attributed to secondary metabolites such as phenolics, flavonoids, terpenoids, alkaloids, fatty acids, and sulfated polysaccharides. Metabolomic profiling has enabled the identification of these compounds and their correlation with functional bioactivities. One of the most prominent biological activities is antioxidant activity, which is mainly associated with phenolic compounds, flavonoids, and pigments such as carotenoids and chlorophyll. These compounds act as free radical scavengers, reducing oxidative stress and preventing cellular damage. Studies have shown that red and brown seaweeds possess high total phenolic content, which directly correlates with strong antioxidant potential.

Seaweeds also exhibit significant antimicrobial activity, which is attributed to metabolites such as fatty acids, terpenoids, and polyphenols. These compounds can disrupt microbial cell membranes and inhibit the growth of pathogenic bacteria and fungi. For instance, GC-MS profiling of *Sargassum* species revealed the presence of bioactive fatty acids responsible for antibacterial activity [10,11]. Another important activity is antidiabetic potential, which is linked to enzyme inhibition properties of certain metabolites. Compounds such as flavonoids and polyphenols inhibit key enzymes like α -amylase and α -glucosidase, thereby regulating blood glucose levels. Studies on Indian seaweeds have demonstrated significant enzyme inhibitory activity, indicating their potential use in diabetes management.

Seaweed metabolites also exhibit anticancer activity, which is primarily associated with sulfated polysaccharides, phenolics, and carotenoids. These compounds can induce apoptosis, inhibit tumor cell proliferation, and modulate signaling pathways involved in cancer progression. Research has shown that extracts of red algae such as *Gracilaria* species possess cytotoxic effects against cancer cell lines. In addition, seaweeds show anti-inflammatory activity, largely due to the presence of terpenoids, sterols, and polyphenols. These compounds inhibit inflammatory mediators such as cytokines and enzymes like cyclooxygenase (COX), thereby reducing inflammation. Marine algal polysaccharides have also been reported to exhibit immunomodulatory effects.

Furthermore, antiviral and anticoagulant activities are linked to sulfated polysaccharides such as carrageenan and fucoidan, which are abundant in red and brown algae. These compounds interfere with viral attachment and replication and also influence blood coagulation pathways. This highlights the importance of comprehensive metabolomic profiling in understanding the therapeutic potential of seaweeds and supporting their application in pharmaceutical and nutraceutical industries [12].

Applications of Bioactive Seaweeds

Seaweeds from the South Indian peninsular coast, especially regions like the Gulf of Mannar and Palk Bay, have gained significant attention due to their diverse metabolite composition and wide-ranging applications in various sectors. In the pharmaceutical field, seaweed-derived metabolites such as phenolics, flavonoids, terpenoids, and sulfated polysaccharides exhibit antioxidant, antimicrobial, anti-inflammatory, and anticancer properties. Compounds like fucoidan and carrageenan have been widely studied for their antiviral and immunomodulatory effects, making seaweeds promising candidates for drug discovery.

In the nutraceutical and functional food industry, seaweeds are valued for their high nutritional content, including proteins, essential amino acids, vitamins, minerals, and dietary fibers. Bioactive compounds such as polyphenols and omega fatty acids contribute to health benefits like improved digestion, reduced oxidative stress, and prevention of chronic diseases [13]. Seaweeds also play an important role in industrial applications, particularly in the production of hydrocolloids such as agar, alginate, and carrageenan, which are widely used as gelling, thickening, and stabilizing agents in food, pharmaceutical, and cosmetic industries.

In the environmental sector, seaweeds are used for bioremediation due to their ability to absorb heavy metals and nutrients from polluted water bodies. This makes them effective in wastewater treatment and marine ecosystem restoration. Additionally, in agriculture, seaweed extracts are used as biofertilizers and plant growth stimulants. They enhance seed

germination, crop yield, and resistance to environmental stress due to the presence of plant growth regulators and micronutrients [14]. The metabolomic richness of seaweeds supports their multifunctional applications across pharmaceutical, nutraceutical, industrial, environmental, and agricultural domains, highlighting their importance as sustainable marine resources.

CONCLUSION

Metabolomic profiling of bioactive seaweeds from the South Indian peninsular coast, particularly regions such as the Gulf of Mannar and Palk Bay, highlights the immense chemical diversity and biological potential of marine macroalgae. Advanced analytical techniques such as GC-MS, LC-MS, FTIR, and NMR have enabled the comprehensive identification of a wide range of primary and secondary metabolites, including phenolics, flavonoids, fatty acids, terpenoids, pigments, and sulfated polysaccharides. These metabolites are strongly associated with important biological activities such as antioxidant, antimicrobial, antidiabetic, anti-inflammatory, and anticancer effects. The findings from various studies demonstrate that environmental factors such as salinity, temperature, and nutrient availability significantly influence the metabolomic composition of seaweeds, resulting in species-specific bioactive profiles. The integration of metabolomics with multivariate statistical tools has further enhanced the understanding of chemotaxonomy, functional properties, and biomarker identification in different seaweed species. Seaweeds from the South Indian coast represent a promising and sustainable resource for the development of novel pharmaceuticals, functional foods, and industrial products. However, further research is required to standardize extraction methods, expand metabolite databases, and validate bioactivities through clinical studies. Continued exploration and conservation of marine biodiversity will be essential to fully harness the potential of seaweed metabolites for future applications.

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