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Chemical Profiling and Bioactivity Screening of a Cyanobacterium: *Phormidium* Species as a Source of α-Amylase Inhibitors and Antioxidants

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Abstract

Cyanobacteria represent a promising but underexplored source of novel bioactive compounds for food and therapeutic applications. This study investigated the chemical profile and bioactivities of a methanolic extract from *Phormidium* species isolated from the Marakkanam salt pan (Tamil Nadu, India). Gas chromatography-mass spectrometry (GC-MS) analysis revealed a diverse chemical composition dominated by a major sesquiterpenoid (9.13% relative abundance), alongside fatty acids, phenolic derivatives, and other secondary metabolites. The extract demonstrated significant, dose-dependent biological activity *in vitro*. It exhibited potent α-amylase inhibition, with activity increasing from 14.39 ± 2.22% at 10 µg/mL to 72.05 ± 1.67% at 50 µg/mL. Concurrently, it showed strong free radical scavenging capacity in the 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay, with inhibition ranging from 12.55 ± 2.15% at 25 µg/mL to 83.99 ± 1.49% at 200 µg/mL. However, 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) assays on normal cell lines (MCF-10A and L929) revealed a significant dose-dependent cytotoxic effect, reducing viability to 32.73 ± 3.09% and 47.46 ± 2.24% at 200 µg/mL, respectively. These results confirm the extract as a rich source of bioactive molecules with pronounced anti-diabetic and antioxidant potential, while highlighting its cytotoxic effects on normal cells, which presents a critical limitation for direct therapeutic use. This underscores the necessity for compound purification to isolate specific agents with a safer therapeutic profile for future development in functional food ingredients or nutraceuticals.

Keywords

Phormidium, Cyanobacteria, α-Amylase inhibition, Antioxidant, Cytotoxicity, Bioactive compounds

Introduction

The escalating global burden of metabolic syndromes, particularly type 2 diabetes, coupled with the deleterious health impacts of oxidative stress, underscores an urgent need for novel therapeutic and preventive strategies [1]. The limitations of conventional synthetic drugs, including side effects and incomplete efficacy, have reinvigorated scientific interest in natural products as reservoirs of unique and potent bioactive molecules [2]. In this context, the exploration of underexplored biological resources for compounds with targeted enzyme inhibition and free radical scavenging capabilities represents a critical frontier in nutritional and pharmaceutical research, aiming to develop safer, multi-target interventions [3-5].

Among nature's diverse biosynthetic libraries, cyanobacteria stand out as prolific yet underexploited producers of structurally novel secondary metabolites [6]. These ancient photosynthetic prokaryotes thrive in extreme environments, a factor that drives the evolution of unique biochemical pathways and defensive compounds. Historically studied for toxins, cyanobacteria are now recognized as promising sources of a wide array of beneficial bioactive, including those with demonstrated anti-diabetic, antioxidant, anti-inflammatory, and antimicrobial properties [7-9]. Their potential as sustainable, bioactive ingredients for functional foods and nutraceuticals is immense but requires systematic chemical and biological profiling to move from ecological curiosity to applied science [10, 11].

The genus *Phormidium*, a filamentous, non-heterocystous cyanobacterium, is commonly found in benthic mats of diverse aquatic ecosystems, including saline environments like salt pans [12, 13]. Life in such fluctuating, often harsh conditions necessitate robust metabolic adaptability, suggesting a rich chemodiversity. Cyanobacteria thriving in high-salinity habitats, such as salt pans, are known to evolve unique biosynthetic pathways as an adaptive response to osmotic stress, potentially leading to the production of novel secondary metabolites with distinct bioactivities. While some *Phormidium* species have been preliminarily investigated, a comprehensive analysis linking their detailed phytochemical constitution to specific, therapeutically relevant bioactivities-particularly in the context of metabolic regulation-remains largely uncharted [14-16]. This gap presents a significant opportunity to characterize a new biological resource with direct implications for food chemistry and health.

Unlocking the therapeutic potential of any natural extract hinges on precise chemical characterization. GC-MS has emerged as an indispensable analytical technique for this purpose, enabling the separation, detection, and tentative identification of volatile and semi-volatile compounds within complex biological matrices [17, 18]. By providing a chemical 'fingerprint' of an extract, GC-MS analysis forms the essential foundation for linking specific metabolites to observed biological activities, guiding fractionation efforts, and ensuring the reproducibility of future research-a cornerstone of quality control in developing standardized functional ingredients [19].

Based on the foregoing rationale, this study was designed to systematically investigate the bioactive potential of *Phormidium* species isolated from the Marakkanam salt pan (Tamil Nadu, India). The work is driven by the hypothesis that this cyanobacterium produces a spectrum of metabolites with relevant therapeutic properties. The specific objectives were: (i) to isolate, culture, and morphologically identify the cyanobacterium; (ii) to profile the volatile and semi-volatile chemical constituents of its methanolic extract using GC-MS; (iii) to evaluate its *in vitro* anti-diabetic potential through α-amylase enzyme inhibition assays; and (iv) to assess its antioxidative capacity via the DPPH radical scavenging assay, thereby establishing a preliminary bioactivity profile linked to its chemical composition.

Furthermore, this fundamental chemical and biological profiling align with the broader objectives of food chemistry and nanotechnology. The identification and characterization of novel bioactive compounds from underexplored sources like saline-adapted cyanobacteria are crucial first steps toward developing high value-added functional food ingredients. The detailed chemical data generated in this study provides the essential foundation for future applied research, such as the nano-encapsulation of sensitive bioactives to enhance their stability and bioavailability, or their integration into active food packaging systems. Thus, this work not only explores a new biological resource but also initiates a pipeline from ecological discovery to potential technological innovation in the food and health sectors.

Materials and Methods

Materials

All reagents and 0.22 µm polyvinylidene fluoride (PVDF) syringe filters were sourced from HiMedia Laboratories Pvt. Ltd. (India). The chemicals employed for GC-MS analysis, obtained from Sigma-Aldrich (India), were of GC-MS grade and exceeded 99% purity. Throughout the study, distilled water, with a pH between 6.6 and 7.4, was used.

Sample collection

In August 2023, samples were obtained from the vicinity of the Marakkanam salt pan in Tamil Nadu, India. The collection site, located at an elevation of 1,033 meters (11.3436992° N, 76.840383° E), provided both 5 L volumes of water and visible cyanobacterial mats gathered from various locations across the salt pan [20].

Isolation and screening of cyanobacteria

Upon returning to the laboratory, the collected water samples were centrifuged at 10,000 rpm for 20 min to yield a concentrated pellet. A small amount of this pellet, collected using an inoculation loop, was streaked onto Petri plates containing solidified BG-11 and F/2 media prepared with 1.5% agar. The inoculated plates were incubated under a light intensity of 3000 lux using a 12 h light/12 h dark photo period under static conditions. The cyanobacterial cultures were then harvested after an approximately 21-day growth period [20].

Dr. Mohamed Halith from the Department of Biotechnology at New College (Chennai, Tamil Nadu, India) performed the identification and authentication of the cyanobacterial cultures. Following this, the cultivation and maintenance of the cyanobacterial culture were carried out within the Department of Biotechnology at Vaagdevi Degree and P.G. College in Warangal (Telangana, India).

Extract preparation

Cyanobacterial cells were harvested from a 500 mL culture flask by centrifugation at 8000× g for 5 min at 15 °C, followed by one wash with distilled water. The fresh cell pellet was then thoroughly homogenized using a mortar and pestle for 20 min at room temperature. For subsequent extraction, the wet biomass was subjected to methanol extraction. Initially, the biomass was spread on a clean glass plate and air-dried at room temperature (25 to 30 °C) for 48 h to constant weight.

To expedite the process for a subset of material, portions were also dried in a hot air oven at 40 °C for 24 h. Approximately 50 g of the dried biomass was then loaded into a Soxhlet apparatus and extracted with 800 mL of methanol for 48 h at a temperature maintained below the solvent's boiling point. The resulting extract was filtered through a 0.22 µm PVDF membrane. The filtrate was concentrated to complete dryness under vacuum, yielding a dry methanolic extract. The total dry weight of the extract obtained was approximately 4 mg, which was then reconstituted in 2 mL of distilled water. This stock solution of the cyanobacterial methanolic extract was stored at 4 °C in a refrigerator for future use [20].

GC-MS analysis

The methanolic extract was analyzed using a JEOL GCMATE II GC-MS system. This high-resolution, double-focusing instrument, with a maximum resolution of 6000 and a calibrated mass range up to 1500 Daltons, offers electron impact and chemical ionization source options. For the analysis, the GC was fitted with a capillary column (30 m × 0.25 mm internal diameter, 0.25 µm film thickness). Helium was used as the carrier gas at a constant flow rate of 1.0 mL/min. The oven temperature was programmed from 40 °C to 350 °C at a rate of 5 °C/min. Sample injections ranged from 1 to 5 µL. The identification of unknown compounds was performed by comparing their acquired mass spectra against reference spectra in the National Institute of Standards and Technology GC/MS library, thereby determining their tentative names and molecular weights [20].

Anti-diabetic assay

Inhibiting the α-amylase enzyme is a central strategy in anti-diabetic research, as it modulates postprandial hyperglycemia by delaying carbohydrate breakdown. Consequently, evaluating potential inhibitors-including natural extracts and synthetic compounds-through α-amylase inhibition assays is critical for developing therapies for type 2 diabetes. These assays quantify the reduction in enzymatic activity to assess inhibitor efficacy, providing a foundation for novel therapeutic approaches. The current analysis was conducted following an established protocol [21].

Antioxidative assay

The DPPH assay is a widely used colorimetric method to evaluate the free radical scavenging capacity of antioxidant compounds. In this assay, antioxidants donate a hydrogen atom to the stable, purple-colored DPPH radical, reducing it to a yellow-colored diphenylpicrylhydrazine. Its importance lies in providing a rapid, simple, and reliable first assessment of antioxidant potential, which is critical for screening natural extracts and compounds for their ability to mitigate oxidative stress associated with numerous diseases. The current analysis was conducted following an established protocol [21].

Cell viability

The MTT colorimetric assay measures cellular metabolic activity to determine viability, proliferation, and cytotoxicity. In this method, viable cells with active mitochondria reduce the yellow tetrazolium dye MTT into insoluble purple formazan crystals. The color intensity, quantified spectrophotometrically, is directly proportional to the number of living cells. Due to this reliable correlation, the MTT assay is extensively applied in studies screening extracts and evaluating cell viability and toxicity. The current analysis was conducted following an established protocol [21].

Statistical analysis

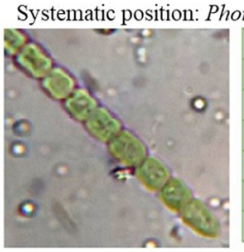
All experiments were conducted with 3 independent replicates (n = 3). Data are expressed as mean ± standard deviation, with error bars representing the standard deviation in graphical presentations. Statistical analysis using student's t-test established significance at $p < 0.05$. All graphs were generated using MS Excel 2021.

Results and Discussion

Morphology identification

Morphologically, *Phormidium* typically develops tangled, flat, slimy mats, long and cylindrical, with a possibility of curvature or spiraling, which may exhibit curvature or spiraling. *Phormidium* cells have thin, rigid, colorless sheaths that cling firmly to any protrusions or appendages. The calyptra of the apical cells may be more rounded, pointed, or narrow than those of the other cells (Figure 1). *Phormidium*, a common genus of non-heterocystous, filamentous cyanobacteria often found in benthic mats in aquatic environments.

Systematic position: *Phormidium* sp.



Empire	Prokaryota
Kingdom	Eubacteria
Phylum	Cyanobacteria
Class	Cyanophyceae
Order	Oscillatoriales
Family	*Oscillatoriaceae*
Genus	*Phormidium*

Figure 1: Morphological identification and taxonomy of *Phormidium* species.

GC-MS analysis

GC-MS analysis of a methanolic extract from *Phormidium* species is essential for identifying and characterizing its complex volatile and semi-volatile chemical constituents. This technique separates individual compounds via GC and then provides their structural identification through unique mass spectral fingerprints [22]. Such analysis is critically important because it can reveal a diverse array of bioactive metabolites, such as fatty acids, alkanes, sterols, and other secondary compounds, which are often responsible for the cyanobacterium's observed biological activities [23]. Identifying these specific compounds is a fundamental step in linking the extract's chemical profile to its potential pharmacological or industrial applications, such as antioxidant, antimicrobial, or cytotoxic effects [24]. Consequently, GC-MS profiling serves as a foundational and indispensable tool in metabolomics and natural product research, transforming a crude extract into a map of identifiable

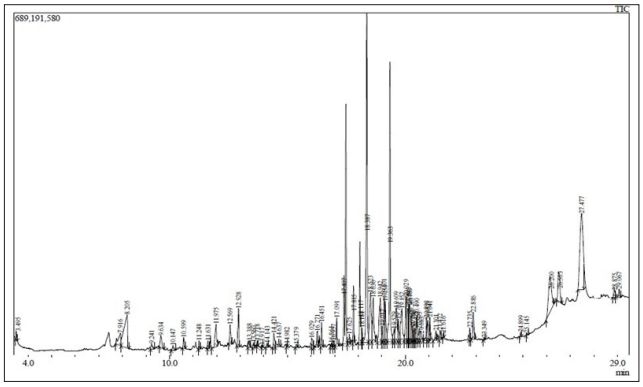


Figure 2: GC-MS spectra of methanolic extract of *Phormidium* species.

chemicals for further validation and development.

Based on the provided table of GC-MS results, the methanolic extract of the cyanobacterium contains a chemically diverse profile with several notable bioactive compounds (Figure 2). The chromatogram is dominated by a major constituent, peak #12, which accounts for 9.13% of the total peak area and has been tentatively identified as a sesquiterpenoid (7-Isopropenyl-1,4a-dimethyl-4,4a,5,6,7,8-hexahydronaphthalen-2(3H)-one). This high relative abundance suggests it is a primary secondary and metabolite in this extract. Additionally, several fatty acid derivatives are present, including n-Hexadecanoic acid (palmitic acid, peak #16) and its methyl ester (peak #15), as well as methyl esters of octadecatrienoic acid (likely linolenic acid, peak #17). These fatty acids are common membrane constituents and often possess reported biological activities such as antimicrobial and antioxidant properties. The extract also features a variety of other compound classes indicative of significant metabolic activity. Notable identifications include benzoic acid (peak #5), a simple aromatic acid with known preservative and antimicrobial functions, and several cyclic compounds like piperitenone oxide (peak #6) and various derivatives of cyclohexane and bicyclic structures (peaks #2, #7, #10). The presence of a phenol derivative with tert-butyl groups (peak #9) is particularly interesting, as such phenolic compounds are frequently associated with potent antioxidant activity. The detection of a fluorobenzoic acid ester (peak #14) is highly unusual, as organofluorine compounds are exceptionally rare in natural cyanobacterial metabolomes. Its presence could be attributed to environmental contamination from anthropogenic sources, given the industrial and agricultural use of fluorinated compounds, or it might represent a rare, true biosynthetic product resulting from unique adaptations to the saline pan environment. Given its rarity, this identification requires definitive confirmation using authentic standards or complementary analytical techniques such as nuclear magnetic resonance spectroscopy.

From a pharmacological perspective, this chemical profile provides a direct rationale for the observed bioactivities of the extract, such as potential antioxidant capacity. The combination of phenolic compounds (peak #9), terpenoids (peak #12), and unsaturated fatty acids (peaks #16, #17) creates a synergistic matrix of molecules capable of free radical scavenging. Furthermore, the antimicrobial potential suggested by benzoic acid and fatty acids aligns with common defensive metabolites in cyanobacteria. The high area percentage and structural complexity of the major sesquiterpenoid (peak #12) highlight it as a prime candidate for isolation and further biological testing to determine its specific role in the extract's overall efficacy. In summary, the GC-MS analysis successfully maps a complex mixture where the identified compounds collectively underpin the extract's bioactive potential, guiding future targeted research on its most abundant and promising constituents. Table 1 presents GC-MS analysis of methanolic extract of *Phormidium* species.

Anti-diabetic assay

Table 1: GC-MS analysis of methanolic extract of *Phormidium* species.

Peak#	Retention time	Area	Area%	Height	Height%	Am-pere-hour	Name
1	8.205	662199318	4.13	66889813	2.33	9.90	2-butenoic acid, 3-methyl-
2	9.241	43100694	0.27	10630908	0.37	4.05	Cyclohexene, 1-methyl-4-(1-methylethyl)-, (R)-
3	10.147	32733910	0.20	9085480	0.32	3.60	7-octen-2-ol, 2,6-dimethyl-
4	11.631	33566889	0.21	15005790	0.52	2.24	Acetic acid, phenylmethyl ester
5	11.975	202066103	1.26	45128390	1.57	4.48	Benzoic acid
6	13.388	57077276	0.36	13526208	0.47	4.22	Piperitenone oxide
7	14.421	101599717	0.63	28255046	0.98	3.60	1,2-cyclohexanediol, 1-methyl-4-(1-methylethenyl)-
8	14.982	10105934	0.06	5905022	0.21	1.71	L-proline, 5-oxo-, methyl ester
9	16.451	92364724	0.58	49104609	1.71	1.88	Phenol, 3,5-bis(1,1-dimethylethyl)-
10	18.117	482963050	3.01	50875581	1.77	9.49	Cyclohexanol, 3-ethenyl-3-methyl-2-(1-methylethyl)-
11	19.017	68291765	0.43	31753813	1.10	2.15	Sobrerol 8-acetate
12	19.363	1464892892	9.13	107369176	3.73	13.64	7-isopropenyl-1,4a-dimethyl-4,4a,5,6,7,8-hexahydro-3H-naphthalen-2-one
13	19.529	114778851	0.72	25895939	0.90	4.43	Bicyclo[3.1.1]hept-2-ene-2-ethanol, 6,6-dimethyl-
14	20.183	274576751	1.71	73092829	2.54	3.76	3-fluorobenzoic acid, heptadecyl ester
15	21.041	92276423	0.58	46441791	1.61	1.99	Hexadecanoic acid, methyl ester
16	21.472	62098380	0.39	18791059	0.65	3.30	n-hexadecanoic acid
17	22.735	54484190	0.34	23818261	0.83	2.29	9,12,15-octadecatrienoic acid, methyl ester, (Z,Z,Z)-
18	23.349	7107200	0.04	3973135	0.14	1.79	2-propenoic acid, 3-(4-methoxyphenyl)-

The α-amylase enzyme plays a central role in carbohydrate digestion by breaking starch into sugars, thereby influencing postprandial blood glucose levels [25]. In antidiabetic research, inhibiting this enzyme is a key therapeutic strategy, as it slows glucose absorption and helps manage hyperglycemia [26]. Therefore, *in vitro* α-amylase inhibition assays serve as a critical, initial screening tool for evaluating the potential of natural extracts or synthetic compounds to develop new anti-diabetic agents.

Figure 3 presents the results of an α-amylase inhibition assay for a *Phormidium* species methanolic extract, demonstrating a potent and dose-dependent inhibitory effect. As the concentration of the extract increases from 10 to 50 µg/mL, the average percentage of enzyme inhibition rises sharply and consistently from 14.39% to 72.05%. This strong positive correlation confirms that anti-diabetic activity is directly linked to the amount of extract present, a key characteristic of an

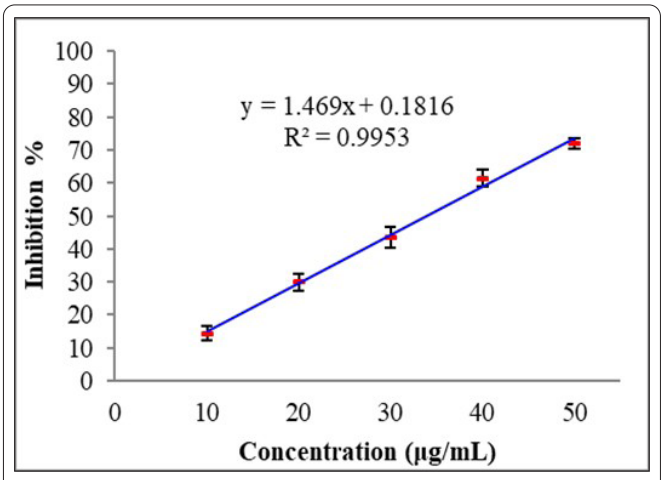


Figure 3: Anti-diabetic (α-amylase enzyme inhibition) assay results of methanolic extract of *Phormidium* species.

effective inhibitor. Furthermore, the accompanying standard deviation values are notably low (ranging from 1.67 to 3.14), indicating that the measurements were highly reproducible with minimal experimental errors. The combination of a clear dose-response trend and low variability validates the reliability of the results and suggests the presence of stable, bioactive compounds within the extract capable of effectively blocking α-amylase function. This profile establishes the *Phormidium* species extract as a promising candidate for further investigation.

Antioxidative assay

The DPPH assay serves as a vital preliminary tool in antioxidative research by providing a rapid and reliable measure of a substance's ability to neutralize stable free radicals [27]. Its importance lies in modeling a compound's hydrogen-donating capacity, which is a fundamental mechanism for combating oxidative stress linked to chronic diseases and aging [27]. Consequently, this assay is indispensable for the initial screening and ranking of natural extracts or synthetic molecules for their potential as protective antioxidants [27].

The DPPH radical scavenging assay data for the *Phormidium* species methanolic extract demonstrates a clear

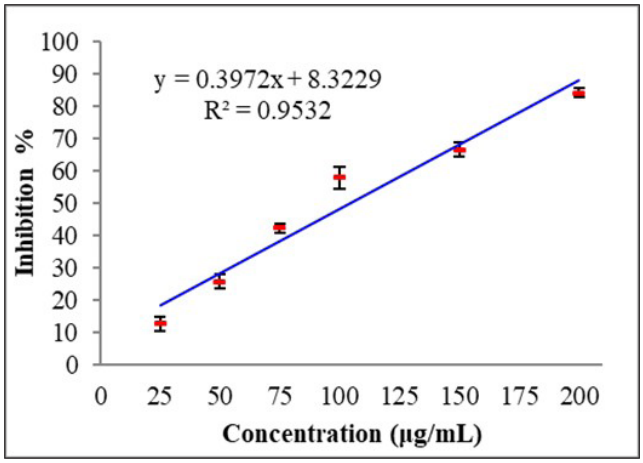


Figure 4: Antioxidative (DPPH radical inhibition) assay results of methanolic extract of *Phormidium* species.

and concentration-dependent antioxidant activity (Figure 4). The average inhibition percentage increases steadily from 12.55% at 25 µg/mL to 83.99% at 200 µg/mL, confirming that the extract's ability to neutralize free radicals is directly proportional to its concentration. The low standard deviation values across all tested concentrations, ranging from 1.42 to 3.34, indicate high experimental reproducibility and reliability of the results. This strong dose-response relationship, coupled with low data variability, validates the *Phormidium* species methanolic extract as a promising source of bioactive antioxidants capable of effectively donating hydrogen atoms to quench DPPH radicals.

Cell viability assay

Cell viability assays, such as the MTT assay, are fundamental in biomedical research for determining the cytotoxicity or safety profile of chemical compounds, drugs, and natural extracts [28]. They provide a direct, quantitative measure of cell health and metabolic activity, which is essential for evaluating therapeutic windows and potential toxic side effects [29]. Consequently, these assays are a critical step in drug discovery and toxicology, enabling researchers to screen for selective agents that target diseased cells while sparing healthy ones.

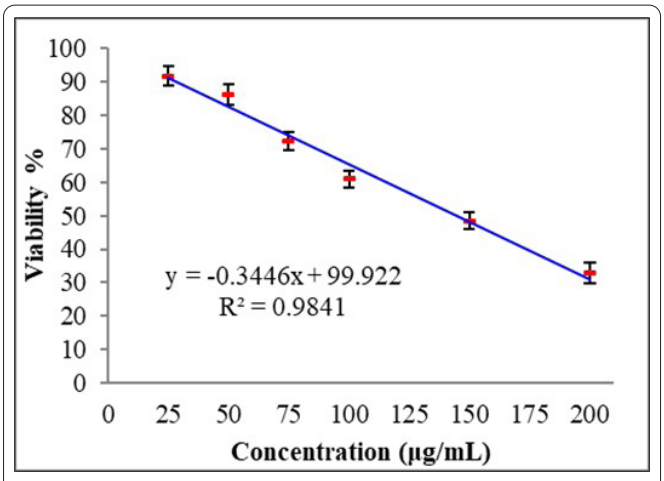


Figure 5: Cell viability assay results against MCF-10A normal cell line of methanolic extract of *Phormidium* species.

Based on the results (Figure 5), the methanolic extract from the cyanobacterium exhibits a significant and dose-dependent cytotoxic effect on the MCF-10A cell line, which is a model of non-tumorigenic, normal human breast epithelial cells. The cell viability, as measured by an assay like MTT, decreases consistently as the concentration of the extract increases. At a low concentration of 25 µg/mL, average cell viability remains high at 91.87%, indicating minimal toxicity. However, viability drops sharply with higher doses, declining to 86.41% at 50 µg/mL, 72.37% at 75 µg/mL, 60.92% at 100 µg/mL, 48.50% at 150 µg/mL, and finally to 32.73% at the highest tested concentration of 200 µg/mL. The low standard deviation values (ranging from 2.39 to 3.09) across all concentrations

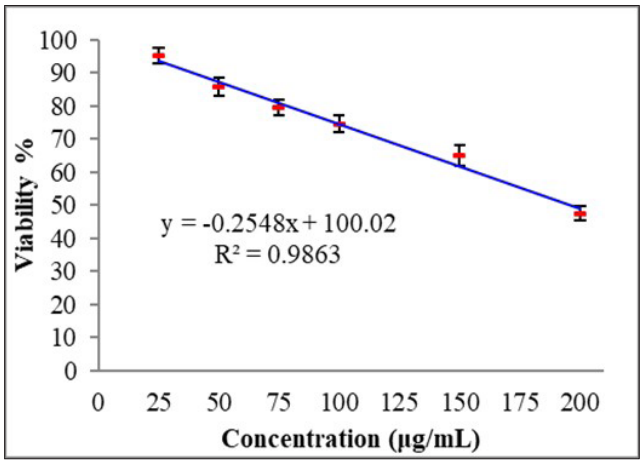


Figure 6: Cell viability assay results against L929 normal cell line of methanolic extract of *Phormidium* species.

confirm the reproducibility and reliability of these results.

Based on the results (Figure 6), the methanolic extract from the cyanobacterium also demonstrates a dose-dependent cytotoxic effect on the L929 cell line, a standard model of mouse fibroblast cells commonly used to assess general cytotoxicity and biocompatibility. The average cell viability decreases progressively from 95.13% at the lowest concentration (25 µg/mL) to 47.46% at the highest concentration (200 µg/mL). This indicates that the extract's toxicity increases with dose, reducing metabolic activity and cell survival in this normal fibroblast cell line. The accompanying standard deviation values are consistently low (ranging from 2.23 to 3.16), which confirms the high reproducibility and reliability of the experimental measurements.

The results from both the MCF-10A (human breast epithelial) and L929 (mouse fibroblast) cell lines reveal a consistent pattern: the cyanobacterial extract exhibits significant, dose-dependent toxicity against normal, non-cancerous cells. In a therapeutic context, this is a critical finding. While the extract contains bioactive compounds (as evidenced by its antioxidant and enzyme inhibition activities), its non-selective cytotoxicity toward normal cell lines suggests a broad toxic mechanism that would be undesirable for a systemic drug candidate. This outcome underscores the importance of such cell viability assays in the early stages of drug discovery. The results indicate that further work, such as compound isolation, modification, or testing on specific cancer cell lines, is necessary to determine if any components possess a therapeutic window—targeting diseased cells without harming healthy ones.

Conclusion

In conclusion, this study successfully isolated and identified a *Phormidium* species from the Marakkanam salt pan and prepared a methanolic extract for comprehensive bioactivity profiling. GC-MS analysis revealed a chemically diverse profile rich in potential bioactive compounds, including a major sesquiterpenoid, fatty acids, and phenolic derivatives. The extract demonstrated promising dose-dependent α-amylase inhibition and significant DPPH radical scavenging activity, confirming its anti-diabetic and antioxidant potential. However, the concurrent, dose-dependent cytotoxicity observed against normal MCF-10A and L929 cell lines represents a significant constraint that precludes the direct use of the crude extract for therapeutic or nutraceutical purposes. Therefore, these findings collectively emphasize that while the *Phormidium* extract is a valuable source of bioactive leads, its therapeutic application is strictly contingent upon the purification and isolation of specific compounds to separate the desired bioactivities from the cytotoxic effects, thereby achieving a favorable therapeutic window for future development.

Future Prospects

Building on the identification of key bioactive compounds, the immediate research prospects focus on translating these findings into practical applications for food science. To advance this extract from a bioactive lead to a functional food ingredient, future work must prioritize the purification of the major sesquiterpenoid (peak #12) and phenolic compounds (peak #9) through bioassay-guided fractionation. Their efficacy and safety as natural preservatives or antioxidant agents should then be evaluated in real food matrices—such as edible oils, dairy, or meat products-to assess their ability to inhibit spoilage, prevent lipid oxidation, and extend shelf-life. Concurrently, detailed toxicological studies, including *in vivo* models and genotoxicity assays, are essential to establish their safety profile for human consumption.

Looking toward innovative applications in food nanotechnology, the isolated cyanobacterial bioactive offer significant potential for development into advanced delivery systems. Future studies should explore nanoencapsulation techniques-using liposomes, biopolymer nanoparticles, or nanoemulsions to protect these sensitive compounds from degradation, mask any undesirable flavors, and enhance their bioavailability in functional food formulations. Furthermore, leveraging the selective bioactivity of these compounds could lead to the development of active and intelligent packaging materials. Incorporating them into packaging films could create systems that actively release antimicrobial or antioxidant agents or function as nanosensors for the colorimetric detection of food spoilage, directly contributing to active-packaging and food safety technologies.

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Conflict of Interest

None.

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