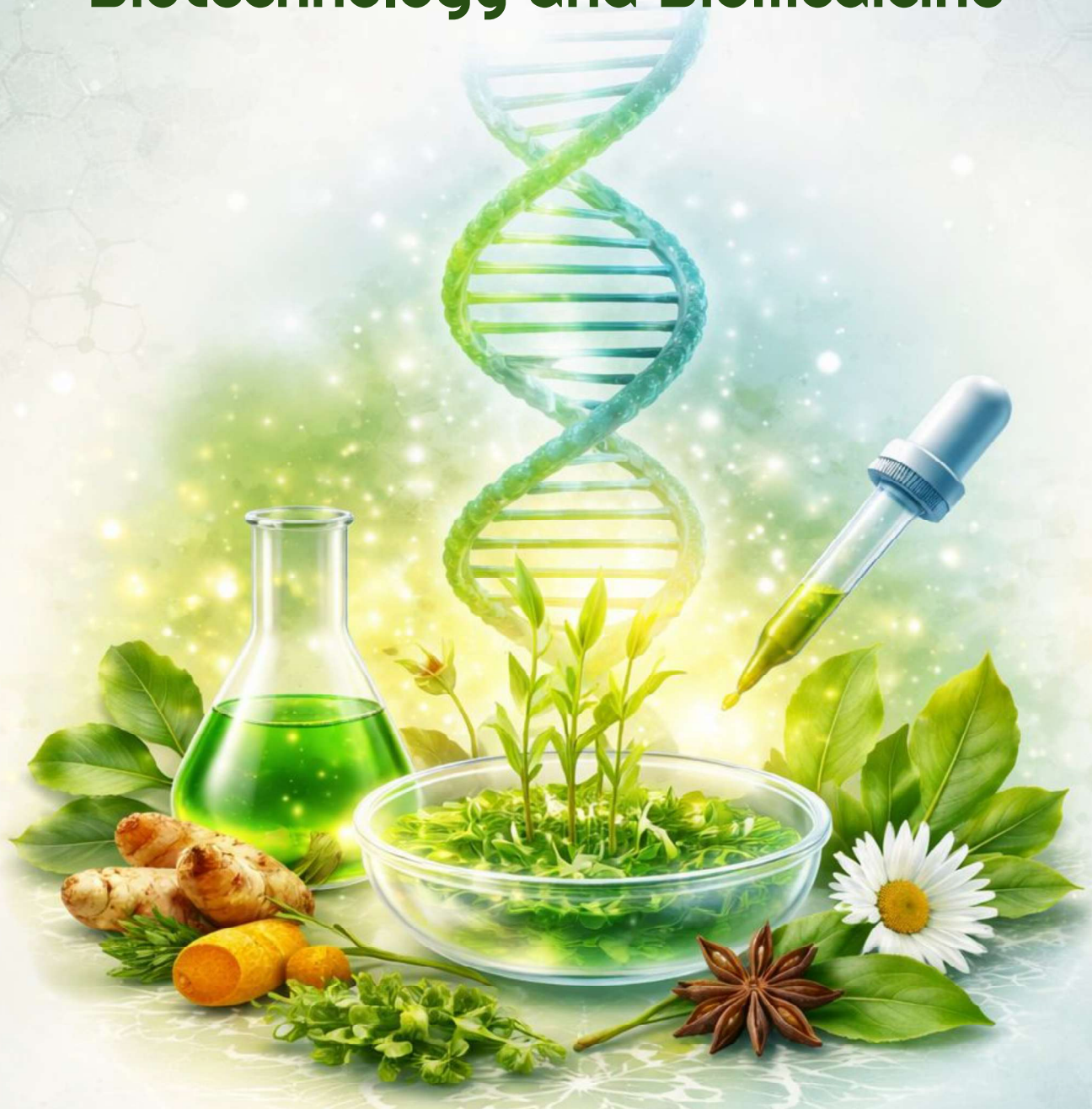
Emerging Bioactive Resources in Biotechnology and Biomedicine



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ISBN 978-816855383-5

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April 2026

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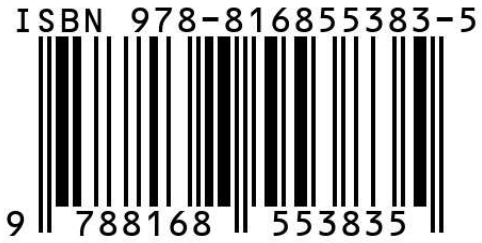
April 2026

ISBN: 978-81-685538-3-5



Published By

SCIENTIFIC RESEARCH REPORTS
(A Book Publisher, approved by Govt. of India)

I Floor, S S Nagar, Chennai - 600 087,
Tamil Nadu, India.

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www.srrbooks.in

PREFACE

The rapid advancement of biotechnology and biomedicine has ushered in a transformative era in the exploration and utilization of bioactive resources derived from nature. The book ***Emerging Bioactive Resources in Biotechnology and Biomedicine*** is conceived as a comprehensive compilation that highlights innovative research directions, bridging fundamental biological insights with applied technological solutions. It brings together diverse studies that emphasize the immense potential of plant, microbial, and marine-derived bioactive compounds in addressing critical challenges in healthcare, environmental sustainability, and industrial applications.

This volume is structured to reflect the interdisciplinary nature of modern biotechnological research. The initial chapters focus on endophytic fungi and phytochemical investigations of medicinal plants, illustrating how naturally occurring bioactive compounds can be harnessed for therapeutic and preservative applications. Detailed studies on species such as *Commelina benghalensis*, *Euphorbia hirta*, *Heliotropium indicum*, and *Allium sativum* provide valuable insights into their chemical composition and pharmacological relevance, reinforcing the importance of traditional knowledge in contemporary biomedical research.

A significant portion of the book is dedicated to microbial and marine bioresources, which are increasingly recognized as rich reservoirs of novel compounds. Contributions on marine microorganisms and sponge metabolites explore their roles in environmental bioremediation and anticoagulant development, respectively. These chapters underscore the untapped potential of

marine ecosystems in yielding next-generation bioactive agents with significant clinical and ecological applications.

The integration of biotechnology with sustainability is another central theme of this book. Chapters addressing enzyme-assisted waste degradation, microbial pigments, and agro-industrial waste utilization demonstrate innovative approaches to waste management and value addition. Furthermore, the development of biodegradable packaging systems, colorimetric sensor labels, and bio-based preservatives reflects the growing emphasis on eco-friendly and smart materials in food technology and environmental protection.

Advancements in material science and nanobiotechnology are also prominently featured. The inclusion of research on nanoencapsulation-driven hydrogel systems for autonomous concrete crack healing exemplifies how biological principles can be applied beyond traditional biomedical boundaries, extending into infrastructure and engineering domains. Such interdisciplinary innovations highlight the evolving scope of biotechnology in solving real-world problems.

Collectively, this book aims to serve as a valuable resource for researchers, academicians, and industry professionals seeking to explore emerging trends in bioactive resource utilization. By integrating phytochemistry, microbiology, nanotechnology, and environmental biotechnology, it provides a holistic perspective on the future directions of the field. It is hoped that this compilation will inspire further research, foster collaboration, and contribute to the development of sustainable and impactful biotechnological solutions.

We extend our sincere thanks to our publisher, Scientific Research Reports, Chennai, India, for their dedicated efforts in preparing this book and for ensuring the inclusion of enriched and high-quality technical content.

Wishes and Regards,

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CONTENTS

Chapter 8

Exploring Marine Sponge Metabolites as Next-Generation Anticoagulant Agents

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Abstract

Thrombotic and cardiovascular diseases constitute major global health problems because they rank among the top reasons people get sick and die throughout the world. Anticoagulant therapy functions as an essential treatment method which helps patients avoid thromboembolic events while also treating these medical conditions. The current anticoagulants which include heparin and warfarin and direct oral anticoagulants (DOACs) present numerous challenges because they create bleeding dangers and drug interaction problems and they have narrow treatment ranges and their extended use creates safety issues. The existing problems with anticoagulant agents demonstrate an urgent requirement for new anticoagulant drugs which offer better safety features and more reliable performance. The vast biological diversity and distinct chemical properties of marine ecosystems create an exceptional opportunity to discover new therapeutic drugs which remain mostly unexplored. Sponges from the Porifera phylum function as the main sources which produce bioactive secondary metabolites in marine environments. The simple body structure of sponges together with their microbial symbiotic relationships enables them to create a wide

ISBN 978-816855383-5

range of chemical substances that contain valuable medicinal properties. Marine sponge metabolites exist in several different classes which include sulfated polysaccharides and alkaloids and terpenoids and steroids and peptides and glycosaminoglycan-like molecules because most of these substances demonstrate powerful anticoagulant properties. The compounds produce their effects through several pathways which include thrombin and factor Xa coagulation factor inhibition and antithrombin III activation and platelet aggregation suppression and fibrin formation disruption. The studies which used in vitro coagulation assays and in vivo thrombosis models produced results that showed anticoagulant effectiveness with potentially reduced side effects when compared to traditional medications. The advantages which exist with these benefits face multiple obstacles which need to be addressed before proceeding.

Keywords: Marine sponges, Anticoagulant therapy, bioactive metabolites, Thrombotic disorders, Sulfated polysaccharides.

1. Introduction

Anticoagulants play a vital role in thromboembolic event management because thrombotic and cardiovascular diseases continue to cause severe worldwide human suffering and death. The medical use of heparin warfarin and direct oral anticoagulants (DOACs) has advanced patient care but these medications still present dangers which include bleeding risks and monitoring requirements and drug interaction issues and long-term safety doubts (Weitz & Eikelboom, 2016). The development of novel agents with improved safety and selectivity needs to take place now. Marine sponges (phylum Porifera) provide a wide range of bioactive metabolites which their anticoagulant compounds demonstrate as

potential sources for creating advanced therapeutic solutions (Mehbub et al., 2014).

1.1 Global burden of thrombotic and cardiovascular disorders

Thrombosis and cardiovascular diseases represent significant global health threats which contribute to both disease burden and mortality rates. Blood clots lead to critical medical emergencies which include heart attacks and strokes and pulmonary embolism and vascular thrombosis. The World Health Organization reports that cardiovascular diseases result in approximately one-third of worldwide deaths each year with thrombotic complications serving as a primary factor (World Health Organization, 2023). The increasing number of elderly people combined with the rising occurrence of sedentary behavior and obesity and diabetes and hypertension leads to higher rates of these conditions in developing nations (Roth et al., 2020). Thrombosis prevention and management require priority status in cardiology because these conditions create severe financial and social impacts.

1.2 Limitations of conventional anticoagulant drugs

Anticoagulant medications serve as essential treatments for thromboembolic disorders, but their clinical applications face multiple challenges. The use of unfractionated heparin and low-molecular-weight heparins leads to two major complications because they cause bleeding and heparin-induced thrombocytopenia and require patients to receive intravenous or subcutaneous treatment which prevents their long-term use (Greinacher, 2015). Patients face difficulties with warfarin therapy because of two main factors which include its narrow therapeutic window and high inter-patient variability together with its multiple drug and dietary interactions

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that require regular monitoring. Direct oral anticoagulants (DOACs) provide better convenience for users but still present bleeding hazards together with problems related to renal clearance and the availability of reversal agents and patient eligibility limitations (Connolly et al., 2018).

1.3 Marine biodiversity as a source of novel therapeutics

Marine biodiversity functions as a major repository of chemical and biological diversity which holds significant potential for finding new medical treatments. Organisms that inhabit marine environments develop specialized metabolic processes which enable them to create complex secondary metabolites that exhibit powerful biological effects. Marine natural products have played a vital role in developing new treatments for cancer and infectious diseases and inflammatory disorders and cardiovascular diseases since their discovery (Molinski et al., 2009). The combination of biotechnology and analytical tools together with genomics technologies has expedited the process of developing marine-based medications. The chemical compounds present in these substances display more diverse molecular structures combined with specific targeting capabilities which make them suitable candidates for developing safer and more effective anticoagulant medications (Leal et al., 2023).

1.4 Biological and chemical uniqueness of marine sponges

Marine sponges stand out as unique ocean species which serve as essential resources for discovering new drugs. Sponges function as basic multicellular organisms that create advanced chemical protection systems to endure extreme marine environments. The organisms produce multiple complex secondary metabolites because they must protect themselves from predators while remaining

stationary (Hentschel et al., 2012). Marine sponges establish tight relationships with their associated microorganisms which include bacteria and archaea and fungi because these microorganisms make up 40 to 60 percent of their total biomass while generating essential metabolites (Thomas et al., 2010). The metabolites produced by the organisms include sulfated polysaccharides and alkaloids and terpenoids and peptides and hybrid molecules which possess uncommon structural features that terrestrial organisms do not typically exhibit.

2. Marine Sponges as Reservoirs of Bioactive Metabolites

Marine sponges serve as crucial resources which provide a wide range of intricate secondary metabolites that scientists use for their drug research work. The metabolites which they produce include saponins and alkaloids and steroids and sulfated polysaccharides that show important medicinal properties through their anticancer and antimicrobial and anti-inflammatory and anticoagulant functions (Proksch et al., 2002). The organism shows chemical diversity because it possesses biological traits which include its ability to move and its close relationship with microorganisms that impact its production of metabolites. The ecological and taxonomic diversity of sponges enables them to produce various chemical compounds which scientists can use to find new drugs that treat cardiovascular diseases and thrombotic disorders (Laport et al., 2009).

2.1 Taxonomy and Ecological Diversity of Marine Sponges (Porifera)

Sponges belong to the phylum Porifera and they represent the earliest form of multicellular marine life which exists in various species throughout the ocean. Their ability to adapt to different environments

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enables them to live in shallow coral reefs as well as deep abyssal zones. The four major classes include Demospongiae, Calcarea, Hexactinellida, and Homoscleromorpha, which display different patterns of body structure and internal framework and reproductive methods. More than 8000 sponge species have been documented worldwide according to the research of Boury-Esnault and Rützler in 1997. Sponges take on essential ecological functions because they filter water and regulate nutrient flow while creating underwater environments that serve as homes for sea life. The organisms produce various secondary metabolites to help them cope with environmental pressures and conflicts which makes them important sources of medicinal components that have bioactive properties.

2.2 Sponge–Microbial Symbiosis and Metabolite Biosynthesis

Marine sponges develop intricate relationships with their microbial partners which include bacteria and fungi and archaea and cyanobacteria. The microbial population of sponges constitutes approximately 40 to 60 percent of their total biomass and this population generates various bioactive secondary metabolites which include alkaloids and polyketides and terpenoids and peptides (Thomas et al. 2016). Sponges and their microbial partners create complex molecules through their metabolic interactions which neither organism can produce independently. Microbial community composition and host species selection and environmental factors determine which metabolites will be produced. Researchers study this sponge–microbe relationship because it offers potential for sustainable drug production through marine biotechnology research which includes developing anticoagulant agents (Piel 2009).

2.3 Chemical Diversity of Sponge-Derived Secondary Metabolites

Marine sponges create multiple secondary metabolites through their environmental interactions and their evolutionary development. The compounds obtained from this research study include alkaloids and terpenoids and polyketides and steroids and peptides which demonstrate important medicinal properties through their ability to fight germs and treat cancer and reduce body inflammation and prevent blood clotting (Faulkner 2002). Their structural complexity in most cases surpasses the natural products found on land, which makes the compounds valuable for drug discovery. The sponge host together with its microbial symbionts establishes biosynthetic pathways which produce distinct chemical structures and functional components. The field of analytical chemistry together with molecular biology has achieved better methods for separating and identifying these metabolites, which proves that marine sponges function as effective sources for discovering new anticoagulant and therapeutic drugs.

2.4 Factors Influencing Metabolite Production and Variability

Several internal and external factors control how sponges create secondary metabolites and what chemical makeup those metabolites possess. The production of metabolites depends on environmental factors which include temperature, salinity, nutrient availability and water depth according to Hentschel and his colleagues. The presence of different microbial symbionts and the genetic diversity of sponge populations and the host's current biological state all work together to create different concentrations of active compounds. Seasonal variations together with ecological processes such as predation and competition track changes in metabolite profiles. Scientists need to

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learn about these elements because they will help improve sustainable production processes and create standardized extraction techniques and boost the medicinal value of sponge metabolites which contain anticoagulant compounds.

3. Classes of Marine Sponge-Derived Metabolites with Anticoagulant Activity

Marine sponges create various secondary metabolites which demonstrate powerful anticoagulant and antithrombotic effects. The compounds present in this study consist of sulfated polysaccharides along with alkaloids and terpenoids and steroids and glycosaminoglycan-like substances. The sulfated polysaccharides contain heparin-like structures which function as coagulation factor inhibitors whereas specific alkaloids and terpenoids can alter thrombin and factor Xa activity (Shanmughapriya et al, 2008). Bioactive peptides together with glycosaminoglycan derivatives have the ability to disrupt fibrin development while also blocking platelet aggregation. The diverse structural characteristics of these metabolites enable different anticoagulant pathways which create excellent possibilities for developing new medications. The development of techniques for isolating compounds and studying their structures together with bioassays has made it possible to conduct organized research on compounds derived from sponges Rangel et al 2019.

3.1 Sulfated Polysaccharides and Heparin-like Compounds

The sulfated polysaccharides which researchers extracted from marine sponges represent the most effective anticoagulant metabolites because their structural composition resembles that of heparin. The compounds contain sugar units which have sulfate

groups that produce high negative charge density, thus enabling them to bind with coagulation factors and antithrombin III, which results in thrombin and factor Xa activity suppression (Farias et al., 2011). The heparin-like polysaccharides which researchers derived from sponges show strong antithrombotic effects in both laboratory and living organism tests while showing lower bleeding tendency than mammalian heparin. The development of NMR spectroscopy and mass spectrometry as analytical methods has led to the discovery of new structures that show improved anticoagulant properties (Li et al., 2018).

3.2 Alkaloids with Thrombin and Factor Xa Inhibitory Properties

Marine sponge-derived alkaloids represent a significant category of nitrogen-containing compounds which display strong anticoagulant properties. The metabolites function through their capability to block essential coagulation enzymes which include thrombin and factor Xa because these enzymes play vital roles in the process of fibrin creation and the maintenance of blood clots (Mayer et al., 2010). The structural components of the compounds which include their heterocyclic rings and halogenated parts and their conjugated side chains enable them to bind with greater strength and selectivity to coagulation enzymes. The in vitro testing of sponge alkaloids revealed their capacity to extend blood coagulation time while they also affected how platelets function. The process of chemical isolation together with high-resolution spectroscopy techniques and bioassay-guided fractionation methods has enabled researchers to find new alkaloids which show potential as anticoagulant drugs (Kijjoa & Sawangwong, 2004).

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3.3 Terpenoids and Steroidal Metabolites Affecting Coagulation Pathways

Marine sponges contain terpenoids and steroids which show potential as anticoagulant substances. The lipophilic compounds present in this study demonstrate capacity to block thrombin function and disrupt fibrin production during the blood clotting process (Wang et al., 2015). Terpenoids which include sesquiterpenes and diterpenes contain hydroxyl and epoxy and sulfate functional groups which improve their ability to bind with coagulation factors. Sponge-derived steroids which include polyhydroxylated and sulfated derivatives show capability to inhibit both thrombin and factor Xa while also displaying antiplatelet effects in preclinical research (Carroll et al., 2019). The structural diversity of these compounds combined with their low toxicity profile establishes them as potential new anticoagulant therapeutic agents.

3.4 Bioactive Peptides and Glycosaminoglycan Derivatives

Bioactive peptides and glycosaminoglycan (GAG) derivatives from marine sponges function as anticoagulant compounds because they bind to specific coagulation factors and platelets. Sponge-derived peptides contain unique amino acid sequences together with post-translational modifications and sulfation which enable them to effectively block thrombin and factor Xa (Mayer et al., 2011). GAG-like molecules such as heparan sulfate analogues function to enhance antithrombin III activity while they control fibrin production which leads to increased clotting duration (Pomin & Mulloy, 2018). The advanced techniques of peptide synthesis combined with mass spectrometry and NMR have produced detailed structural analysis for evaluation of these potential anticoagulant agents.

4. Mechanisms of Anticoagulant Action and Experimental Evaluation

Marine sponge metabolites demonstrate multiple anticoagulant mechanisms which operate by interacting with essential elements of the coagulation cascade and platelet function. The compounds sulfated polysaccharides and glycosaminoglycan derivatives and certain peptides together boost antithrombin III activity which results in thrombin and factor Xa inhibition while alkaloids and terpenoids show potential to directly block coagulation enzymes according to (Li et al., 2019). The metabolites block platelet aggregation and fibrin formation which stops thrombus formation. The assessment of anticoagulant activity depends on in vitro testing methods which include activated partial thromboplastin time aPTT and prothrombin time PT and thrombin inhibition tests together with animal thrombosis experiments that test both safety and effectiveness according to (Zhou et al., 2020).

4.1 Inhibition of Coagulation Factors (Thrombin, Factor Xa)

The anticoagulant activity of marine sponge metabolites functions through their mechanism which directly blocks vital blood coagulation proteins, specifically thrombin and factor Xa. Thrombin activates fibrin formation and platelet activation, whereas factor Xa transforms prothrombin into active thrombin. Sponge-derived sulfated polysaccharides, glycosaminoglycan analogs, and certain alkaloids inhibit these enzymes through their active site binding, which results in extended clotting duration according to (Li et al., 2020) the structural characteristics of these compounds, including sulfation degree, chain length, and functional groups, determine their ability to inhibit. The combined results from chromogenic and clotting

ISBN 978-816855383-5

assays demonstrate that test compounds show strong dose-dependent inhibition, which sometimes produces effects that resemble standard anticoagulants but results in fewer side effects.

4.2 Activation of Antithrombin III and Modulation of Coagulation Cascades

The anticoagulant properties of marine sponge metabolites which include sulfated polysaccharides and glycosaminoglycan analogs demonstrate their ability to potentiate the natural blood clotting inhibitor antithrombin III (ATIII). The compounds interact with ATIII proteins by changing their shape which leads to faster thrombin and factor Xa and serine proteases inhibition that controls blood clotting (Pomin, Mourão, & Mulloy, 2015). The method establishes prolonged blood clotting duration because it provides protection against excessive bleeding through non-competitively binding to enzymes. The metabolites from sponges can affect both fibrin creation and platelet clumping which helps to sustain normal blood clotting processes (Wang, Guo, & Sun, 2017). The research evidence demonstrates that ATIII activation functions as the main mechanism through which they produce their blood-thinning effects.

4.3 Effects on Platelet Aggregation and Fibrin Formation

Marine sponge metabolites function as anticoagulants because they disrupt two essential processes that lead to thrombus formation through their effects on platelet aggregation and fibrin formation. The sulfated polysaccharides and glycosaminoglycans together with bioactive peptides work to inhibit platelet activation through their ability to block receptor signaling, which results in decreased platelet adhesion and aggregation at vascular injury sites (Zhao, Li, & Wang, 2018). The metabolites that (Kim et al., 2019) discovered can change

the process of fibrin polymerization because they prevent the development of strong fibrin clots and extend the duration of clotting. The combination of platelet inhibition together with fibrin modulation creates an effective antithrombotic treatment that has reduced likelihood for causing major bleeding events.

4.4 In vitro Anticoagulant Assays and Biochemical Evaluation Methods

Researchers apply various laboratory tests to examine how marine sponge metabolites impact blood clotting and platelet activity because these tests enable them to discover new anticoagulant substances. The activated partial thromboplastin time (aPTT) and prothrombin time (PT) tests enable assessment of both intrinsic and extrinsic pathways in the coagulation system (Soma et al., 2017). The assays use chromogenic assays and thrombin inhibition tests to measure direct thrombin and factor Xa inhibitory effects (Wang et al., 2019). The tests assess how the compounds affect platelet activity and blood clot formation which gives vital information about their strength response to different doses and how they work before testing in live animals.

5. Translational Potential, Challenges, and Future Perspectives

Marine sponges serve as essential resources to create new anticoagulant medications which will be developed in the future. Their metabolites show high structural diversity which enables them to create various effects while maintaining low toxicity (Mayer et al., 2017). The compounds function by two mechanisms which include their capacity to block coagulation factors and their ability to control platelet aggregation while increasing antithrombin III activity which leads to lower thrombus formation and minimal bleeding problems.

ISBN 978-816855383-5

The clinical development process faces multiple obstacles which include maintaining metabolite sources and dealing with compositional changes and handling complex chemical structures and producing products at industrial scales (Blunt et al., 2018). Future research efforts which concentrate on high-throughput screening and structure–activity relationship studies and synthetic analogs and microbial fermentation will help to advance drug development and supply processes.

5.1 Comparative Advantages over Existing Anticoagulant Therapies

Marine sponge metabolites present multiple benefits which exceed the properties of traditional anticoagulants including heparin warfarin and direct oral anticoagulants. They often exhibit lower bleeding risk and broader mechanisms of action which include selective inhibition of thrombin and factor Xa and modulation of platelet aggregation (Pomin & Mulloy, 2018). Natural compounds typically act on multiple points of the coagulation cascade which may reduce the likelihood of therapeutic resistance (Mayer et al., 2010). The structural diversity of compounds enables researchers to conduct chemical modifications which enhance their pharmacokinetic and pharmacodynamic properties. The method of production through microbial fermentation and biotechnological techniques provides an environmentally friendly process which creates a production system with sustainable resources.

5.2 Toxicological, Pharmacokinetic, and Biocompatibility Considerations

Anticoagulants derived from marine sponges require complete testing of their toxicological profile and drug absorption and elimination and

safety testing before they can enter clinical practice. Research shows that experimental subjects demonstrate safe results when they receive sulfated polysaccharides and peptides and glycosaminoglycan derivatives (Farias et al., 2011). The pharmacokinetic properties of drugs which include how the body absorbs and distributes and processes and eliminates drugs depend on molecular weight and sulfation patterns and structural changes according to research by Silchenko et al. The detection of adverse effects and the establishment of extended safety records necessitate biocompatibility testing which includes tests for immunogenicity and hematological performance. Chemical modifications and formulation strategies enable the creation of products with enhanced stability and improved bioavailability and precise target delivery capabilities.

5.3 Challenges in Scalability, Standardization, and Formulation

Marine sponge metabolites display strong anticoagulant properties but face multiple barriers which hinder their progress toward becoming pharmaceutical products. The production process cannot achieve large-scale manufacturing because different species exhibit unique metabolite profiles which result from their environmental surroundings and their associated microbial populations (Sipkema et al., 2005). The chemical synthesis and purification processes, which produce stable outputs of sulfated polysaccharides and peptides and terpenoids, face challenges because of the compounds' structural complexity. The development of therapeutic delivery systems requires researchers to solve formulation problems associated with stability and solubility and bioavailability (Faulkner, 2002). The production of these anticoagulant compounds can be achieved through sustainable methods which enable reproducible results according to the

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biotechnological methods that include microbial fermentation and sponge cell culture and semi-synthetic modification.

5.4 Regulatory, Ethical, and Environmental Considerations

Researchers need to evaluate regulatory requirements and ethical considerations and environmental impacts when they want to develop anticoagulants from marine sponge organisms. The process of obtaining clinical approval requires extensive testing to establish safety and efficacy and product quality which includes adherence to Good Manufacturing Practices (GMP) and all preclinical and clinical testing (Molinski et al., 2009). The practice of ethical sourcing works to stop overharvesting and habitat destruction and biodiversity loss. Researchers need to conduct environmental impact assessments to confirm that sponge collection or cultivation will not damage marine ecosystems (Leal et al., 2012). Drug development follows environmentally responsible and ethically sound practices through the use of sustainable production methods which include sponge aquaculture and microbial fermentation and cell culture.

6. Conclusion

The research demonstrates that marine sponge metabolites can serve as future anticoagulant drug development candidates. Marine sponges provide a wide range of bioactive substances which medical research uses to develop treatments for thrombosis and cardiovascular disorders. The organisms produce sulfated polysaccharides and alkaloids and terpenoids and steroids and peptides and glycosaminoglycan-like molecules because they possess distinct chemical properties and live in harmony with their existing microorganisms. The compounds produce anticoagulant effects through multiple pathways which include direct thrombin and factor

Xa inhibition together with antithrombin III activation and platelet aggregation suppression and fibrin formation disruption. The research shows their effectiveness together with safety and medicinal properties through laboratory tests and animal models that study thrombosis. The majority of sponge metabolites function as multiple types of drugs which produce less bleeding than regular anticoagulant medications. The process of developing these compounds into approved medical treatments faces multiple obstacles that involve difficulties in sustainable sourcing and variations in metabolite makeup and complexities in chemical structure and challenges in producing the product and issues with product development and various regulatory demands. The scientific fields of biotechnology and sponge aquaculture and microbial fermentation and semi-synthetic modification and computational drug design provide effective methods to solve these existing challenges. The development of safe and effective and sustainable anticoagulant treatments from marine sponges requires interdisciplinary research that combines marine biology with chemistry and pharmacology and biotechnology.

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