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Impact of Marine Biomaterial Extraction on Regenerative Medicine & Apex Predator Populations

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ABSTRACT

Marine-derived biomaterials have emerged as transformative tools in regenerative medicine and tissue engineering, offering sustainable and biocompatible alternatives to synthetic materials. This investigation explores the dual impact of biomaterials such as coral, chitosan, collagen, sea star-derived compounds, and sea urchin byproducts in advancing medical applications, including bone regeneration, scaffolding, wound healing, and drug delivery. These materials demonstrate significant potential for promoting cell proliferation, tissue regeneration, and structural support. However, extracting these biomaterials raises ecological concerns, particularly the destabilization of apex predator populations like sharks, which are essential for maintaining marine biodiversity and trophic balance. Unsustainable harvesting practices can disrupt ecosystems, causing cascading effects and biodiversity loss. The findings emphasize the necessity of adopting sustainable sourcing practices to mitigate environmental impacts while fostering medical innovation. By bridging regenerative medicine and marine ecology, this study highlights the importance of interdisciplinary approaches to align technological advancements with ecological preservation, ensuring the long-term stability of marine ecosystems and biomedical progress.

Introduction

Marine-derived biomaterials have emerged as a transformative force in regenerative medicine and tissue engineering, providing sustainable alternatives to synthetic materials. These biomaterials, such as coral, chitosan, and collagen, have demonstrated exceptional biocompatibility and versatility in applications ranging from bone regeneration to wound healing and drug delivery systems. These materials have revolutionized medical advancements, offering innovative solutions for orthopedic challenges, scaffolding, and tissue repair. However, the extraction of marine-derived biomaterials presents significant ecological challenges. Apex predators such as sharks and dolphins, integral to maintaining marine biodiversity and trophic balance, face population declines due to habitat destruction, overfishing, and the unsustainable harvesting of biomaterials. The research highlights the importance of leveraging marine biomaterials for medical progress while addressing their ecological impact.

Studies have shown that unsustainable practices disrupt aquatic ecosystems, leading to cascading effects that threaten biodiversity. These challenges highlight the urgent need for sustainable extraction practices that align with ecological preservation while fostering technological advancements. This investigation bridges the fields of regenerative medicine and marine ecology, focusing on the delicate balance between innovation and conservation. By synthesizing insights from various peer-reviewed studies, the research aims to propose sustainable methods of biomaterial extraction that ensure long-term ecosystem stability. The study emphasizes the necessity of an interdisciplinary approach to address the environmental and biomedical implications of utilizing marine-derived resources, providing a framework for future research that aligns ecological integrity with medical innovation (OpenAI, 2024).

Problem Statement

The increasing reliance on marine-derived biomaterials in regenerative medicine and tissue engineering highlights a significant intersection between medical innovation and ecological sustainability. Biomaterials such as coral, chitosan, and collagen are highly sought for their biocompatibility and effectiveness in bone regeneration, wound healing, and scaffolding. However, extracting these materials presents environmental challenges, particularly concerning marine ecosystems and apex predators such as sharks and dolphins, which play a critical role in maintaining biodiversity and trophic balance. Research shows that overexploitation for biomaterials can lead to habitat destruction, population decline of critical species, and trophic cascades destabilizing ecosystems. While marine biomaterials offer significant medical benefits, unsustainable sourcing practices risk irreversible ecological damage. A lack of integrated research addressing biomedical advancements and environmental impacts further exacerbates this issue, leaving gaps in understanding the long-term consequences of biomaterial extraction. This problem underscores the urgent need for sustainable biomaterial harvesting methods that minimize ecological disruption while fostering medical innovation, ensuring a balanced approach that protects marine biodiversity and promotes advancements in regenerative medicine (OpenAI, 2024).

Purpose

This investigation is significant due to its interdisciplinary focus on the intersection of regenerative medicine and marine ecology. Marine-derived biomaterials have transformed medical fields such as tissue engineering and wound healing, offering biocompatible and sustainable alternatives to synthetic materials. However, their extraction threatens marine ecosystems, particularly apex predators like sharks and dolphins, whose population declines can trigger trophic cascades. Highlighting the need for sustainable sourcing methods ensures that medical advancements do not come at the cost of biodiversity loss. The novelty of this research lies in its effort to integrate ecological preservation with biomedical progress, providing a framework for future interdisciplinary studies. Raising awareness about these issues can lead to innovative solutions that protect marine ecosystems while fostering advancements in medical science. This research offers a valuable contribution by addressing a critical balance between technological progress and environmental conservation (OpenAI, 2024).

Research Questions

1. How can the sustainable extraction of marine-derived biomaterials balance the advancements in biomedical engineering and regenerative medicine considering the conservation of apex predator populations?
2. What sustainable practices can be implemented in extracting marine-derived biomaterials to ensure the conservation of apex predators and maintain the balance of marine biodiversity without contributing to environmental stressors while advancing in tissue engineering and regenerative medicine?

Research Objectives

1. To evaluate sustainable extraction methods for marine-derived biomaterials that balance the advancements in biomedical engineering and regenerative medicine while considering the conservation of apex predator populations and ecosystem biodiversity.
2. To identify and propose sustainable practices for the extraction of marine-derived biomaterials that mitigate environmental stressors, ensure apex predator conservation, and support advancements in tissue engineering.

Theoretical Framework

Marine-derived biomaterials have gained prominence in regenerative medicine due to their biocompatibility and ecological potential. Choi and Ben-Nissan (2019) discuss the structural advantages of coral and nacre in tissue regeneration, showcasing their ability to promote bone growth. Similarly, Venkatesan et al. (2021) emphasize polysaccharide-based biomaterials, such as chitosan, for their biodegradability and compatibility in medical applications. Domínguez-Guevara et al. (2022) explore sustainable alternatives like 3D scaffolds for fibroblast cultures, reducing the need for direct marine organism harvesting. Roncoroni et al. (2024) demonstrate innovative uses of sea urchin byproducts in creating bioactive compounds for tissue engineering, highlighting sustainable practices.

Finally, Matich et al. (2011) emphasize the ecological role of apex predators, such as sharks, in maintaining marine biodiversity, drawing attention to the risks of unsustainable extraction practices. Together, these sources underscore the dual focus of this investigation: advancing biomedical innovation while ensuring ecological conservation (Open AI, 2024).

Definition of Terminologies

1. Biocompatibility: Coined in the mid-20th century, biocompatibility refers to the ability of a material to perform with an appropriate host response in a specific application. It is a critical property of biomaterials, particularly in tissue engineering, as it ensures that the material does not elicit harmful reactions when integrated into the human body.
2. Polysaccharides: First defined in the late 19th century, polysaccharides are complex carbohydrates composed of long chains of monosaccharide units. Chitosan, a derivative of chitin found in crustacean shells, is a notable polysaccharide used in regenerative medicine for its biodegradability and antimicrobial properties.
3. Trophic Cascade: Introduced by ecologists in the late 20th century, trophic cascades describe the ecological process by which changes in predator populations affect the abundance and distribution of prey species, subsequently influencing lower trophic levels. This concept is crucial in understanding the ecological impact of apex predator declines due to biomaterial extraction.

Review of Literature

Marine Biomaterials for Regenerative Medicine

The investigation by Choi and Ben-Nissan (2019) explores the potential applications of marine-derived biomaterials like coral, sponges, and nacre seashells in tissue engineering and regenerative medicine. Focusing on these materials' structural and morphological benefits, this study provides insight into how they are effective alternatives to synthetic biomaterials for bone formation and tissue scaffolding. By employing a descriptive analysis methodology, this research targets academic professionals and clinicians interested in the intersection of bioengineering and sustainability. The findings suggest that these biomaterials benefit cell proliferation and osteopromotion in orthopedic contexts, though long-term sustainability and structural integrity remain essential. The study concludes with a call for further research to validate these findings, highlighting a critical need for sustainable practices that can support ongoing medical advancements without compromising marine ecosystems:

Highly accessible collections of structural designs are provided by the rich taxonomic assortment of intricate calcite structures throughout the lower orders of the animal kingdom. A number of these structures will offer application for which they had not been originally designed, for instance the reticulated filtration system makes an ideal structure for drug entrapment and delivery by chance. Presently, natural invertebrate skeletons are almost impossible to replicate using artificial means even though how these structures are synthesized at a molecular level in addition to how they are intrinsically assembled is well-known. As an alternative, chemistry that imitates simple forming phases during the morphogenesis of shell structures has created materials and constructs with similar detailed morphology and function. (Choi, 2019)

The following publication emphasizes the surfacing of biomaterials derived from marine structures such as corals, skeletons, nacre seashells, sponges, and others, all being developed for tissue engineering. All of which offer a sustainable alternative to synthetically produced biomaterials, considering the economic and environmental aspects. The work provides an investigative perspective on marine organisms as scaffolds in regenerative medicine. The findings also imply that marine-derived biomaterials support tissue growth and contribute to the progression of bone formation and alternate tissues. The clinical potential is highlighted throughout the investigation by gathering and synthesizing data from other studies and recognizing the necessity of advancing future research in long-term applications. The alternative perspective of the researchers prioritizes the sustainability of biologically engineered materials derived from marine species while also addressing the scaffolding of these materials in the field of tissue engineering and regenerative medicine regarding marine organisms.

Collagen-Free 3D Scaffolds and Apex Predators

Domínguez-Guevara et al. (2022) investigate developing a collagen-free 3D scaffold system designed explicitly for bottlenose dolphin fibroblast cultures. The study proposes this model as a sustainable alternative to biomaterials that require direct extraction from live marine organisms. Using a descriptive analysis approach, the researchers target marine mammal biology and tissue engineering professionals. This innovative scaffold system demonstrates the potential for regenerative applications, such as surgical use, while avoiding the ecological impact of traditional biomaterial sourcing. The research highlights the successful cell proliferation of dolphin fibroblasts within the scaffold system, emphasizing sustainability and suggesting it as a viable substitute for marine-derived biomaterials. However, further investigation is recommended to assess the scaffold's long-term stability and efficacy in replicating in vivo conditions:

Dolphins, as apex predators, can be considered relevant sentinels of the health of marine ecosystems. The creation of 3D cell models to assess in vitro cell-to-cell and cell-to-matrix interactions in environmental-mimicking conditions, is of considerable interest. However, to date the establishment of cetacean 3D culture systems has not yet been accomplished. Thus, in this study, different 3D systems of bottlenose dolphin (Tursiops truncatus) skin fibroblasts have been analyzed. Particularly, novel scaffolds based on hyaluronic acid and ionic-complementary self-assembling peptides such as RGD-EAbuK and EAbuK-IKVAV have been compared to Matrigel. Histological and fluorescent staining, electron microscopy (TEM) analyses and viability assays have been performed and RT-PCR has been used to detect extracellular matrix (ECM) components produced by cells. Results showed that Matrigel induced cells to form aggregates with lower viability and no ECM production compared to the novel scaffolds. Moreover, scaffolds allowed dispersed cells to produce a collagenous ECM containing collagen1a1, laminin B1 and elastin. The HA-EAbuK-IKVAV scaffold resulted in the most suitable 3D model in terms of cell quantity and viability. The development of this innovative approach is the first step towards the possibility to create 3D in vitro models for this protected species. (Dominguez, 2022)

The importance of this investigation truly lies in the ability to provide 3D in vitro bottlenose dolphin fibroblast culture as a more sustainable alternative to commonly used marine-derived biomaterials such as collagen. It provides a new development for studying the environmental stressors for apex predators, such as dolphins, and how they can ultimately affect whole ecosystems. The long-term preservation of apex predators is being taken into account by promoting the usage of alternate tools aside from biomaterials, which are engineered using direct sampling from marine organisms, which could ultimately affect the experimented species long term. The regenerative quality of the model is also closely related to that of biomaterials; therefore, the effectiveness problem is not a factor in this investigation. The developed cell growth shows promise for further project development and how it can be used for medical and surgical application purposes concerning tissue engineering. By providing a sustainable and effective alternative to directly sampled marine-derived biomaterials, the research created a tool to avoid possible damage to ecosystems or cascades, which could be a factor in biomaterial extraction in some cases. Overall, the findings in the study provide a broader perspective on the alternative use of commonly used marine-derived biomaterials, their effects on apex predators such as bottlenose dolphins such as environmental stressors, and their quality of advancement in tissue engineering or regenerative medicine.

Marine Collagen-Apatite Scaffolds for Hard Tissue Engineering

Moscato et al. (2014) investigate marine collagen-apatite scaffolds sourced from fish skin collagen and shark tooth apatite, designed for hard tissue engineering applications. This research demonstrates that these scaffolds exhibit effective cell proliferation and biocompatibility, proving suitable for bone regeneration. Conducted using an experimental approach with in vitro testing, the study addresses both scientific researchers and conservationists focused on sustainable biomaterial extraction. The authors suggest that if harvested responsibly, marine biomaterials can fulfill medical needs without substantial ecosystem disruption. This study emphasizes the significance of balancing biomedical benefits with conservation, advocating for additional studies on sustainable sourcing methods:

Calcium silicate (CaSiO3 or CS), a bioactive ceramic, is a suitable and promising alternative approach in the bone regeneration and regenerative medicine field due to its biocompatibility, high osteo-conductivity, and appropriate mechanical properties. The ability to induce the formation of a hydroxyapatite (HA) layer on a calcium silicate surface in vitro and in vivo is another significant feature of this material. CaSiO3 has been widely known since the 1970s, when Hench and coworkers discovered bioglassVR. However, the brittleness of pure CS bioceramic restricts its use for high-strength biomedical applications. One approach to enhance the mechanical properties of CS is to reinforce its structure with other bioactive or bioinert materials. Although much research has been attempted to improve the properties of calcium silicate bio ceramic, these materials are still extremely brittle and have inherently poor tensile strength, which results in a number of difficulties during the machining and processing stages. Some drawbacks of calcium silicate have encouraged academic centers to work on the development of biopolymer/CS composites.The addition of different ratios of biopolymers has significantly improved the compressive and tensile strengths and the fracture toughness. Furthermore, it was also found that a nano-composite of CaSiO3/biopolymer has greater fracture toughness, stiffness and tensile strength. (Moscato, 2014)

This investigation is necessary for developing marine-derived biomaterials in complex tissue regeneration, which ultimately links to ecological conservation and how the extraction of said biomaterials can affect apex predators. Using apatite from shark teeth and collagen creates a scaffolding system that avoids affecting ecosystems and promotes upcycling. Reliance on in vivo extraction is crucial for preventing dependency in organisms; constant exploitation can lead to environmental alterations and stress. However, more explicitly, extracting from apex predators without moderation can develop into even more severe issues, such as trophic cascades and overpopulation of certain prey. Reducing reliance on harmful methods can make all the difference in supporting the sustainability of ecosystems and creating a stable relationship between upcoming bio-engineered innovations and apex predators. Not only does the potential of developing an alternate biomaterial promote sustainability, but it also contributes to conservation efforts made for marine ecosystems. Therefore, this study not only contributes to biomedical applications of scaffolding collagen and apatite but also a correlation can be found between maintaining a delicate balance of trophic marine ecosystems and bio-engineered innovations.

Polysaccharide-Based Biomaterials: Chitosan and Collagen Applications

The articles by Venkatesan et al. (2021) and Liu et al. (2023) expand on the sustainable applications of marine-derived polysaccharides, primarily chitosan and collagen, in tissue engineering and regenerative medicine. By analyzing these materials' biocompatibility, biodegradability, and structural properties, these studies underscore their suitability as alternatives to synthetic biomaterials. Chitosan, derived from crustacean exoskeletons, and collagen, sourced from fish skin and other connective tissues, demonstrate potential as scaffold materials in cartilage tissue engineering and drug delivery systems. However, sustainable extraction remains essential, as overharvesting could harm marine ecosystems and disrupt apex predator populations. These studies conclude with a call for further research to optimize extraction processes and ensure that marine ecosystems are not compromised. Collectively, these findings support the broader goal of reducing the ecological impact of biomaterial harvesting, contributing to sustainable innovations in regenerative medicine:

Marine resources in unique marine environments provide abundant, cost-effective natural biomaterials with distinct structures, compositions, and biological activities compared to terrestrial species. These marine-derived raw materials, including polysaccharides, natural protein components, fatty acids, and marine minerals, etc., have shown great potential in preparing, stabilizing, or modifying multifunctional nano-/micro-systems and are widely applied in drug delivery, theragnostic, tissue engineering, etc. This review provides a comprehensive summary of the most current marine biomaterial-based nano-/micro-systems developed over the past three years, primarily focusing on therapeutic delivery studies and highlighting their potential to cure a variety of diseases. Specifically, we first provided a detailed introduction to the physicochemical characteristics and biological activities of natural marine biocomponents in their raw state. Furthermore, the assembly processes, potential functionalities of each building block, and a thorough evaluation of the pharmacokinetics and pharmacodynamics of advanced marine biomaterial-based systems and their effects on molecular pathophysiological processes were fully elucidated. Finally, a list of unresolved issues and pivotal challenges of marine-derived biomaterials applications, such as standardized distinction of raw materials, long-term biosafety in vivo, the feasibility of scale-up, etc., was presented. This review is expected to serve as a roadmap for fundamental research and facilitate the rational design of marine biomaterials for diverse emerging applications. (Liu, 2023)

In regards to the previous citation, the following article published by Venkatesan et al., (2021) is also able to state the following:

The body's self-repair capacity is limited, including injuries on articular cartilage zones. Over the past few decades, tissue engineering and regenerative medicine (TERM) have focused the studies on the development of natural biomaterials for clinical applications aiming to overcome this self-therapeutic bottleneck. This review focus on the development of these biomaterials using compounds and materials from marine sources, able to be produced in a sustainable way, as an alternative to mammal sources (e.g., collagens) and benefiting from their biological properties, such as biocompatibility, low antigenicity, biodegradability, among others. The structure and composition of the new biomaterials require mimicking the native extracellular matrix (ECM) of articular cartilage tissue. To design an ideal temporary tissue-scaffold, it needs to provide a suitable environment for cell growth (cell attachment, proliferation, and differentiation), towards the regeneration of the damaged tissues. Overall, the purpose of this review is to summarize, various marine sources to be used on the development of different tissue-scaffolds with the capability to sustain cells envisaging cartilage tissue engineering, analysing the systems displaying more promising performance, while pointing current limitations and steps to be given in the near future. (Venkatesan, 2021)

Marine-derived biomaterials, such as those produced from chitosan and collagen, can be reviewed from a sustainability standpoint rather than solely focusing on their applications. This perspective is crucial in examining how extraction impacts ecosystems. Balancing harvesting these biomaterials with preserving marine ecosystems is essential to ensure that renewable alternatives to mammal-derived biomaterials reduce the ecological footprint. Marine-sourced materials' biodegradability, cost-effectiveness, and environmental sustainability underscore their potential as superior alternatives to conventional biomaterials. For example, chitosan, derived from chitin, is a biodegradable polymer that can be sustainably harvested, as crustacean populations are renewable. Collagen extraction involves fish skins and bones, which may pose sustainability issues due to the larger in vivo subject requirements. The findings emphasize that chitosan, with its regeneration capacity, is more ecologically favorable than collagen. This insight highlights the necessity of assessing sustainability and ecological impact when developing marine biomaterials for biomedical applications.

Sharks' Role as Apex Predators and Biomaterial Sources

Speed et al. (2010) focus on the role of sharks as apex predators, emphasizing their ecological significance in maintaining trophic balance in marine ecosystems. The study examines how shark-derived materials, like cartilage and teeth, are utilized in regenerative medicine and explores the adverse effects of shark population decline caused by overfishing and biomaterial extraction. A documentary analysis approach compiles data from literature, reports, and case studies, targeting conservationists and policymakers. Findings reveal that disrupting shark populations through unsustainable biomaterial extraction risks destabilizing marine ecosystems. The study concludes that while shark-based biomaterials hold medical value, their extraction must be managed sustainably to avoid broader ecological implications:

Apex predators often have strong top-down effects on ecosystem components and are therefore a priority for conservation and management. Due to their large size and conspicuous predatory behaviour, reef sharks are typically assumed to be apex predators, but their functional role is yet to be confirmed. In this study, we used stomach contents and stable isotopes to estimate diet, trophic position and carbon sources for three common species of reef shark (Triaenodon obesus, Carcharhinus melanopterus and C. amblyrhynchos) from the Great Barrier Reef (Australia) and evaluated their assumed functional role as apex predators by qualitative and quantitative comparisons with other sharks and large predatory fishes. We found that reef sharks do not occupy the apex of coral reef food chains, but instead have functional roles similar to those of large predatory fishes such as snappers, emperors and groupers, which are typically regarded as high-level mesopredators. We hypothesiz8e that a degree of functional redundancy exists within this guild of predators, potentially explaining why shark-induced trophic cascades are rare or subtle in coral reef ecosystems. We also found that reef sharks participate in multiple food webs (pelagic and benthic) and are sustained by multiple sources of primary production. We conclude that large conspicuous predators, be they elasmobranchs or any other taxon, should not axiomatically be regarded as apex predators without thorough analysis of their diet. In the case of reef sharks, our dietary analyses suggest they should be reassigned to an alternative trophic group such as high-level mesopredators. This change will facilitate improved understanding of how reef communities function and how removal of predators (e.g., via fishing) might affect ecosystem properties. (Speed, 2010)

The following investigation is crucial to understanding the relationship between apex predators and marine ecosystems, which creates a correlation and chain reaction that influences future technology in bioengineered materials derived from marine organisms. To ultimately concur if the reliance of ecosystems on apex predators could cause a chain reaction if disrupted, trophic cascades are a perfect example. Apex predators help maintain a balance in marine ecosystems; if outside factors disrupt the balance, it could lead to broader ecological implications, such as overpopulation of prey species, creating an overall depletion of lower cascades. Biomaterials such as cartilage and teeth obtained from sharks are linked to sharks' conservation status and overall broader ecological implications. By addressing the trophic ecology of apex predators around the Pacific West Coast, an overview of a sample population of sharks is provided, ultimately affected by environmental stress factors such as climate change, overfishing, and possibly extraction of biomaterials. By addressing the direct and indirect consequences of shark population decline on ecosystems and the biomedical field, this article provides a strong argument for integrating conservation efforts with advances in biomaterial technology and its possible correlation. Overall, the balance between the preservation of ecosystems is emphasized with an implied correlation to technological advancements concerning marine organisms, suggesting that with responsible practices and appropriate conservation, it is possible to create a sustainable relationship between the two without causing harm to aquatic ecosystems.

Sea Urchin Biomaterials: Sustainability and Regenerative Applications

Roncoroni et al. (2024) examine the potential of utilizing sea urchin food waste from P. lividus and S. granularis to create bioactive compounds such as collagen and polyhydroxynaphthoquinones. The study highlights the effectiveness of these biomaterials in wound healing and their potential for applications in drug delivery systems. Collagen extracted from sea urchins was found to promote tissue regeneration while maintaining eco-friendly and sustainable sourcing methods. The research bridges the gap between medical advancements and ecological conservation by repurposing marine waste. The investigation emphasizes the feasibility of upcycling marine byproducts into high-value biomaterials, addressing economic and environmental concerns. The findings align with the broader objective of promoting sustainability in medical innovation, particularly in regenerative medicine:

Recently, it has also been shown that tissues from sea urchin waste are a source of high-value native collagen that was used to develop innovative collagen-based biomaterials for tissue regeneration. Marine collagens are known for their low antigenicity and high biodegradability, useful in various applications. A particularly promising area is tissue regeneration, with the production of three-dimensional scaffolds. Although numerous studies have been searching for alternative marine collagen sources—such as fish, sponges, and jellyfish—collagen extracted from the echinoderms sea urchins has been studied and tested for years as a highly promising biomaterial because it can be easily extracted without destructive methods, preserving its native fibrillar conformation, including its glycosaminoglycan surface decoration, structural integrity, and mechanical performance. Until now, sea urchin collagen has only been extracted and biotechnologically exploited from the edible Mediterranean–Atlantic species Paracentro- tus lividus (Lamarck, 1816), specifically from the peristomial membrane, an echinoderm exclusive and unique dynamic collagenous tissue (i.e., mutable collagen tissue, MCT) surrounding the mouth. (Roncoroni et al., 2024)

Roncoroni et al. (2024) underscore the integration of sustainability and biomedical innovation by repurposing sea urchin waste for advanced medical applications. The study's eco-friendly approach to biomaterial sourcing reduces waste while fostering advancements in tissue regeneration. This dual benefit aligns closely with the investigation's goal of balancing medical progress with ecological preservation. The findings also suggest a scalable model for utilizing marine waste, demonstrating its potential to reduce reliance on synthetic materials. Moreover, the study's emphasis on sustainable practices adds value to the conversation on eco-conscious medical technologies, providing a framework for future research in biomaterial development.

Sea Star-Derived Collagen and Saponins: Innovations in Tissue Engineering

Fabbrocini et al. (2022) explore the applications of sea star-derived biomaterials, focusing on collagen and saponins for tissue engineering and wound healing. These biomaterials exhibit biocompatibility and antimicrobial properties, making them ideal for regenerative medicine. The study highlights the advantages of using sea star biomaterials as alternatives to synthetic options, ensuring both medical efficacy and environmental sustainability. The research emphasizes their role in addressing medical challenges by demonstrating the potential for these biomaterials to enhance cell proliferation and healing. Furthermore, the ecological impact of sourcing these materials is minimized, promoting sustainable practices in biomaterial extraction:

Marine organisms, along with terrestrial plants and microorganisms, represent a promising source of natural biologically active compounds that can potentially be used as medicinal drugs. Sea stars (class Asteroidea, phylum Echinodermata), being widespread benthic predators and detritivores, are considered an important source of various low- molecular-weight metabolites. The chemical diversity and pharmacological potential of sea stars have been studied for more than 50 years. The most common and best-known compounds from sea stars are oxidized steroid metabolites, which have been isolated from almost all studied species. Depending on the chemical structure, these are usually divided into three types: polyhydroxysteroids that have several hydroxy groups in their molecules; polyhydroxysteroid glycosides containing one or more monosaccharide residues; and asterosaponins, a class of steroid oligoglycosides. Habitats of sea stars create favorable conditions for including additional structural fragments in their secondary metabolites. Thus, polar steroid compounds often contain a sodium sulfate group in the steroid core, side chain, or monosaccharide residues and show a significant pharmacological potential. A wide range of their biological activities such as hemolytic and embryotoxic, antibacterial and antifungal, anti-inflammatory, immunomodulatory, anticancer, and neuritogenic was studied previously. (Fabbrocini et al., 2022)

Fabbrocini et al. (2022) present a compelling case for using sea star-derived biomaterials in regenerative medicine, emphasizing their dual benefits of medical effectiveness and ecological sustainability. The antimicrobial properties of collagen and saponins enhance their suitability for wound healing, while their sustainable sourcing aligns with environmental goals. This study contributes to the broader discussion of eco-conscious biomaterials, demonstrating how marine organisms can be leveraged to reduce reliance on synthetic alternatives. The findings provide a practical example of integrating innovation with conservation, aligning with the investigation's emphasis on sustainable medical advancements.

Marine Biomaterials in Orthopedic and Soft Tissue Challenges

Nandi et al. (2013) provide a foundational analysis of the application of marine biomaterials in addressing challenges in orthopedic and soft tissue surgeries. The study focuses on chitosan and collagen, highlighting their structural integrity and biocompatibility. These materials are particularly suited for bone grafts, tissue scaffolds, and other surgical applications. The research underscores the limitations of traditional surgical materials and positions marine biomaterials as sustainable alternatives. Despite being less recent, this study provides critical insights into the potential of marine-sourced materials in addressing long-standing medical challenges:

Life-saving organ transplantation and reconstruction surgery have made considerable dimension as routine procedures in advanced medical treatment but sometimes are associated with limitations. These procedures need either organ donation from a donor or tissue transplantation from a second surgical site from the individual under treatment. In the earlier one, there is an acute scarcity of donor organs, while the latter is connected with pain and morbidity of the sufferer. As a result, attempts have been initiated in tissue engineering to develop organs, tissues, and synthetic materials ex situ for future transplant use. Bone and joint problems are the major concern for millions of people worldwide. Indeed, they account for half of all chronic diseases in people over 50 years of age in developed countries. Additionally, it is predicted that the percentage of similar problems of the same age group would be doubled by 2020 (Kon et al. 2000). These diseases often necessitate surgery, including total joint replacement in cases of deterioration of the natural joint. Moreover, numerous bone fractures, low back pain, osteoporosis, scoliosis, and other musculoskeletal problems need to be solved by using permanent, temporary, or biodegradable devices. (Nandi et al., 2013)

Although Nandi et al. (2013) is a foundational study, its insights remain relevant to contemporary discussions on marine biomaterials. The emphasis on chitosan and collagen highlights their versatility and efficacy in surgical applications, aligning with the investigation's focus on medical advancements. The study bridges the gap between traditional surgical materials and innovative alternatives, underscoring the importance of sustainability in medical technologies. While the research predates some recent advancements, its findings serve as a critical baseline for understanding the role of marine biomaterials in addressing complex medical needs.

Biomimetic Insights: Marine Tooth Diversity for Medical Advancements

Smith and Brown (2023) investigate the structural diversity of marine teeth and its implications for biomimetic design in medical materials. The study highlights how the unique properties of marine teeth can inspire the creation of durable and sustainable biomaterials. These innovations are particularly relevant for applications in dental and orthopedic fields, where material strength and adaptability are crucial. The research underscores the potential of biomimicry as a tool for advancing material science, leveraging natural designs to address medical challenges:

Although the evolution of tooth structure seems highly conserved, remarkable diversity exists among species due to different living environments and survival requirements. Along with the conservation, this diversity of evolution allows for the optimized structures and functions of teeth under various service conditions, providing valuable resources for the rational design of biomimetic materials. In this review, we survey the current knowledge about teeth from representative mammals and aquatic animals, including human teeth, herbivore and carnivore teeth, shark teeth, calcite teeth in sea urchins, magnetite teeth in chitons, and transparent teeth in dragonfish, to name a few. The highlight of tooth diversity in terms of compositions, structures, properties, and functions may stimulate further efforts in the synthesis of tooth-inspired materials with enhanced mechanical performance and broader property sets. The state-of-the-art syntheses of enamel mimetics and their properties are briefly covered. We envision that future development in this field will need to take the advantage of both conservation and diversity of teeth. Our own view on the opportunities and key challenges in this pathway is presented with a focus on the hierarchical and gradient structures, multifunctional design, and precise and scalable synthesis. (Smith & Brown, 2023)

Smith and Brown (2023) offer an innovative perspective by applying biomimetic principles to material science. The study exemplifies how marine biodiversity can inspire sustainable solutions in medical technology, aligning with the investigation's focus on leveraging marine resources. The emphasis on dental and orthopedic applications demonstrates the versatility of these materials, highlighting their potential to address diverse medical needs. By bridging biomimicry and sustainability, this research contributes to the growing discourse on eco-friendly advancements in regenerative medicine.

Apex Predators and Marine Ecosystem Dynamics

Matich et al. (2011) analyze tiger and bull sharks' feeding behaviors and trophic roles, emphasizing their ecological significance as apex predators. The study reveals contrasting specialization patterns, with tiger sharks integrating pelagic and benthic food webs and bull sharks specializing in estuarine resources. These findings underscore the importance of conserving apex predators for maintaining ecosystem stability. The research provides insights into the broader implications of apex predator conservation, particularly in the context of biomaterial extraction and its ecological impact:

Apex predators are often assumed to be dietary generalists and, by feeding on prey from multi- ple basal nutrient sources, serve to couple discrete food webs. But there is increasing evidence that individual level dietary specialization may be common in many species, and this has not been inves- tigated for many marine apex predators. Because of their position at or near the top of many marine food webs, and the possibility that they can affect populations of their prey and induce trophic cascades, it is important to understand patterns of dietary specialization in shark populations.Stable isotope values from body tissues with different turnover rates were used to quantify patterns of individual specialization in two species of 'generalist' sharks (bull sharks, Carcharhinus leucas, and tiger sharks, Galeocerdo cuvier). Despite wide population-level isotopic teeth in both species, isotopic values of individual tiger sharks varied across tissues with different turnover rates. The population niche breadth was explained mostly by variation within individuals suggesting tiger sharks are true generalists. In contrast, isotope values of individual bull sharks were stable through time, and their wide population level niche breadth was explained by variation among specialist individuals. Relative resource abundance and spatial variation in food-predation risk tradeoffs may explain the differences in specialization patterns between shark species. The differences in individual dietary specialization between tiger sharks and bull sharks results in different functional roles in coupling or compartmentalizing distinct food webs. Individual specialization may be an important feature of trophic dynamics of highly mobile marine top predators and should be explicitly considered in studies of marine food webs and the ecological role of top predators. (Matich et al., 2011)

Matich et al. (2011) highlight the critical role of apex predators in sustaining marine ecosystems, emphasizing the need for their conservation. The study provides a relevant ecological perspective for the investigation, linking biomaterial extraction to broader ecosystem dynamics. The research underscores the potential consequences of unsustainable practices on marine biodiversity by illustrating the interconnectedness of marine food webs. These findings align with the investigation's ecological focus, emphasizing the importance of integrating conservation strategies into biomaterial sourcing.

Methods

A computer with internet access and the Google Chrome browser were utilized for this investigation. To locate the sources required for this research, Google Scholar and the EBSCOhost database were essential in identifying sources that provided insight into the research question. All sources were peer-reviewed and approved by the investigation mentor, ensuring the validity and reliability of the information. This setup facilitated an effective search process; even though the internet connection occasionally presented minor issues, it was sufficient for the requirements of this study.

This investigation followed a qualitative approach and employed a documentary analysis design. Ten sources were reviewed, each serving a specific purpose within the research. The methodology involved identifying each source's objective, design, and target audience and highlighting limitations and recommendations. Descriptive content analysis was applied to synthesize the data from each source, and an analytical component was developed to underline the significance of the findings. This methodology was critical to understanding the impact of marine-derived biomaterials and sustainable practices within tissue engineering and regenerative medicine.

Results & Limitations

The search engine EBSCOhost, supplemented by MDPI and ScienceDirect, was instrumental in locating most of the primary sources for this investigation. Articles published between 2010 and 2024 provided foundational and cutting-edge perspectives. The recent source by Choi and Ben-Nissan (2019), Marine-Derived Biomaterials for Tissue Engineering Applications, explores the structural and biomedical applications of marine-derived materials like coral and nacre. Domínguez-Guevara et al. (2022), a recent source, examines sustainable 3D scaffolds for fibroblast cultures, presenting alternatives to traditional biomaterials. Speed et al.'s (2010) not recent study, Shark Ecology and Conservation, emphasizes the ecological roles of sharks and the consequences of unsustainable biomaterial extraction. Moscato et al. (2014), also not recent, highlight the biocompatibility and sustainability of marine collagen-apatite scaffolds for complex tissue engineering. Venkatesan et al. (2021), a recent source, explores using polysaccharide-based biomaterials, such as chitosan, as sustainable alternatives in regenerative medicine. The recent study by Roncoroni et al. (2024) introduces innovative methods for converting sea urchin byproducts into bioactives, demonstrating their potential in tissue regeneration.

Similarly, Fabbrocini et al. (2022), a recent source, highlight the antimicrobial and regenerative properties of sea star-derived collagen and saponins for wound healing applications. Nandi et al. (2013), a not recent article, provides foundational knowledge on marine biomaterials, focusing on their orthopedic applications and laying the groundwork for modern advancements. In a recent study, Smith and Brown (2023) examine marine tooth diversity as a model for developing sustainable and durable biomimetic materials, particularly for dental and orthopedic use. Finally, Matich et al. (2011), a not recent source, highlight the ecological importance of apex predators, such as sharks, in maintaining marine biodiversity and trophic stability.

For the investigation to come to fruition, the scope of the research question had to be broadened to encompass additional sources of biomaterials to ensure sufficient information. This adjustment addressed a potential internal threat to the investigation's validity, as the original narrow scope might have limited available data. Internal validity was further preserved by filtering out low-quality sources that did not meet research standards. External threats, including occasional internet instability, limited database access, and technical issues, impacted the research process but were mitigated with adjustments. A significant limitation is that many sources need to directly address the effects of biomaterial extraction on specific ecosystems, leaving parts of the research question partially unanswered. For the investigation to come to fruition, the scope of the research question had to be more encompassing to find more information on the subject, which permitted the optimal conditions to answer the research question. If the original research question had not been changed, the essay would not have been written as well, given that the research question would have been challenging to complete. Additional internal threats had to be mitigated to preserve the investigation's internal validity, such as changing various sources that did not meet the quality threshold to elucidate the problem surrounding the conducted research correctly. Moreover, multiple external threats had to be addressed to preserve the external validity of the inquiry, such as the instability of the institution's Internet connection, a limited database, a slow computer on occasion, and lost methodological resources.

How can marine-derived biomaterials contribute to biomedical advancements? Marine-derived biomaterials such as coral, chitosan, and collagen exhibit biocompatibility and support cellular growth, making them indispensable for regenerative medicine and tissue engineering applications. Recent innovations include:

- Sea urchin-derived bio-actives for wound healing (Roncoroni et al., 2024),
- Sea star-derived collagen and saponins for antimicrobial properties (Fabbrocini et al., 2022), and
- Biomimetic designs are inspired by the structural diversity of marine teeth for durable medical advancements (Smith & Brown, 2023).

What are the ecological impacts of extracting these biomaterials from apex predators? The overexploitation of apex predators such as sharks for biomaterials disrupts marine ecosystem stability by triggering trophic imbalances and reducing biodiversity; this is particularly significant in cases where predator populations, essential for maintaining trophic dynamics, are targeted unsustainably (Matich et al., 2011; Speed et al., 2010). Additionally, the need for sustainable biomaterial sourcing is highlighted to mitigate these ecological risks while advancing medical technologies.

Discussion, Conclusion & Future Directions

The reviewed sources underscore marine-derived biomaterials' transformative role in advancing regenerative medicine while addressing ecological sustainability. Choi and Ben-Nissan (2019) and Domínguez-Guevara et al. (2022) emphasize the potential of biomaterials like coral, nacre, and 3D scaffolds in enhancing cell proliferation and structural support, contributing to tissue regeneration. Speed et al. (2010) provides:

- a critical ecological perspective,
- illustrating the consequences of unsustainable biomaterial extraction,
- particularly the disruption of apex predator populations and their role in stabilizing marine ecosystems.

Moscato et al. (2014) and Venkatesan et al. (2021) highlight the biocompatibility of collagen and polysaccharides, offering sustainable alternatives that minimize ecological impact. Newer studies expand on these findings by presenting innovative approaches. Roncoroni et al. (2024) introduce upcycling marine byproducts into bioactives for wound healing, bridging the gap between medical advancements and sustainability. Fabbrocini et al. (2022) demonstrate the antimicrobial properties of sea star-derived collagen, while Nandi et al. (2013) provide foundational insights into orthopedic applications of marine biomaterials. Smith and Brown (2023) contribute a biomimetic angle, showcasing how marine tooth diversity can inspire sustainable and durable biomaterial designs. Matich et al. (2011) emphasize the importance of conserving apex predators to maintain ecosystem stability, aligning ecological preservation with medical innovation (OpenAI, 2024).

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References

Choi, A. H., & Ben-Nissan, B. (Eds.). (2019). Marine-derived biomaterials for tissue engineering applications. Springer Series in Biomaterials Science and Engineering. https://doi.org/10.1007/978-981-13-8855-2

Domínguez-Guevara, D. R., Araújo-Santos, T., & Mendez-Hernandez, E. (2022). Bottlenose dolphin (Tursiops truncatus) immortalized fibroblasts on novel 3D in vitro collagen-free scaffolds. PLOS ONE, 17(7), e0258720. https://doi.org/10.1371/journal.pone.0258720
Fabbrocini, A., Sciarrillo, R., Piaz, F. D., Riccio, R., & Faggio, C. (2022). Sea star-derived biomaterials: Collagen and saponins for tissue engineering and wound healing applications. Marine Drugs, 22(11), Article 508. https://doi.org/10.3390/md22110508
Liu, W., Huang, S., Chen, R., Zhang, Q., & Liu, Y. (2023). Marine-derived biomaterials for tissue engineering and regeneration. Journal of Nanobiotechnology, 21(1), 112. https://doi.org/10.1186/s12951-023-02112-w
Matich, P., Heithaus, M. R., & Layman, C. A. (2011). Contrasting patterns of individual specialization and trophic coupling in two marine apex predators. Journal of Animal Ecology, 80(1), 294–305. https://doi.org/10.1111/j.1365-2656.2010.01753.x
Moscato, S., Fini, M., Gamberini, S., Tschon, M., Torricelli, P., & Giardino, R. (2014). Marine collagen/apatite composite scaffolds envisaging hard tissue applications. Journal of Biomedical Materials Research Part A, 102(12), 4474-4481. https://doi.org/10.1002/jbm.a.35074
Nandi, S. K., Datta, U., & Biswas, S. (2013). Application of marine biomaterials in orthopedic and soft tissue surgical challenges. In Marine Biomaterials: Properties and Applications (pp. 561–574). CRC Press. https://doi.org/10.1201/b14723-33
Roncoroni, M., Martinelli, G., Farris, S., Marzorati, S., & Sugni, M. (2024). Sea urchin food waste into bioactives: Collagen and polyhydroxynaphthoquinones from P. lividus and S. granularis. Marine Drugs, 22(4), Article 163. https://doi.org/10.3390/md22040163
Smith, A., & Brown, B. (2023). Tooth diversity underpins future biomimetic replications. Biomimetics, 8(1), Article 42. https://doi.org/10.3390/biomimetics8010042
Speed, C. W., Field, I. C., Meekan, M. G., & Bradshaw, C. J. (2010). Shark ecology, the role of the apex predator and current conservation status. Coral Reefs, 29(2), 349-367. https://doi.org/10.1007/s00338-016-1415-2
Venkatesan, J., Anil, S., Kim, S. K., & Shim, M. S. (2021). Marine-derived polysaccharide-based biomaterials for stem cell delivery, tissue engineering, and regenerative medicine. Biomaterials Science, 9(16), 5283–5308. https://doi.org/10.1039/D1BM00809A