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(Review Article)

Mechanical properties and biodegradability of crab shell-derived exoskeletons in orthopedic implant design

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Abstract

This review paper explores the innovative application of crab shell-derived exoskeleton materials, specifically chitin and chitosan, in the design of orthopedic implants. The urgent need for sustainable, biocompatible, and mechanically robust materials in medical applications guides this comprehensive analysis. We assess the mechanical properties of crab shell derivatives, highlighting their adequate strength and durability which are essential for successful orthopedic applications. This study also evaluates the biodegradability of these materials, an attribute that stands out for its potential to minimize long-term bodily impacts and reduce the need for secondary surgeries. Comparative analyses against traditional implant materials such as metals and ceramics are provided to underline the advantages and current limitations of crab shell-derived biopolymers. The review encompasses recent case studies and design innovations, including advanced fabrication techniques like 3D printing, which could integrate these biopolymers into future orthopedic solutions. Finally, we discuss the ongoing challenges and research gaps that must be addressed to harness the full potential of these biological materials in clinical settings. This paper aims to inform researchers and practitioners about the promising prospects of crab shell-derived materials, advocating for continued research and development in this promising area of orthopedic implant technology.

Keywords: Orthopedic Implants; Biodegradable; Crab Shell Exoskeletons; Mechanical Properties

1. Introduction

Orthopedic implants are pivotal in the restoration of function and alleviation of pain in patients suffering from musculoskeletal disorders. The choice of materials for these implants is critical, as they must possess high mechanical strength, durability, and biocompatibility. Metals like titanium and stainless steel have traditionally dominated the field due to their robust mechanical properties, with titanium alloys showing a tensile strength of approximately 900 MPa and a yield strength of about 830 MPa (Jin & Chu, 2019). However, the search for materials that can integrate more seamlessly with biological tissues has led to significant interest in biodegradable and biocompatible alternatives, such as those derived from natural sources (Mantripragada & Lecka-Czernik, 2013). Recent advancements have focused on enhancing the functional integration of implants by using materials that encourage osseointegration and reduce the risk of infection (Bandopadhyay et al., 2019). The emergence of composite materials and biopolymers has started to

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challenge the traditional dominance of metals, offering comparable strengths with added benefits of lower stiffness, which can match more closely to the mechanical properties of bone, typically ranging from 100 to 500 MPa (Mohamed, 2016; Idoko et al., 2023; Idoko et al., 2024a). These innovative material solutions not only promise enhanced patient outcomes but also align with a growing demand for sustainable medical practices, setting a transformative direction for future orthopedic solutions.

1.1. Problem Statement

The widespread use of conventional materials such as titanium and stainless steel in orthopedic implants has been challenged by several critical issues impacting long-term patient outcomes. One of the primary concerns is the risk of metal ion release, which can lead to metallosis, a condition causing pain and inflammation in tissues surrounding the implant (Wang et al., 2011). Studies have shown that titanium implants can release metal ions that accumulate in the bloodstream, leading to systemic toxic reactions in approximately 1-3% of patients (Kim et al., 2020). Furthermore, the biocompatibility of these materials, though generally high, can sometimes fail, leading to rejection rates that, while low (estimated around 2%), still pose significant health risks and necessitate revision surgeries (Bandopadhyay et al., 2019). Additionally, the rigidity of metal implants can lead to stress shielding—a condition where the implant takes more load than the bone, leading to bone resorption and weakening. This effect has been quantified, showing a mismatch in the elastic modulus with bone by a factor of 10 to 15 times, which is far from ideal for bone healing processes (Filip et al., 2022).

These issues underline the need for innovative materials that not only match the mechanical properties of bone but also enhance biocompatibility and reduce the long-term systemic impacts of implants. The search for such materials is critical in evolving the next generation of orthopedic solutions to improve patient safety and implant longevity.

1.2. Relevance of Crab Shell-Derived Exoskeletons

Crab shell-derived exoskeletons, primarily composed of chitin and its derivative chitosan, have emerged as significant contenders in the development of new materials for orthopedic implants. These biopolymers are favored for their excellent biocompatibility, bioactivity, and biodegradability properties, which align closely with the requirements for materials used in medical implants (Mukherjee et al., 2022). Chitosan, in particular, has shown great potential in promoting osteoconductivity, which is critical for bone healing and integration of implants with native bone tissue. Recent studies have highlighted the role of chitin and chitosan in drug delivery systems within orthopedics, where their natural antimicrobial and anti-inflammatory properties can significantly reduce post-operative infections and enhance healing processes (Umesh et al., 2023). Additionally, the mechanical properties of these biopolymers can be enhanced through various processing techniques to meet the specific demands of load-bearing applications typical in orthopedic implants (Oktar et al., 2023; Idoko et al., 2024b; Idoko et al., 2024c).

Furthermore, the environmental impact of using crab shell-derived materials is considerably lower compared to conventional synthetics like metals and ceramics. The extraction and processing of chitin and chitosan have a smaller carbon footprint, promoting a more sustainable approach in medical material science. The ability of these materials to be naturally resorbed by the body eliminates the need for secondary surgeries to remove implants, offering a dual benefit of improved patient outcomes and reduced long-term healthcare costs (Hart, 2020; Idoko et al., 2024d; Idoko et al., 2024e).

The ongoing development and research into crab shell-derived exoskeletons represent a promising frontier in orthopedic implant technologies, potentially revolutionizing how bone-related ailments are treated with more sustainable, patient-friendly materials.

1.3. Organization of the Paper

The review paper on "Mechanical Properties and Biodegradability of Crab Shell-Derived Exoskeletons in Orthopedic Implant Design" is meticulously organized into a comprehensive structure, ensuring a logical flow that facilitates an in-depth understanding of the topic. The paper commences with an "Introduction" section, which sets the stage by providing essential background information on orthopedic implants and the significance of selecting appropriate materials, with a specific focus on crab shell-derived exoskeletons like chitin and chitosan. It also delineates the problems associated with traditional implant materials and outlines the objectives and scope of the review. Following the introduction, the paper is divided into several main sections to address the core topics. "Mechanical Properties of Crab Shell-Derived Exoskeletons" analyzes the composition, strength, and durability of these materials compared to traditional options, emphasizing their advantages and suitability for implant applications. The subsequent section, "Biodegradability and Bio-compatibility," examines the degradation behaviors and biological compatibility of these materials, crucial for ensuring safe and effective integration into the human body. "Applications in Orthopedic Implant Design" showcases practical case studies and discusses innovative design and fabrication techniques, highlighting recent advancements and the application of these materials in real-world medical scenarios. The final sections, "Challenges and Future Perspectives," address the current limitations, research needs, and provide a conclusive summary of the potential future developments in the field. This organization not only ensures a thorough analysis and discussion of each topic but also interlinks them to provide a holistic view of the potentials and challenges of crab shell-derived materials in orthopedic implants.

2. Composition and Structure of Crab Shell-Derived Materials

Crab shell-derived materials, particularly those processed into carbon forms, exhibit unique structural properties conducive for various applications, including orthopedic implants. The primary composition of crab shells includes chitin, a natural polysaccharide, which upon deacetylation forms chitosan. These materials are combined with proteins and minerals such as calcium carbonate, making the exoskeletons tough and resilient (Hart, 2020; Ijiga et al., 2024a; Ijiga et al., 2024b). Advanced processing methods convert these biological materials into highly porous, graphitized carbon structures. For example, crab shell-derived graphitized carbons display an organized, honeycomb-like porous structure that enhances mechanical stability and bioactivity, crucial for medical implants (Shi et al., 2019; Ijiga et al., 2024c; Ijiga et al., 2024d). The hierarchical porosity of these materials facilitates nutrient flow and cell adhesion, which are vital for bone integration and regeneration.

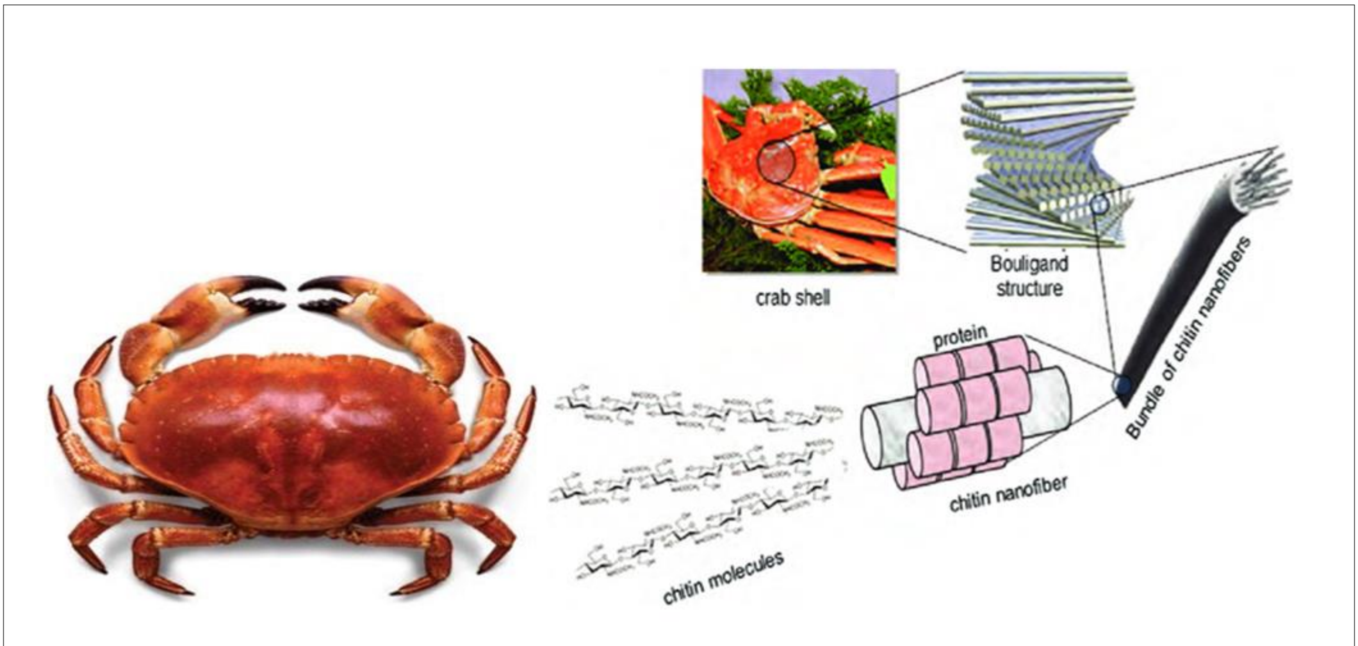

Figure 1 Structural Composition of Crab Shell-Derived Materials (Azuma et al., 2014)

Figure 1 illustrates the composition and structure of crab shell-derived materials. It starts with a crab shell, highlighting its intricate internal structure known as the Bouligand structure. This structure is characterized by the layering of chitin nanofibers, which are bundled together to provide mechanical strength and flexibility. At a molecular level, the chitin molecules form long chains, which are organized into nanofibers. These nanofibers are embedded with proteins, further enhancing the toughness and resilience of the material. This hierarchical organization, from chitin molecules to nanofibers and then to the Bouligand structure, showcases the complex and efficient design of crab shells, making them a valuable resource for developing advanced biomaterials.

Additionally, the inherent biocompatibility and osteoconductive properties of chitosan derived from crab shells make them suitable for bone tissue engineering. The biochemical makeup, including the presence of nitrogen groups in chitosan, promotes better cellular responses and osteoblast adhesion, essential for bone healing and growth (Fu et al., 2019; Ijiga et al., 2024e). Moreover, these materials have been tested for their adsorption capabilities, indicating their potential in controlling surgical site infections through adsorption of contaminants and delivery of therapeutic agents (Cai et al., 2019). The versatility and advantageous properties of crab shell-derived materials underscore their potential in creating the next generation of sustainable and efficient orthopedic implants, blending mechanical robustness with biological functionality.

Table 1 Summary of Composition and Structure of Crab Shell-Derived Materials

Aspect	Details
Crab Shell Composition	- Chitin: Natural polysacchari
	Deacetylation Process: Converts chitin into chitosan
	- Chitosan: Combined with proteins and minerals (e.g., calcium carbonate) for a tough and resilient exoskeleton
Processing Methods	- Advanced Processing: Converts biological materials into highly porous, graphitized carbon structures
	- Graphitized Carbons: Honeycomb-like porous structure enhances mechanical stability and bioactivity
Applications	- Orthopedic Implants
	- Nutrient Flow and Cell Adhesion: Facilitates nutrient flow and cell adhesion for bone integration and regeneration
	- Biocompatibility and Osteoconductive Properties: Promotes better cellular responses and osteoblast adhesion for bone healing and growth
	- Infection Control: Adsorbs contaminants and delivers therapeutic agents, controlling surgical site infections

Table 1 provides a clear and concise summary of the composition, processing methods, and applications of crab shell-derived materials. Crab shell-derived materials, particularly those processed into carbon forms, possess unique structural properties beneficial for various applications, notably in orthopedic implants. The primary composition includes chitin, which transforms into chitosan through deacetylation, combined with proteins and calcium carbonate, resulting in a tough and resilient exoskeleton. Advanced processing methods convert these materials into highly porous, graphitized carbon structures with a honeycomb-like pattern, enhancing mechanical stability and bioactivity. These materials facilitate nutrient flow and cell adhesion, crucial for bone integration and regeneration, while their biocompatibility and osteoconductive properties promote better cellular responses and osteoblast adhesion. Additionally, their adsorption capabilities make them effective in controlling surgical site infections and delivering therapeutic agents, highlighting their potential in creating sustainable and efficient orthopedic implants.

2.1. Mechanical Strength and Durability

The mechanical strength and durability of crab shell-derived materials are critical factors for their potential applications in orthopedic implants. The intrinsic properties of chitosan, derived from the deacetylation of chitin, which is abundantly found in crab shells, offer significant mechanical strength suitable for load-bearing applications. The process of graphitization further enhances these properties by creating a structured carbon network, leading to materials that exhibit superior strength and resilience (Shi et al., 2019). Crab shell-derived chitosan has shown potential to replace conventional materials such as polymethyl methacrylate (PMMA) in bio-composites. The addition of crab shell-derived fillers to PMMA significantly enhances its mechanical properties, making it a more durable option for medical applications, including implants (Hart, 2020). The compressive strength of these composites can be enhanced by up to 25%, which is critical for their use in high-load areas within the human body. Moreover, the hierarchical porous structure of crab shell-derived carbons contributes to their durability and mechanical integrity under physiological conditions. These structures not only support the mechanical loads but also facilitate the integration and growth of bone tissues, making them highly effective for orthopedic implants (Cai et al., 2019).

Environmental considerations also play a role in the suitability of crab shell-derived materials for medical applications. These materials are not only stronger and more durable but also environmentally sustainable, making them an ideal candidate for future development in the medical field, especially in areas requiring bio-compatibility and long-term implant integrity (Su et al., 2019). These findings suggest that crab shell-derived materials hold significant promise for enhancing the mechanical strength and durability of orthopedic implants, providing a sustainable and efficient alternative to traditional implant materials.

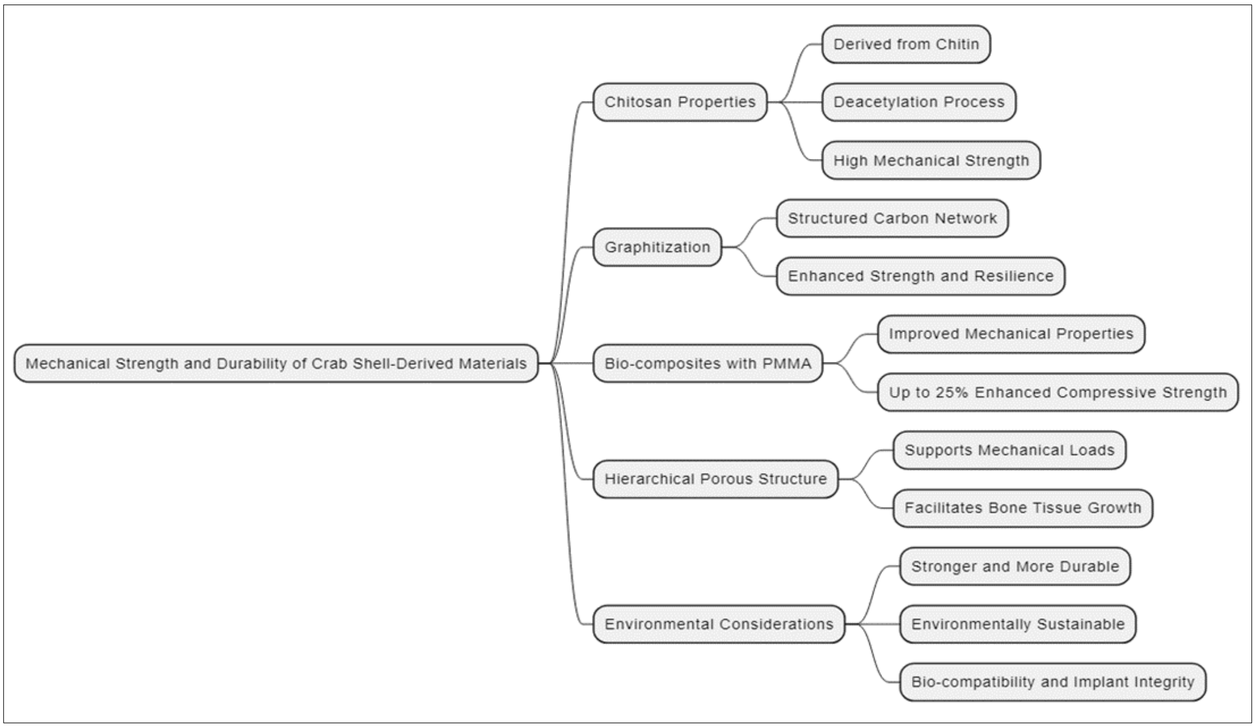

Figure 2 Mechanical Strength and Durability of Crab Shell-Derived Materials in Orthopedic Applications

Figure 2 illustrates the key aspects of mechanical strength and durability of crab shell-derived materials. At the core, these materials derive their properties from chitosan, which is produced through the deacetylation of chitin found in crab shells. Chitosan offers high mechanical strength, crucial for load-bearing applications. The graphitization process further enhances these properties by forming a structured carbon network, leading to improved strength and resilience. Bio-composites incorporating crab shell-derived fillers with polymethyl methacrylate (PMMA) significantly enhance mechanical properties, including up to a 25% increase in compressive strength. The hierarchical porous structure of these materials supports mechanical loads and promotes bone tissue growth, essential for orthopedic implants. Additionally, crab shell-derived materials are environmentally sustainable, offering bio-compatibility and long-term implant integrity, making them a viable alternative to traditional materials.

2.2. Comparison with Traditional Materials

Crab shell-derived materials, particularly chitosan and hydroxyapatite (HAp) composites, show promising mechanical properties when compared to traditional materials used in orthopedic implants such as titanium and stainless steel. Marine-derived HAp, often enhanced with strontium to improve its mechanical properties, exhibits superior bioactivity and potentially better osteointegration than synthetic HAp commonly used in bone implants (Balu et al., 2021).

The mechanical properties of chitosan-based composites from crab shells have been demonstrated to improve by more than 50% compared to traditional polymethylmethacrylate (PMMA), a common material in bone cement. This is due to the natural polymer networks and the filling effect of chitosan, which enhance the composite's overall strength and durability (Su et al., 2019). Additionally, biomimetic approaches using crab shell-derived materials have led to the development of scaffolds that mimic the bone's natural architecture. These scaffolds not only support the mechanical loads similar to bone but also promote faster and more effective bone regeneration compared to conventional materials like alumina or bio-inert ceramics, which are less conducive to cell growth and differentiation (Handa et al., 2024).

In terms of environmental impact and sustainability, crab shell-derived materials offer a significant advantage. Their production involves recycling of food industry waste, which is a more sustainable process compared to the high-energy manufacturing processes for metals and synthetic ceramics. The lower environmental footprint, combined with their biodegradability, makes crab shell-derived materials highly attractive for future developments in orthopedic implants (Hart, 2020). These comparisons indicate that crab shell-derived materials are not only comparable but, in some aspects, superior to traditional implant materials, offering benefits in mechanical properties, bioactivity, and environmental sustainability.

Table 2 Comparison of Crab Shell-Derived Materials with Traditional Orthopedic Implant Materials

Property	Crab Shell-Derived Materials	Titanium	Stainless Steel	PMMA
Mechanical Properties	Improved by >50% compared to PMMA	High strength, good mechanical properties	Good strength, less biocompatible than titanium	Lower strength compared to metals, improved by chitosan
Bioactivity	Superior (especially with strontium-enhanced HAp)	Good	Good	Poor
Osteointegration	Potentially better than synthetic HAp	Standard	Standard	Poor
Bone Regeneration	Supports mechanical loads similar to bone, promotes faster regeneration	Moderate	Moderate	Less effective
Environmental Impact	Significant advantage (recycling of food industry waste, biodegradable)	High-energy manufacturing, non-biodegradable	High-energy manufacturing, non-biodegradable	Synthetic, non-biodegradable

Table 2 provides a comparative overview of crab shell-derived materials, particularly chitosan and hydroxyapatite (HAp) composites, against traditional orthopedic implant materials like titanium, stainless steel, and polymethylmethacrylate (PMMA). Crab shell-derived materials demonstrate superior mechanical properties, with strength improvements of over 50% compared to PMMA. They also show enhanced bioactivity, especially when marine-derived HAp is enhanced with strontium, potentially offering better osteointegration than synthetic HAp. These materials support bone regeneration more effectively, promoting faster healing compared to less conducive materials like alumina or bio-inert ceramics. Additionally, crab shell-derived materials have significant environmental advantages, being biodegradable and produced from recycled food industry waste, unlike the high-energy manufacturing and non-biodegradability associated with traditional materials. This makes them a promising alternative in the development of orthopedic implants.

3. Biodegradation Process

The biodegradation process of crab shell-derived materials, particularly those based on chitosan and chitin, is a critical attribute for their potential application in orthopedic implants. These materials naturally decompose through enzymatic and microbial actions, making them an environmentally friendly option for temporary implants that require eventual biodegradation. Chitosan, derived from the deacetylation of chitin found in crab shells, is known for its biocompatibility and biodegradability. Studies have shown that chitosan can degrade within weeks to months, depending on the degree of deacetylation and the environmental conditions, such as the presence of lysozyme—an enzyme found in human bodily fluids that breaks down glycosidic bonds in chitosan (Su et al., 2019).

Additionally, crab shell-derived biochar materials have shown a promising degradation profile, as they are embedded with heteroatoms (O and N), which increase their biodegradability. These materials not only support growth and integration into bodily tissues but also safely degrade without leaving harmful residues (Chen et al., 2020). The degradation rate of these materials can also be engineered by modifying their chemical structure or by combining them with other biodegradable polymers, which can tailor their degradation time to match the healing process of tissues, thereby avoiding the necessity for surgical removal (Qu et al., 2022).

Moreover, the degradation products of these materials, primarily glucosamine and N-acetylglucosamine, are non-toxic and can even provide nutritional benefits to surrounding tissues, thus supporting the healing process (Cai et al., 2019). The biodegradation process of crab shell-derived materials aligns well with the requirements for sustainable and temporary orthopedic implants, offering a balance between functionality and environmental consciousness.

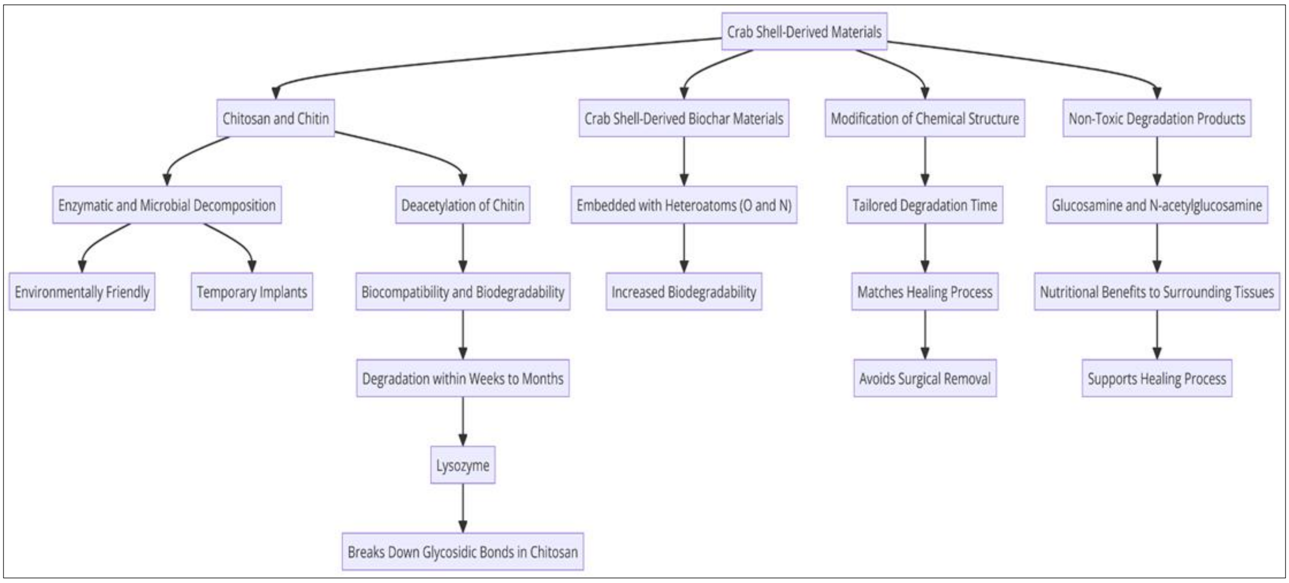

Figure 3 Biodegradation Process of Crab Shell-Derived Materials

Figure 3 outlines how chitosan and chitin from crab shells decompose naturally through enzymatic and microbial actions. These materials, suitable for temporary implants, degrade within weeks to months due to enzymes like lysozyme. Crab shell-derived biochar materials with embedded heteroatoms show increased biodegradability. The degradation rate can be tailored by modifying their chemical structure, aligning with tissue healing processes and avoiding surgical removal. The non-toxic degradation products, such as glucosamine and N-acetylglucosamine, benefit surrounding tissues, supporting healing. This process emphasizes the environmental sustainability and medical effectiveness of crab shell-derived materials for orthopedic implants.

3.1. Biocompatibility Issues

The biocompatibility of crab shell-derived materials, such as chitosan and hydroxyapatite composites, is critical for their application in medical fields, particularly in orthopedic implants. These materials have shown low cytotoxicity and favorable interactions with human cells, making them promising candidates for bioactive coatings and implant materials (Su et al., 2019). Recent studies have developed multifunctional composites from crab shell-derived hydroxyapatite, metal oxides, and polyhydroxybutyrate, which not only improve mechanical properties but also enhance antibacterial capabilities and biocompatibility. These composites have been applied to stainless steel implants, showing improved cell adhesion and proliferation, crucial for successful implant integration (Mathina et al., 2022). However, the biocompatibility of these materials can be influenced by their processing and purification methods. Residual proteins and other organic components from the original crab shells can provoke immune responses if not properly removed during material processing. Thus, extensive purification and characterization are essential to ensure the materials are free from potential allergens or irritants (Hart, 2020).

Furthermore, the biocompatibility of crab shell-derived materials can be enhanced by modifying their surface properties. Techniques such as surface functionalization with bioactive molecules or integration with other biocompatible polymers can further improve their interaction with human tissue, thereby minimizing any adverse immune reactions and promoting healing processes (Ismail et al., 2022). These attributes highlight the potential of crab shell-derived materials in medical applications, provided that their biocompatibility issues are adequately addressed through careful material processing and enhancement techniques.

Table 3 Enhancing Biocompatibility of Crab Shell-Derived Materials for Medical Applications

Aspect	Details	Applications	Challenges	Enhancement Techniques
Key Materials	Chitosan, hydroxyapatite composites	Medical fields, particularly orthopedic implants	Residual proteins and organic components can provoke immune responses	Surface functionalization with bioactive molecules
Biocompatibility	Low cytotoxicity and favorable interactions with human cells (Su et al., 2019)	Bioactive coatings and implant materials	Extensive purification and characterization are essential	Integration with other biocompatible polymers
Multifunctional Composites	Hydroxyapatite, metal oxides, and polyhydroxybutyrate improve mechanical properties and biocompatibility	Stainless steel implants	Potential allergens or irritants if not properly removed (Hart, 2020)	Enhancing interaction with human tissue
Study Results	Improved cell adhesion and proliferation (Mathina et al., 2022)	Successful implant integration	Ensuring materials are free from contaminants	Minimizing adverse immune reactions
Conclusion	Significant potential in medical applications if biocompatibility issues are addressed	Various medical applications	Processing and purification are crucial	Promoting healing processes

Table 3 illustrates the biocompatibility issues and enhancement techniques for crab shell-derived materials, focusing on key materials like chitosan and hydroxyapatite composites used primarily in orthopedic implants. These materials show low cytotoxicity and favorable interactions with human cells, making them suitable for bioactive coatings and implant applications. Multifunctional composites improve mechanical properties, antibacterial capabilities, and biocompatibility, with studies showing enhanced cell adhesion and proliferation on stainless steel implants. Challenges include the need for extensive purification to remove residual proteins and organic components that could provoke immune responses. Enhancement techniques such as surface functionalization with bioactive molecules and integration with other biocompatible polymers are essential to improve interactions with human tissue, minimize adverse immune reactions, and promote healing processes.

3.2. Advantages Over Non-biodegradable Implants

Biodegradable materials offer several significant advantages over non-biodegradable implants, particularly in reducing long-term complications and the need for secondary surgeries. These materials naturally break down and are absorbed by the body, eliminating the need for surgical removal once the healing process is complete. This aspect is crucial in reducing patient exposure to additional surgical risks and decreasing the overall healthcare costs associated with follow-up surgeries (García-Estrada et al., 2021). In the treatment of conditions like osteomyelitis, biodegradable antibiotic delivery devices have shown distinct advantages by providing targeted drug release at the infection site and subsequently biodegrading, thereby reducing systemic toxicity and enhancing local treatment effectiveness. This localized treatment minimizes the potential for antibiotic resistance, a critical concern with systemic antibiotic therapies (Kluin et al., 2013).

Biodegradable materials also contribute to better stress distribution in surrounding bone tissues. Non-biodegradable implants can lead to stress shielding, where the implant takes most of the mechanical load, causing the surrounding bone to weaken due to lack of stimulation. Biodegradable materials, however, are designed to transfer load progressively to the healing bone, thereby maintaining normal bone stress and promoting natural bone regeneration and strengthening (Adeosun et al., 2014). Furthermore, the use of biodegradable materials aligns with sustainable healthcare practices. They are often produced from natural or synthetic polymers that have minimal environmental impact compared to the extraction, processing, and disposal issues associated with metals and other non-biodegradable materials. This eco-friendly attribute makes biodegradable implants particularly appealing in the current climate of environmental consciousness (Kirby et al., 2021).

Overall, the use of biodegradable materials in implants offers significant clinical and environmental benefits, supporting their growing preference in various medical disciplines, including orthopedics and drug delivery systems.

Table 4 Advantages of Biodegradable Implants Over Non-Biodegradable Implants

Aspect	Advantages	Clinical Benefits	Environmental Benefits	Sources
Reduction in Complications	Naturally break down and are absorbed by the body	Eliminates need for surgical removal post-healing	Reduces healthcare costs associated with follow-up surgeries	García-Estrada et al., 2021
Targeted Drug Delivery	Provide localized antibiotic release in infection sites	Reduces systemic toxicity and enhances local treatment effectiveness	Minimizes potential for antibiotic resistance	Kluin et al., 2013
Stress Distribution	Transfers mechanical load progressively to healing bone	Maintains normal bone stress, promotes natural bone regeneration and strengthening	Prevents stress shielding, which weakens surrounding bone	Adeosun et al., 2014
Sustainability	Produced from natural or synthetic polymers with minimal environmental impact	Aligns with sustainable healthcare practices	Eco-friendly compared to metal extraction, processing, disposal	Kirby et al., 2021
Overall Benefits	Reduces long-term complications and secondary surgeries, provides targeted treatments, supports natural healing	Preferred in orthopedics and drug delivery systems	Environmentally conscious choice	Various sources summarized above

Table 4 highlights the advantages of biodegradable implants over non-biodegradable ones, emphasizing their clinical and environmental benefits. Biodegradable materials naturally decompose and are absorbed by the body, eliminating the need for secondary surgeries and reducing healthcare costs. They offer targeted antibiotic delivery at infection sites, enhancing treatment effectiveness and minimizing antibiotic resistance. These materials also promote better stress distribution in bone tissues, preventing stress shielding and aiding natural bone regeneration. Additionally, biodegradable implants are eco-friendly and align with sustainable healthcare practices, making them a preferred choice in various medical fields.

4. Case Studies

Crab shell-derived materials, particularly apatite nanoparticles, have been explored for their potential in orthopedic, prosthetic, and dental implant applications. These materials are sourced from waste crab shells, offering an eco-friendly and cost-effective solution for recycling seafood waste while creating high-value biomedical products. One significant case study involves the development of apatite nanoparticles from crab shells, which have been tested for their bone-forming efficacy. The nanoparticles have shown promising results in promoting osteoconductivity and osteointegration due to their similarity in composition to natural bone minerals. This makes them suitable for applications in bone grafting and as coatings for metal implants to enhance their integration with bone tissue (Bhattacharjee et al., 2019a; Bhattacharjee et al., 2019b).

Another review highlighted the versatility of waste shell-derived materials, noting their potential in developing bioceramics that can be used in various medical applications including orthopedic and dental surgeries. These bioceramics, derived from crab and other marine shells, are processed to create nano-bioceramic structures, which are advantageous for their high biocompatibility and enhanced mechanical properties suitable for load-bearing applications (Oktar et al., 2023). The successful implementation of these materials in clinical settings is still in the exploratory phase, requiring further in vitro and in vivo studies to fully understand their long-term interactions with human tissue. However, preliminary findings suggest that crab shell-derived nanoparticles could significantly improve the outcomes of implants by reducing the risk of implant rejection and enhancing the healing process. These case studies demonstrate the innovative use of marine waste in developing advanced materials for critical healthcare applications, showcasing the potential of sustainable resources in modern medicine.

Table 5 Case Studies on the Medical Applications of Crab Shell-Derived Materials

Case Study	Material	Applications	Findings	References
Development of Apatite Nanoparticles	Apatite nanoparticles from crab shells	Orthopedic, prosthetic, dental implants	Promotes osteoconductivity and osteointegration; suitable for bone grafting and coatings for metal implants	Bhattacharjee et al., 2019a; Bhattacharjee et al., 2019b
Versatility of Waste Shell-Derived Materials	Nano-bioceramic structures from crab and other marine shells	Orthopedic and dental surgeries	High biocompatibility, enhanced mechanical properties for load-bearing applications	Oktar et al., 2023
Implementation in Clinical Settings	Crab shell-derived nanoparticles	Various medical applications	Requires further in vitro and in vivo studies; preliminary findings suggest reduced implant rejection and enhanced healing	Various sources summarized

Table 5 summarizes case studies involving crab shell-derived materials, highlighting their potential in various medical applications. One case study focuses on apatite nanoparticles from crab shells, which have shown promise in promoting osteoconductivity and osteointegration, making them suitable for orthopedic, prosthetic, and dental implants (Bhattacharjee et al., 2019a; Bhattacharjee et al., 2019b). Another study explores the versatility of nano-bioceramic structures derived from marine shells, noting their high biocompatibility and enhanced mechanical properties for use in orthopedic and dental surgeries (Oktar et al., 2023). Although further in vitro and in vivo studies are needed, preliminary findings indicate that crab shell-derived nanoparticles could reduce implant rejection and enhance healing, demonstrating the innovative use of marine waste in developing advanced materials for healthcare applications.

4.1. Innovative Design Approaches

Crab shell-derived materials, specifically chitosan and hydroxyapatite (HAP), are gaining attention for their potential in innovative design approaches in orthopedic implant fabrication. The development of ceramics-polymer composites from crab shells offers a promising route for creating biocompatible and mechanically robust implants. These composites are tailored to enhance bioactivity and structural integrity, suitable for load-bearing applications in orthopedics (Shinyjoy et al., 2023). Chitosan-based composites, particularly those derived from the Scylla serrata species of crabs, have been explored for their utility in bone tissue engineering. These materials are not only sustainable but also possess inherent properties such as biodegradability and bioactivity, which are essential for facilitating bone growth and repair. The fabrication techniques involve the use of 3D printing and freeze-drying methods to create scaffolds that mimic the natural bone architecture, promoting osteointegration and cellular activities (Setiawati et al., 2024).

Additionally, marine-derived bioceramics, such as those developed from crab shells, are being used to manufacture bone plates, orthopedic hip implants, and bone cements. The processing techniques involve calcination followed by sintering to produce fine ceramic powders that can be used in composite formulations. These materials offer improved mechanical properties and enhanced biocompatibility compared to traditional ceramics, making them suitable for diverse surgical applications (Oktar et al., 2023). Furthermore, the use of waste shell-derived materials in additive manufacturing processes showcases the potential for these biocomposites in more customized and patient-specific implant solutions. These techniques allow for the precise control of pore size, shape, and mechanical properties, crucial for implants that need to match the specific anatomical and functional requirements of patients (Hart, 2020). These innovative approaches highlight the versatility of crab shell-derived materials in orthopedic implant design, offering sustainable and effective solutions to enhance patient outcomes in bone repair and replacement.

Figure 4 Innovative Design Approaches Using Crab Shell-Derived Materials for Orthopedic Implants

Figure 4 illustrates the innovative design approaches using crab shell-derived materials, highlighting their application in creating biocompatible and mechanically robust ceramics-polymer composites. These materials, derived from species like Scylla serrata, are used in bone tissue engineering through 3D printing and freeze-drying to mimic natural bone architecture and promote osteointegration. Marine-derived bioceramics are utilized in bone plates, hip implants, and cements, enhanced by calcination and sintering processes. Additionally, waste shell-derived materials are applied in additive manufacturing to produce customized, patient-specific implants with precise control over pore size and shape. These approaches offer sustainable and effective solutions for improving patient outcomes in bone repair and replacement.

4.2. Future Potential

The future of implant design using crab shell-derived materials is poised for significant advancements, particularly in the fields of tissue engineering and regenerative medicine. These materials, primarily derived from chitin and chitosan, are being explored for their potential to be integrated into more complex and functionally diverse implant systems. Research indicates that marine-derived bioceramics, such as those developed from crab shells, have promising applications in orthopedic and dental implants due to their excellent biocompatibility and bioactivity. Future trends suggest that these materials can be enhanced through nanotechnology to improve their mechanical properties and functionality in biological environments (Khrunyk et al., 2020; Oktar et al., 2023).

The development of three-dimensional (3D) printing technologies presents a transformative potential for crab shell-derived materials. By using 3D printing, highly customized and patient-specific implants can be fabricated, which are crucial for achieving optimal integration and functionality within the body. Recent studies demonstrate the ability to print scaffolds combining crab shell-derived calcium hydroxide with other biocompatible materials, indicating substantial improvements in cell growth and osteo-integration (Wu et al., 2023). Furthermore, the integration of crab shell-derived materials with polymers to create composite biomaterials for biomedical applications is gaining traction.

These composites can be engineered to possess unique properties such as controlled biodegradability, enhanced strength, and improved elastic modulus, making them suitable for a range of medical applications from bone grafting to load-bearing implants (Shinyjoy et al., 2023).

These innovations underline the growing importance of sustainable and naturally derived materials in medical applications, promising enhanced patient outcomes through environmentally friendly and technologically advanced solutions. The future of crab shell-derived materials in orthopedic implant design is not only promising but also represents a pivotal shift towards more sustainable and biologically harmonious medical practices.

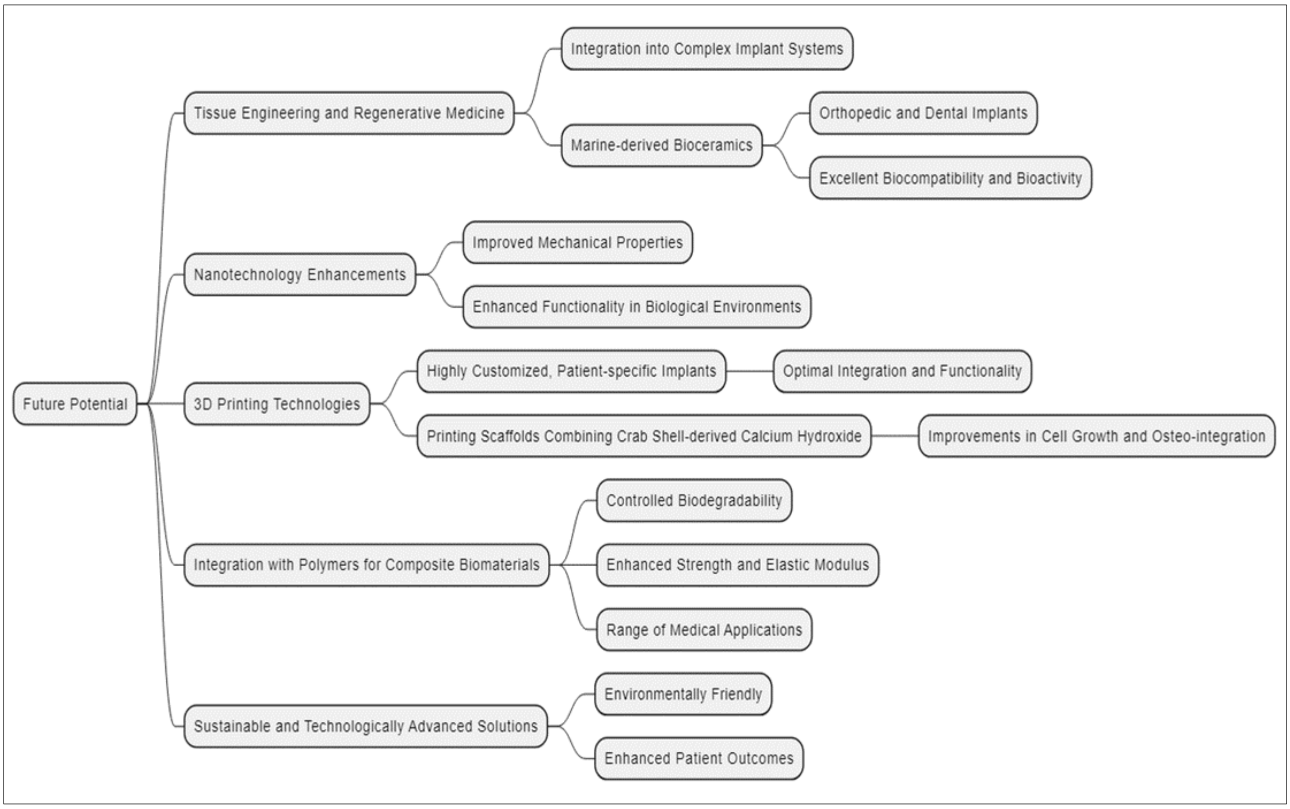

Figure 5 Future Potential of Crab Shell-Derived Materials in Implant Design

Figure 5 illustrates the future potential of crab shell-derived materials in implant design. It highlights their use in tissue engineering and regenerative medicine, including integration into complex implant systems and marine-derived bioceramics for orthopedic and dental implants. Nanotechnology enhancements and 3D printing technologies enable improved mechanical properties, functionality, and customized patient-specific implants. The integration with polymers creates composite biomaterials with controlled biodegradability and enhanced strength. These advancements promise sustainable, environmentally friendly solutions with improved patient outcomes.

5. Current Limitations

Despite the promising attributes of crab shell-derived materials for orthopedic implants, several challenges limit their widespread clinical adoption. One of the primary limitations is the mechanical stability of these materials when subjected to the rigorous demands of load-bearing applications in the human body. While the addition of metal oxides and polyhydroxybutyrate has been shown to enhance the mechanical properties of hydroxyapatite derived from crab shells, achieving consistency in mechanical performance across different batches remains a challenge (Mathina et al., 2022). Furthermore, while marine-derived bioceramics show potential, the current scaffold designs often fall short in mimicking the complex hierarchical structure of natural bone. This limitation can affect the integration and functionality of the implants, leading to compromised patient outcomes in some cases (Oktar et al., 2023).

Additionally, the processing techniques used to convert crab shell materials into usable forms for medical applications can sometimes introduce variability in the final product's properties. Issues such as inadequate purification or inconsistent material properties can lead to variability in biocompatibility and performance (Balu et al., 2021).

Environmental sustainability, though a significant advantage of using crab shell-derived materials, also poses limitations. The availability and quality of raw materials (crab shells) can vary, influenced by factors such as seasonal availability and environmental regulations affecting shellfish harvesting. This variability can affect the scalability and reliability of producing these biomaterials for large-scale clinical use (Hart, 2020). Addressing these limitations requires ongoing research and development to refine the material properties, processing techniques, and implant designs to ensure that crab shell-derived materials can meet the rigorous standards required for medical applications.

5.1. Research Needs

Despite significant progress in the use of crab shell-derived materials for orthopedic applications, several critical research gaps need addressing to optimize their clinical efficacy and safety. One such gap is the detailed understanding of the bio-resorption kinetics of these materials. While preliminary studies, such as those using hydroxyapatite nano gels derived from crab shells, have shown promising results in bone healing, comprehensive studies are needed to quantify the resorption rates and their impact on long-term bone health and stability (Mohammed et al., 2023). Moreover, there is a need for advanced biomimetic studies that can replicate the complex hierarchical structures of natural bone more accurately. Research into multi-layer bio-composite coatings and their interaction with existing bone tissue could provide insights into enhancing the osteogenic properties of these materials (Mehnath et al., 2022; Al-Ali et al., 2024).

The development of 3D printing technologies using crab shell-derived powders presents another significant research area. Studies focusing on the optimization of process parameters, such as particle size, binder type, and sintering conditions, could lead to the production of more durable and precisely engineered scaffolds suitable for a variety of orthopedic conditions (Cestari, 2023). Additionally, the potential immunological responses elicited by these biogenic materials remain poorly understood. There is a crucial need for in-depth immunological studies to assess the potential for allergic reactions or chronic inflammation, which could compromise implant success. Addressing these gaps through targeted research will be essential for advancing the development of crab shell-derived materials, ensuring their safety, and enhancing their performance in clinical orthopedic applications.

6. Conclusion and Future Perspectives

The utilization of crab shell-derived materials, particularly hydroxyapatite (HA) and chitosan, has introduced a sustainable and potentially more compatible alternative to synthetic materials in orthopedic implants. Studies underscore the consistent potential of biogenic HA, which not only aligns with the natural biochemistry of human bone but also supports environmental sustainability through the recycling of marine biological waste. Research advancements suggest a promising future for these materials in diverse surgical applications, including bone plates and orthopedic implants. The exploration of marine-derived bioceramics is seen as a path toward less invasive and more biocompatible medical solutions, reducing the body's adverse reactions and enhancing the healing process.

Moreover, the scalability of technologies for processing waste shell-derived materials poses a challenge yet offers a direction for substantial impact in both waste reduction and medical material innovation. The ongoing development in this field is expected to bridge the gap between experimental success and clinical application, necessitating further research to optimize material properties and surgical outcomes. There is a need for ongoing innovation in material synthesis and application techniques, suggesting that future research should focus on enhancing the osteogenic properties of these materials. Developing composites that integrate crab shell-derived HA with other biocompatible materials could lead to breakthroughs in personalized medicine through advanced 3D printing techniques. While significant progress has been made, the full potential of crab shell-derived materials in orthopedic applications will depend on targeted research efforts to overcome current limitations and explore innovative fabrication technologies. This promising field holds the potential not only for advancing human health care but also for contributing to environmental sustainability in medical material production.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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