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Exploration of the Mechanism and Process of Pearl Formation

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Abstract As a rare and precious gemstone, pearls are naturally beautiful and do not require manual carving and processing, making them a beautiful and precious accessory. Since ancient times, it has held an important position in people's hearts, carrying rich historical, cultural, and emotional values. With the maturity of pearl farming technology in modern society, the production of pearls continues to increase, and pearl products continue to enrich. Pearls have also become one of the fastest growing varieties in jewelry consumption. This review analyzes the influencing factors of pearl formation by exploring the process and internal mechanisms of pearl formation. At the same time, by collecting existing research methods, we look forward to the development of the pearl industry. The exploration of the process and mechanism of pearl formation has important scientific significance and social value. By strengthening scientific research and protective measures, sustainable development of pearl aquaculture can be achieved, and more contributions can be made to the inheritance and development of pearl culture.
Keywords Pearl formation mechanism; Formation process; Influencing factors

Pearl, as a rare and precious gemstone in the natural world, has held an important place in people's hearts since ancient times due to its unique charm and noble status. It is not only one of the representatives of the jewelry art but also carries a long history, rich cultural significance, and rich emotional value. The history of pearls can be traced back to ancient times, where people began to appreciate and use them thousands of years ago. In ancient legends and historical records, pearls were often praised as "nature's treasure" and "teardrops of the moon," being revered as a symbol of nobility and auspiciousness. In ancient cultures, pearls were often endowed with mysterious symbolism, seen as a representation of divinity and purity, and hailed as the "jewel of kings" or "tears of goddesses." The beauty and mystique of pearls have captivated people's attention worldwide, making them treasures in multiple cultures.

With the continuous advancement of science and technology, there has been a deeper exploration of the formation process and mechanism of pearls. The formation of pearls is considered a natural wonder, involving complex biological, chemical, and physical processes. Despite the increased understanding of pearl formation, there are still many mysteries and unanswered questions. In-depth research into the mechanisms and processes of pearl formation is of significant importance for the development of pearl farming, the protection of ecological environments, and the development of new materials and technologies. Understanding the biology and ecology of mollusks helps promote the conservation and management of ecosystems, achieve sustainable utilization of pearl oyster resources, and protect marine ecological balance. Furthermore, the understanding of pearl formation mechanisms provides new ideas and directions for the development of new biomaterials and technologies, expanding their applications. Pearls also find certain applications in the field of medicine, with their components and therapeutic effects being used in some traditional Chinese medicine and healthcare products. Understanding the process of pearl formation can provide important guidance for pearl farming, helping improve pearl production and quality to meet people's demand for pearls. Finally, the exploration of the pearl formation process reminds us to value environmental protection and sustainable development, combining the development and preservation of marine resources to jointly safeguard the beautiful blue home of the Earth.

The exploration of the mechanisms and processes of pearl formation is a complex and challenging field that requires continuous scientific research and technological innovation. Through in-depth research and protection of pearls, we will better inherit and develop pearl culture, allowing this natural treasure to continue shining in the river of human civilization. At the same time, pearls will continue to play an important role in the advancement of modern medicine and technology, making greater contributions to human health and technological innovation. Let us work together to protect this precious natural wealth, preserve its beautiful historical culture, and explore its scientific value, so that pearls can exhibit a more brilliant and diverse appearance in future development.

1 Exploration of the Mechanisms of Pearl Formation

1.1 Chemical composition of pearls

The main component of pearls is calcium carbonate, primarily in the form of the mineral aragonite. Calcium carbonate is formed by the combination of calcium ions and carbonate ions within the mollusk's body, resulting in the formation of nacre through a series of biochemical reactions. The composition and structure of pearl determine its refraction effects under light, giving pearls their unique luster and color. Additionally, pearls also contain small amounts of organic substances such as proteins, polysaccharides, and lipids, which play a significant role in the texture and luster of pearls.

Research has found that the chemical composition during the process of pearl formation is primarily influenced by the physiological metabolism within the mollusk's body and the external environment. Mollusks absorb calcium ions and organic substances from the water, converting them into nacre while simultaneously eliminating excess inorganic salts and organic waste (Gardner et al., 2015). The water quality conditions and oxygen content in the environment also affect the metabolic processes within the mollusk's body, thereby impacting the speed and quality of pearl formation. Therefore, understanding the chemical composition and regulatory mechanisms of pearl formation is of significant importance in improving pearl production and quality.

1.2 Biological mechanisms of pearl formation

The formation of pearls is a defensive response by mollusks. When a foreign object such as a grain of sand or a parasite enters the interior of the mollusk's shell, the mollusk produces a membrane called the "pearl sac" to wrap these foreign objects. Under the encapsulation of the pearl sac, cells within the mollusk's body secrete nacre, gradually enveloping the foreign object and forming a pearl (Figure 1).

Figure 1 The pearl inside a shell

The biological process of pearl formation involves the participation of various cells and proteins, among which an important protein is a mucous protein produced within the mollusk's body. This mucous protein plays a crucial role in the formation of the pearl sac. It can bind calcium ions and carbonate ions together, facilitating the formation of nacre. Additionally, the process of pearl formation also involves the regulation of growth factors and cellular signaling pathways. These factors and pathways can influence the speed and quality of pearl formation.

1.3 Physical mechanisms of pearl formation

The physical mechanisms of pearl formation primarily involve crystal growth and the assembly process of microcrystalline structures. Within the mollusk's body, calcium ions and carbonate ions undergo biochemical reactions, forming tiny crystalline nuclei. Then these crystal nuclei then continuously absorb surrounding calcium ions and carbonate ions, gradually growing into larger crystals. The growth rate and direction of these crystals are influenced by physiological conditions within the mollusk's body and environmental factors, thereby affecting the speed and morphology of pearl formation.

Moreover, the microcrystalline structure within the nacre also plays a significant role in the properties and quality of pearls. The crystal structure within the nacre exhibits a layered arrangement, formed a structure similar to tiles. This layered structure can reflect and refract light, giving pearls their vibrant luster and color. Therefore, the assembly process of the microcrystalline structure has a crucial influence on the texture and luster of pearls.

2 The Process of Pearl Formation

2.1 Classification of pearls

Pearls can be classified into two main categories based on their origin and formation process: natural pearls (Figure 2) and cultured pearls. Natural pearls are formed in a natural environment, typically within the bodies of mollusks or oysters, as a result of their defense mechanisms against foreign objects (Cuif et al., 2011). Cultured pearls, on the other hand, are formed through human intervention in the breeding process of mollusks. This involves the implantation of foreign objects or stimulation of the pearl-producing organ within the mollusk to induce pearl formation.

Figure 2 Natural pearl

2.2 The basic process of pearl formation

Natural pearls are often non-nucleated pearls. Non-nucleated pearls refer to pearls that are formed by the mollusk's defense mechanisms in response to the intrusion of foreign objects in a natural environment. When the mantle epithelium of a clam or oyster is invaded by a foreign object, the outer epithelial cells of the mantle sense the external stimulus. These cells undergo abnormal proliferation and become embedded within the connective tissue of the mantle. Subsequently, the outer epithelial cells continue to divide, forming multiple pearl sacs which secrete nacre, eventually resulting in the formation of a pearl. These pearls, which lack a nucleus or seed, are known as "non-nucleated pearls." The formation process of non-nucleated pearls is highly complex, requiring a significant amount of time and a stable ecological environment.

In cultured pearls, nucleated pearls are predominant. When the mantle epithelium of a clam or oyster is invaded by a foreign object such as a grain of sand or a parasite, the mollusk initiates its self-defense mechanism. The outer epithelial cells in the stimulated area of the mantle surround the foreign object and become embedded within the connective tissue, continuously dividing and enveloping the foreign object. This process results in the formation of a sac-like structure called a pearl sac, with the foreign object as its nucleus. The cells of the pearl sac secrete nacre, continuously layering and enclosing the foreign object. Over time, the nacre layer thickens, eventually forming a "nucleated pearl" (Figure 3). Nucleated pearls refer to the process in which a foreign object is implanted into the mollusk's body as a nucleus during the artificial cultivation process. The mollusk then secretes nacre around the foreign object, gradually forming a complete pearl. In this process, the selection and implantation techniques of the nucleus are crucial (Arnaud-Haond et al., 2007). The material and shape of the nucleus directly impact the quality and morphology of the pearl.

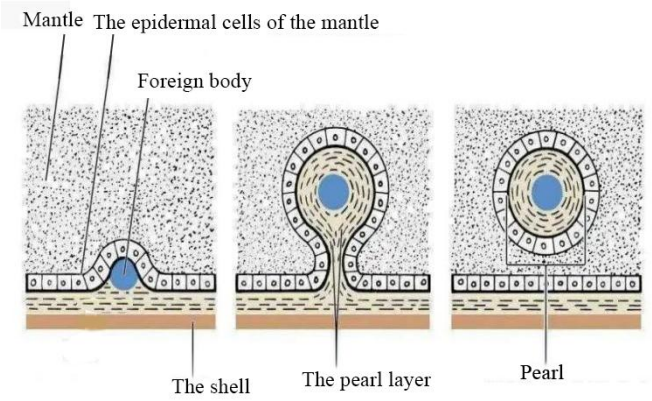

Figure 3 Process of nucleated pearl formation

2.3 Factors affecting pearl formation

2.3.1 Ecological factors

The ecological environment and water quality of the aquatic habitat play a crucial role in pearl formation. The types and abundance of planktonic organisms in the ocean, as well as variations in water temperature and seasons, also influence the physiological metabolism and pearl formation process of mollusks (Collado et al., 2023). For example, in pearl-producing regions like the South China Sea, clear seawater, abundant planktonic organisms, and stable water temperatures are important factors that promote pearl formation. These ecological conditions provide mollusks with ample nutrients and a suitable living environment, facilitating the formation of nacre within their bodies.

2.3.2 Environmental factors

The concentration of calcium ions and organic matter in the water, as well as the pH level of the aquatic environment, play a significant regulatory role in pearl formation (Li et al., 2020). Calcium ions are essential components in the process of pearl formation. Mollusks absorb calcium ions from the water to form nacre. Additionally, the pH level of the water affects the solubility and availability of calcium ions, thereby influencing the quality and speed of pearl formation (Tan et al., 2019). The instability of environmental factors can lead to abnormal or incomplete pearl formation in mollusks. Therefore, maintaining stable environmental conditions is crucial for the successful formation of pearls.

2.3.3 Biological factors

Pearl formation is closely related to the species and genetic differences of mollusks. Different species of mollusks exhibit distinct characteristics and rates of pearl formation. For example, South Sea pearl oysters and Tahitian black pearl oysters demonstrate different biological traits during the pearl formation process, resulting in variations in the appearance and quality of the nacre they produce. Additionally, the dietary sources and health conditions of mollusks, as well as the presence of diseases and injuries, can impact their internal pearl formation

process (Adzigbli et al., 2020). For instance, mollusks affected by environmental pollution or disease infections may experience abnormalities or interruptions in pearl formation.

3 Advances in Pearl Formation Research

In recent years, significant progress has been made in the exploration of the pearl formation process, driven by continuous advancements in scientific technologies and innovative research methods. Researchers have employed various approaches and techniques to delve into the chemical composition, biological processes, and physical mechanisms underlying pearl formation, unraveling some of its mysteries.

3.1 Innovations in research methods

In recent years, researchers have continuously innovated research methods for studying the pearl formation process, driven by advancements in biotechnology and materials science. Traditional research methods have mainly involved microscopic observations, chemical analyses, and biological experiments. Through microscopic observations, researchers can visually examine the assembly of microcrystalline structures and crystal growth processes during pearl formation. Chemical analyses aid in a deeper understanding of the chemical composition and structural components of pearls. Biological experiments, on the other hand, reveal the physiological metabolism and responses of mollusks during the process of pearl formation.

In addition to traditional research methods, emerging technologies such as genomics, proteomics, and bioimaging have also been applied to the study of pearl formation processes in recent years. Genomics research helps us gain a deeper understanding of the genomic composition and gene expression regulation in mollusks, revealing key genes and signaling pathways involved in pearl formation. Proteomics research allows us to comprehensively understand the protein composition and functionality within mollusks, thereby elucidating the roles and regulatory mechanisms of proteins in the process of pearl formation. Bioimaging techniques enable real-time observations of the pearl formation process within mollusks, providing a visual representation of the dynamic process of pearl formation.

3.2 Development of research findings

The latest discoveries in pearl formation, driven by advancements in research methods, have provided us with a deeper scientific understanding. For instance, recent genomic research has unveiled several genes related to pearl formation in mollusks, including genes encoding mucin proteins (Liu et al., 2021) and mineralizing enzymes. The discovery of these genes helps us gain insights into the biological processes and regulatory mechanisms underlying pearl formation. Additionally, proteomics research has identified proteins associated with pearl formation, suggesting their involvement in the formation and growth of nacre. The application of bioimaging techniques has also allowed us to visually observe the process of pearl formation, revealing the dynamic changes in growth rate and crystal structure.

In addition to advancements in fundamental research, there have been emerging applications in the study of pearl formation processes in recent years. For example, some researchers have attempted to utilize bioimaging techniques and bioinformatics approaches to synthetically produce pearl-like samples (Figure 4) through biomimetic synthesis, exploring their potential applications in materials science and biomedicine. Furthermore, research on the pearl formation process has provided important guidance for the development of pearl farming industry. By regulating the ecological environment and rearing conditions of mollusks, it is possible to enhance the yield and quality of pearls, thus promoting the sustainable development of the pearl industry.

4 Summary and Outlook

With the increasing awareness and appreciation of pearls, the outlook for the pearl market is promising. Especially in Asian regions, pearls have been regarded as traditional jewelry and are widely loved. As Asian economies develop and people's living standards improve, the demands for pearls is expected to continue to rise. Additionally, with globalization and the growth of the tourism industry, more and more people are being exposed to pearls and developing an interest in them. This will further drive the expansion and development of the pearl market. Looking ahead, with technological advancements, new pearl farming techniques may be developed to increase the

yield and quality of pearls. Furthermore, there will be ongoing innovation in the design and processing of pearls, resulting in a diverse range of pearl products to meet the needs of different consumers. These developments will bring new growth opportunities and prospects for the pearl market.

Figure 4 Artificially synthesized pearls

Despite the enormous potential of the pearl farming industry, it also faces sustainability issues. Overexploitation of pearl oyster resources can lead to resource depletion and ecological degradation. Therefore, it is necessary to strengthen the conservation and management of pearl oyster resources to ensure their sustainable utilization. Additionally, some traditional pearl farming methods may have adverse effects on the environment, such as water pollution and ecosystem disruption. Hence, there is a need to promote the application of green farming technologies to minimize environmental impacts and achieve sustainable development in the pearl farming industry.

So far, there are still many mysteries surrounding the process of pearl formation that require further exploration. For instance, there is a need for deeper research into the biomineralization and crystal growth mechanisms during pearl formation, uncovering the detailed molecular and cellular-level mechanisms involved. Additionally, studying the interactions between different environmental and biological factors during pearl formation can provide insights into the complex regulatory networks at play. Furthermore, leveraging modern technologies such as genomics and proteomics can contribute to a better understanding of the biological characteristics and ecological adaptability of pearl oysters. These research endeavors will provide new avenues for a deeper understanding and practical applications of the pearl formation process.

Overall, the future prospects of pearl formation are promising, but they also face some challenges. Through strengthening scientific research, promoting the application of green farming technologies, and enhancing resource conservation and management, we can achieve sustainable development in the pearl farming industry, protect pearl oyster resources, preserve and develop pearl culture, and contribute more to the development of human society. Moreover, research on the process of pearl formation will provide new insights and directions for advancements in modern medicine and technology, expanding its application areas and driving technological innovation and social progress. Therefore, the study of pearl formation holds significant scientific significance and social value. We have every reason to believe that with the continuous development of science and technology, a deeper understanding and practical applications of the pearl formation process will bring more surprises and benefits to humanity.

Authors' contributions

XXY is the primary author of the review, responsible for collecting and analyzing relevant literature, as well as drafting the initial manuscript. She also participated in the analysis and organization of the literature. XJ, on the other hand, conceived and supervised the project, providing guidance for the paper's writing. Both authors read and approved the final manuscript.

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