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Review Article

Nutritional Benefits of *Saccostrea cucullata*: Potential Role in Human Health

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Abstract

Saccostrea cucullata, a species of bivalve mollusk native to the Persian Gulf, is highly prized for its nutritional richness and rapid growth, making it a valuable species for aquaculture. Despite its abundance and potential in the Persian Gulf, the aquaculture industry has faced challenges due to limited understanding of its biology and genetics. This review consolidates current knowledge on the life cycle, reproduction, and environmental factors influencing the growth and nutritional quality of *Saccostrea cucullata*. It examines the impact of climate variations and identifies key challenges. Strategies such as closed-system cultivation, selective breeding, and genetic enhancement aimed at producing triploid oysters are discussed, focusing on improving desirable traits such as growth rate, disease resistance, and nutritional content. Enhancing these aspects can lead to increased production of nutrient-rich *Saccostrea cucullata*, thereby advancing the nutritional benefits and sustainability of aquaculture.

Keywords: food security, minerals, nutritional value, omega-3 fatty acids, oysters, *Saccostrea cucullata*, vitamins

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1. Introduction

Oysters are among the most valuable bivalve species found extensively in bays, rivers, ports, typically near rocky shores or other hard substrates. The oyster includes 75 species in 16 genera distributed along coastlines worldwide except the Antarctic and some oceanic islands [1, 2]. Annually, more than 15 million tons of oysters are produced globally for human consumption, constituting 14% of the world's total marine production, with 89% of marine bivalve production coming from aquaculture and having an economic value exceeding $20 billion United States dollar (USD) per year [3].

Oysters serve as biological filters that purify ecosystems and are essential for ecosystem preservation and survival [4, 5]. Additionally, they ensure human food security as a rich source of protein, energy, significant amounts of vitamins A and D, minerals (calcium, selenium, iodine), and omega-3 fatty acids, all beneficial for health [6]. Furthermore, due to their ability to accumulate various pollutants from marine environments, oysters are studied as biological monitors [7, 8]. Today, numerous species of oysters are extensively cultured.

One of the most popular species is the rock oyster from the Ostreidae family, particularly *Saccostrea cucullata*, a valuable bivalve species inhabiting intertidal and subtidal zones in hot and subtropical regions, including parts of the world such as Australia, India, Thailand, China, East Africa, and the northern coasts and some Iranian islands like the Persian Gulf and the Sea of Oman [1, 9]. *Saccostrea cucullata*, commonly known as the "rock oyster," is recognized for its high nutritional value, potential to improve water quality through filter feeding, and high market demand, making it a valuable aquaculture species [10]. Oyster cultivation has a history of over 2,000 years in temperate regions of Asia and has seen a significant surge in recent decades. While aquaculture has been practiced in Iran for three decades, the most significant rise in production has occurred in the past 10 years [11].

Given the potential of Persian Gulf shores for cultivating edible oysters, their aquaculture can significantly contribute to the industrialization and economic development of marine aquaculture in this region [12]. Understanding the growth and development of *Saccostrea* oysters is crucial for optimizing cultivation methods and maximizing production [13].

Oysters, particularly *Saccostrea cucullata*, are highly nutritious and contribute significantly to human health. They are an excellent source of high-quality protein, essential for muscle building and repair. The presence of omega-3 fatty acids in oysters helps in reducing inflammation and improving heart health. The significant levels of vitamins A and D found in oysters play crucial roles in maintaining healthy vision, immune function, and bone health. Additionally, the rich mineral content, including calcium, selenium, and iodine, supports various bodily functions, such as thyroid regulation, antioxidant defense, and bone strength.

The primary aim of this study is to consolidate and expand the current knowledge on *Saccostrea cucullata* with a focus on its nutritional benefits and the factors influencing its growth and cultivation.

By evaluating the life cycle, reproduction, environmental impacts, and optimal cultivation practices, this research seeks to provide a comprehensive understanding that can aid in the enhancement of aquaculture practices. The ultimate goal is to maximize the production of nutrient-rich *Saccostrea cucullata*, thereby improving food security and promoting the economic development of marine aquaculture in the Persian Gulf region.

2. Morphology and Life Cycle of *Saccostrea cucullata*

One of the fascinating features of *Saccostrea cucullata* is its exceptionally rapid growth rate, with many individuals reaching market size (7–11 cm) in less than a year [14, 15]. The oyster exhibits diverse shapes, often nearly round, oval, or rectangular with irregular surfaces [9, 16]. Its shell is thick and robust, typically asymmetrical, with small teeth on the edge of the upper (right) valve that align with grooves on the lower (left) valve. Their color is gray with brownish-purple margins [2, 9, 17].

Despite the abundance of this oyster species in the Persian Gulf, its reproductive biology is not well studied. Successful oyster farming primarily relies on a good source of natural spat (young oysters). Therefore, oyster cultivation is carried out through natural spat fall [1, 18]. The insufficient supply of oyster seed is one of the reasons the oyster industry cannot fully develop [19]. Understanding the reproductive biology of oysters is crucial for maintaining and sustaining their populations. Knowledge of sex, reproductive methods, sex ratio, and settlement, along with the factors influencing them, is essential for effective management policies for cultivation, harvesting, conservation, and restoration of oysters.

3. Reproduction

Oysters reach sexual maturity when their shell size reaches 50 to 80 mm, and the gonadal tissue of mature oysters appears creamy white [20]. The reproductive cycle of *Saccostrea* includes gametogenesis, gamete development, spawning, fertilization, and larval development [21]. Oysters release eggs and sperm into the water, influenced by various factors. Fertilization begins with the random encounter of sperm and eggs, forming a zygote [22–24]. Approximately 30 minutes after fertilization, cell division starts, progressing through the morula, blastula, gastrula, and trochophore stages within 24 hours, reaching a spherical shape about 65 microns in size. After 24 to 48 hours, the shell forms, and the larvae, known as veliger larvae, are recognized by their distinct D-shaped valves [25–27]. Feeding of the larvae starts at this stage [28]. The larvae then pass through the umbo stage (6 –21 days), the pediveliger stage (20–23 days), during which they can swim, and the plantigrade stage (24–26 days). After 25 to 30 days, the larvae transform into spat, measuring approximately 285–300 microns, capable of attachment and settlement on a suitable substrate (Figure **1**)[25, 29, 30].

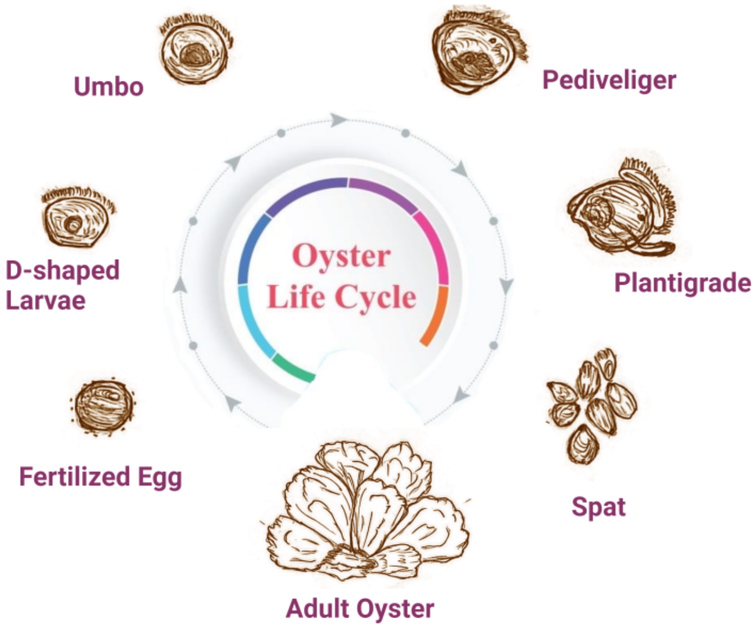

Figure 1: Life cycle of *Saccostrea cucullata* oyster: **Fertilized egg** (10-25m after fertilization, 45±4 μm), **D-shaped Larvae** (1-2 D after fertilization, 57±7 μm, swimming and feeding stage with well-developed velum), **Umbo** (6-21 D after fertilization, 62-188 μm), **Pediveliger** (20-23 D after fertilization, 222±28 μm), **Plantigrade** (24-26 D after fertilization, 265±29 μm, Transformation from free-swimming larvae to crawling stage and start of settlement stage), **Spat** (25-30 D after fertilization, 285-300 μm).

4. *Saccostrea* Aquaculture

The cultivation of oysters involves several stages: production of spat, nursery culture (larval rearing), growth, and harvesting, which typically occur over a period of 12–36 months (Figure **2**). A continuous supply of spat is a major concern for oyster farmers [15, 19]. In temperate and subtropical countries, most spat are produced in hatcheries, but in tropical areas, most of the spat used for aquaculture come from natural sources [31] and are collected using spat collectors. These collectors are usually made from readily available materials such as oyster shells, mangrove roots, cement tiles, stones, bamboo, and plastic [31, 32]. This collection method is feasible only during natural spawning seasons. However, in hatcheries, mature oysters are conditioned by placing them in optimal environmental conditions, such as appropriate temperature and food availability, to stimulate gamete production, which takes approximately 4–8 weeks [28, 33, 34]. Once spawning begins, eggs and sperm are collected and mixed to achieve fertilization. The fertilized eggs are then developed into larvae in a controlled environment [15, 35]. Once the source of spat is secured, the nursery phase begins [15].

Saccostrea larvae require specific conditions for successful growth and development. Temperature, salinity [36, 37], and food availability [38, 39] are critical factors. Larvae are often reared in tanks or specialized larval rearing systems. The water temperature is maintained within an optimal range of 28–30°C, and salinity between 30 and 35 ppt [15, 36]. Larvae are fed a diet of microalgae, which can be cultured alongside oyster farms or sourced externally [15, 40]. In some cases, spat is grown to market size on their initial collector without a separate nursery phase [15]. The nursery system is used to protect spat from predation, sedimentation, and damage from harsh ocean conditions [41]. Nursery systems may be a part of the hatchery facility, including nursery trays or upweller or downweller systems in tanks with various configurations [35, 42]. They may also be located near the growing site, including shore-based tanks, basket systems, or trays situated in calm waters [43]. When the spat reaches approximately 5–10 mm in size, they are transferred from the nursery system to a grow-out system [35].

Grow-out systems used for producing marketable oysters include bottom culture (where oysters are placed directly on the seabed or in mesh bags) [44, 45], rack systems (where oysters are suspended in the water column) [46], floating basket and net systems (where oysters are floated in nets on the water surface) [47–49], and pond culture. The choice of grow-out system depends on site-specific conditions and management preferences. During the growth phase, oysters continue to feed on natural plankton and other organic materials present in the water, aiding their growth and development.

The timing of oyster harvest varies depending on the oyster species, market demand (preferred oyster size), and the cultivation methods used. Harvesting methods also depend on the grow-out system used, and oyster farming is typically done to ensure a continuous supply for market consumption [15].

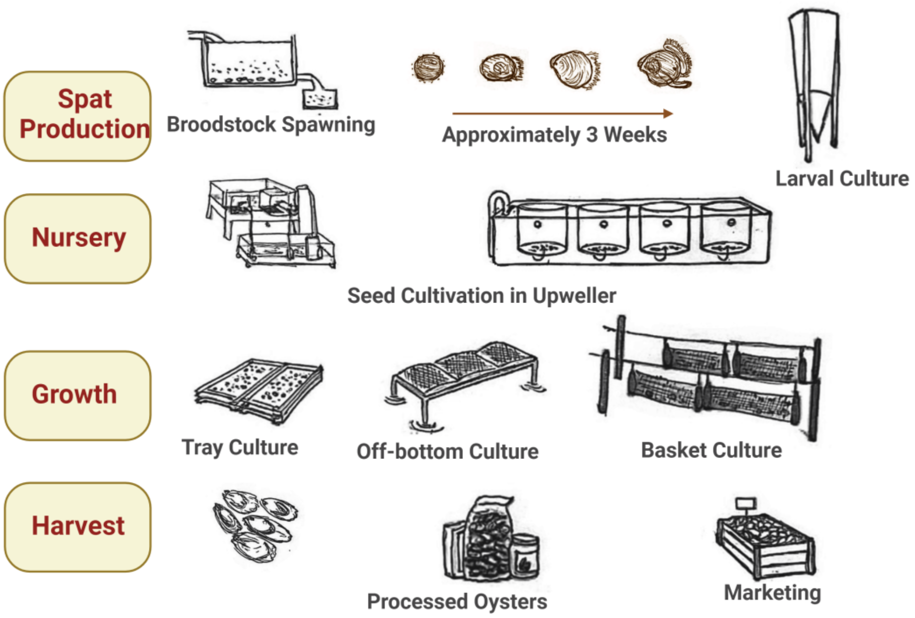

Figure 2: General oyster aquaculture cycle from spat production (about 3 weeks), through nursery culture (2-3 months, 5-10 mm) and growth to harvest.

5. Factors Influencing Successful Oyster Cultivation

5.1. Sex determination

The sex ratio of gametogenesis in mature oysters is crucial for the long-term success of oyster populations. Sex determination describes the development of sexual characteristics in oysters and is therefore intrinsically linked to the sex ratio of the population [50, 51]. Sex determination, followed by the sex ratio and reproductive capacity of oysters, affects the supply of larvae and their population size [52]. For instance, a reduction in the number of female oysters indirectly decreases the supply of offspring, whereas a reduction in the number of males may limit mating opportunities. A reduction in both sexes may limit the genetic diversity of the population, leading to an inability to adapt to environmental changes [52].

Sex determination in *Saccostrea* is influenced by genetic and environmental variables or their interaction [53, 54]. *Saccostrea* is known for protandric hermaphroditism, where they mature as males early in life and change to females in subsequent years [52, 55, 56]. A combination of secondary genes and environmental factors such as temperature, salinity, food concentration, photoperiod, and chemical pollutants are believed to affect the rate of sex change in oysters [54, 57–60]. Some evidence suggests that male oysters become dominant under less favorable environmental conditions, while in a rich environment, oysters change sex, and females become dominant [51, 53].

5.2. Factors influencing gametogenesis

The reproductive cycle in *Saccostrea* is affected by a complex interaction of internal factors such as genetics and developmental parameters, and environmental factors such as water temperature, salinity, light, and food availability [1, 61, 62]. Water temperature and food availability are two critical factors influencing gametogenesis [63, 64]. Water temperature affects the maturation of gonads, and food availability influences fertility, gamete quality, and larval survival [63, 65–67].

The highest and lowest water temperatures in the Persian Gulf are observed in August (30-34°C) and February (19–20°C), respectively [61]. During November to December, most female oysters are in the sexually inactive (resting) stage. Gametogenic activity in *Saccostrea* starts from mid-February [61]. Mature oysters are often seen from May to July and somewhat from August to December when the water temperature exceeds 30°C. Male and female *Saccostrea* oysters generally spawn throughout the year, although peak spawning in the Persian Gulf occurs from June to August [1, 21, 61, 68]. While salinity also influences gametogenesis [36, 69], the relatively constant salinity of the Persian Gulf (39.5 to 40 ppt) means this factor does not affect *Saccostrea* gametogenesis [61].

5.3. Factors influencing settlement and cultivation

Oyster cultivation depends on biotic and abiotic variables. Abiotic factors include water temperature, salinity, dissolved oxygen, and availability of suitable substrate, while biotic factors include food availability, disease incidence, predation, and competition with other organisms for space and resources [30]. Temperature and salinity are two critical ecological factors affecting the development and growth of the embryonic and larval stages of *Saccostrea* [36]. Optimal growth is usually observed within a specific temperature range, typically between 28°C and 30°C, and salinity levels between 30 and 35 ppt are considered optimal for growth [25]. Adequate food availability, primarily microalgae, is essential for achieving rapid growth and increasing survival rates [28, 70]. The growth and development of *Saccostrea* oysters are highly influenced by environmental factors. Water quality parameters, including dissolved oxygen, pH, turbidity, and nutrient levels, play a crucial role in determining the health and growth of oysters. Low oxygen concentration, high turbidity, and extreme pH levels can negatively impact oyster growth and survival [30, 33, 35, 71]. Nutrient availability, particularly nitrogen and phosphorus, affects primary productivity, which in turn influences oyster growth through the food web. A mix of various microalgae species such as Isochrysis, Chaetoceros, Thalassiosira, Nannochloropsis, and Tetraselmis is used to feed oysters [34, 72]. Additionally, water flow and hydrodynamics play a role in larval dispersion and food particle supply [33, 35, 73].

5.4. Impact of climate change on oyster growth and development

The effects of climate change on oceans worldwide have been reported, and these changes are currently beginning to impact the environment, including: increasing temperatures, rising sea levels, ocean acidification, changes in rainfall patterns, and consequently, salinity, nutrient concentration, and quality [74].

The impact of climate change, especially increasing temperatures and ocean acidification, significantly affects oyster populations. Increased temperatures affect the survival, growth, reproduction, health, and phenotypes of marine organisms [75]. Ocean acidification, resulting from CO2 emissions, decreases the pH of water, which is detrimental to fertilization and embryonic development, leading to the formation of D-larvae with heterogeneous sizes and varying degrees of defects and abnormalities [75, 76]. Decreased pH also reduces the saturation level of CaCO3 in surface waters, causing problems in forming calcareous structures (skeletons and shells) in oysters. This delay in larval growth exposes them to predators for a longer period and makes them more susceptible to physiological disorders such as metabolic energy deficiency, impaired metabolism, and incomplete protein synthesis [77, 78].

6. Spawning Methods

Spawning in *Saccostrea* oysters can be induced using various techniques. The aim of these methods is to synchronize the release of eggs and sperm to maximize fertilization success [79]. Some common methods include:

6.1. Thermal induction

Oysters are exposed to a controlled thermal shock, typically by raising the water temperature a few degrees above their optimal range. This sudden temperature change induces the release of eggs and sperm [33, 35, 80].

6.2. Chemical induction

Specific chemical compounds such as hydrogen peroxide, serotonin [81], neuropeptides like APGWamide and PIESVD [82], MgCl2 [83], and even killed sperm from male oysters [84] can be used to induce spawning. These compounds mimic natural spawning signals and stimulate the reproductive response in oysters.

6.3. Stripping

In some cases, oysters can be manually stimulated to release eggs and sperm by gently manipulating their gonads. This method requires skilled handling to avoid damaging the reproductive organs. Due to the potential harm to broodstock oysters and the low yield, this method is not recommended and should only be used to assess gonad maturity [33, 35].

7. Goals of *Saccostrea* Oyster Farming

The objective of *Saccostrea* oyster farming programs is to enhance desirable traits such as growth rate, disease resistance, shell strength, and meat quality [85]. These programs involve selective breeding and genetic selection to propagate individuals with the desired characteristics [86]. The breeding process typically includes the following steps:

7.1. Phenotypic selection

Oysters with desirable physical traits such as size, color, shell shape, faster growth, and disease resistance are identified [85, 87]. These oysters are selected as broodstock for future breeding. Selected male and female oysters with complementary traits are paired, and their offspring are reared and evaluated for the desired traits. Families exhibiting superior performance are selected for further breeding [88]. This method is carried out in traditional hatcheries.

7.2. Crossbreeding

In the past three decades, triploid oysters have become a popular aquaculture product due to their superior growth and meat quality, rapidly becoming an industry standard [89]. Despite significant growth advantages, there are few established physiological or metabolic differences between diploid and triploid oysters [89, 90]. Triploid oysters possess an extra set of chromosomes, resulting in a higher degree of sterility [89]. The demand for triploid oysters is primarily due to their 30% faster growth rate compared to their diploid counterparts and their high meat quality resulting from their sterility [89, 91]. It is believed that the observed faster growth in triploids is due to the reallocation of energy from reproduction to physical growth [89], as spawning in oysters is associated with a reduction in glycogen content and meat quality [92]. Consequently, sterile triploids provide a more consistent product throughout the year, producing larger oysters and preventing increased population heterozygosity in hatcheries [89]. However, triploids are not entirely sterile. In addition to providing a more consistent food product [93], the use of sterile triploids is considered the most efficient and cost-effective mechanism for preventing genetic dispersal of hatchery stocks into wild populations. These oysters are produced by two methods [89]:

i. Chemical induction: This method uses the chemical cytochalasin B to induce triploids by exposing freshly fertilized eggs to cytochalasin B, blocking polar body formation during meiosis I and II, achieving 88% success [94, 95, 98].

ii. Genetic triploidy method: The most effective method for producing triploid offspring is crossing tetraploid and diploid oysters, achieving 100% success [93]. In this method, sperm from tetraploid males is used to fertilize the diploid eggs. This method not only has a higher success rate but also results in better growth and survival of triploids compared to those produced with cytochalasin B [89, 92, 95].

7.3. Genetic markers

In recent years, genetic markers have been used to aid the selection process. These markers help identify specific genes associated with desirable traits, allowing for more precise breeding decisions. Markers such as allozymes [96], mitochondrial genes [97], microsatellite markers [98], and techniques like Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) [99] and Magnetic Resonance Imaging (MRI) [100] have been employed.

Overall, farming methods, spawning techniques, and breeding strategies play a crucial role in the successful production and improvement of *Saccostrea* oysters. These techniques help optimize growth, increase disease resistance, and ensure the sustainability of oyster farming operations.

8. Challenges and Future Directions

Global aquaculture production has increased significantly over the past 50 years, now accounting for over 50% of the world's fish food supply. Aquaculture, including oyster farming, is expected to continue expanding to meet the growing global demand for seafood. Oyster aquaculture, practiced for over two millennia, has seen rapid global growth since 1950, with production increasing fivefold since 1990 due to innovations like larval culture techniques and triploid oysters. These advances have improved the efficiency and quality of oyster production [101].

Overall, there are inherent limitations in natural oyster cultivation. Even when a large number of mature oysters are reproducing, the natural supply and stocking of juvenile oysters (spat) are less than the habitat capacity. For example, many pelagic larvae may perish due to food shortages or be washed away by water currents, preventing successful settlement and leading to predation [30]. Hatchery production focuses on maintaining broodstock, inducing spawning, and obtaining high-quality larvae [102]. Closed cultivation, restocking, and aquaculture aim to correct this situation by supplying spat to match the habitat capacity. In closed cultivation, offspring are raised to maturity in a controlled system before being used as broodstock for the next generation [103].

To prevent domestication and preserve genetic identity, wild oysters are often used in captive breeding. On the other hand, oysters in commercial hatcheries are selectively bred for traits that increase hatchery efficiency [30]. Restocking and enhancing oyster stocks involve releasing hatchery-raised spat into natural habitats to increase and replenish spawning biomass and improve the species [104].

Marine aquaculture involves releasing hatchery-grown oysters into open coastal environments for harvesting at maturity through "set, grow, and harvest" operations, without allowing the grown oysters to complete spawning biomass [30, 104]. To ensure the longevity of triploid use in aquaculture and reduce the risky traditional "trial and error" approach in aquaculture development strategies, further research on the relative safety of triploid and diploid oysters is essential. Such research requires a careful examination of the genetic background of the stocks being studied to reduce or eliminate variations related to genotype-environment interactions [89].

Despite advancements in oyster farming practices, challenges remain. Disease outbreaks, predation, habitat destruction, and climate change threaten *Saccostrea* oyster populations [105]. Future research should focus on developing sustainable aquaculture practices [106], disease management strategies, and identifying genetic traits to improve growth and resilience [107]. Additionally, understanding the interactions between oysters and their environment will help predict and mitigate the effects of climate change on oyster populations [108].

9. Nutritional Benefits of *Saccostrea cucullata*

Oysters are among the most significant bivalves harvested and produced globally. Marine edible species are considered highly nutritious foods due to their chemical composition, being rich in polyunsaturated fatty acids (PUFAs), essential amino acids (EAAs), and micronutrients, all of which can significantly enhance a healthy human diet (Figure **3**). The term "superfood" is often applied to marine edible or potentially edible species because they are enriched with nutrients, concentrated in fatty acids, and rich in protein [109].

Saccostrea cucullata, commonly known as the hooded oyster, is a species of edible oyster found along the coasts of the Indo-Pacific region [110]. This oyster species is not only valued for its culinary appeal but also for its significant nutritional benefits. While the nutritional benefits of consuming molluscan shellfish are well-established, there are food safety concerns associated with these seafood products, especially when eaten raw. Most of these risks can be mitigated by simply cooking the shellfish [111]. The following section explores the key nutritional components of *Saccostrea cucullata* and their potential role in human health (Figure **4**).

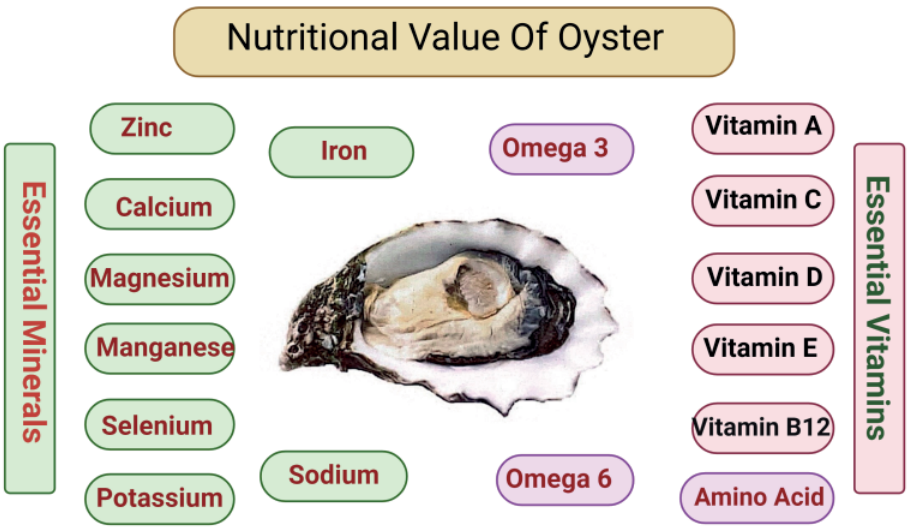

Figure 3: The nutritional benefits of *Saccostrea cucullata:* Rich in essential minerals and vitamins, amino acids, and fatty acids.

9.1. High-quality protein source

Saccostrea cucullata is an excellent source of high-quality protein, which is essential for the growth, repair, and maintenance of body tissues [112]. The proteins found in these oysters contain all essential amino acids, making them a complete protein source. Consuming high-quality protein from oysters can support muscle development, immune function, and overall health [111].

Figure 4: The benefits of consuming oysters for human health.

9.2. Rich in omega-3 fatty acids

Omega-3 fatty acids, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), are abundant in *Saccostrea cucullate* [113]. These essential fatty acids are known for their anti-inflammatory properties and play a crucial role in maintaining heart health by reducing the risk of cardiovascular diseases [114]. Additionally, omega-3 fatty acids support brain health, improve cognitive function, and may reduce the risk of neurodegenerative diseases [115]. Beneficial compounds like polyunsaturated fatty acids (PUFAs) play a crucial role in supporting mental development and cognitive function in infants and children, as well as in preventing diseases such as cancer and cardiovascular disease (CVD). Essential amino acids (EAAs) are key metabolites that are necessary for life; they are fundamental to protein synthesis, regulate various cellular functions, and act as precursors to other important molecules, such as nitrogenous bases. Since the human body cannot produce these essential amino acids, consuming a diet rich in EAAs is vital for maintaining good health [109].

9.3. Mineral content

Saccostrea cucullata is a rich source of essential minerals, including zinc, iron, calcium, magnesium, and selenium [116]. A deficiency in these micronutrients can lead to serious health problems and nonclinical issues such as decreased energy, reduced mental clarity, and impaired overall function [109]. Zinc is crucial for immune function, wound healing, and deoxyribonucleic acid (DNA) synthesis [117]. Iron is vital for oxygen transport and energy production [118]. Macronutrients like calcium (Ca), potassium (K), magnesium (Mg), and sodium (Na) are essential for life, supporting vital functions such as growth, development, reproduction, and survival. These minerals play critical roles in human health, including regulating blood pressure and clotting, supporting nervous and immune system functions, aiding in carbohydrate and protein metabolism, and facilitating muscle contraction, among other processes [109]. Calcium and magnesium are essential for bone health and muscle function [119]. Selenium acts as an antioxidant, protecting cells from oxidative damage and supporting thyroid function [120].

9.4. Vitamins

These oysters are also packed with essential vitamins such as vitamin B12, vitamin D, and vitamin A [121]. Vitamin B12 is important for nerve function, red blood cell formation, and DNA synthesis [122]. Vitamin D plays a key role in calcium absorption and bone health, and it supports immune function [123]. Vitamin A is essential for vision, immune function, and skin health [124].

9.5. Low in calories and fat

Saccostrea cucullata is low in calories and fat, making it an excellent choice for those looking to maintain a healthy weight [125]. The low-fat content also makes it suitable for heart-healthy diets, as it helps in reducing the risk of obesity and related metabolic disorders [126].

9.6. Antioxidant properties

Oysters contain various antioxidants, including selenium, vitamin C, and certain polyphenols, which help in protecting the body against oxidative stress [127]. These antioxidants neutralize free radicals, reducing the risk of chronic diseases such as cancer and cardiovascular diseases [128].

9.7. Improvement in sexual health

Historically, oysters have been regarded as an aphrodisiac [129]. This is partly due to their high zinc content, which is essential for testosterone production and overall sexual health [130]. Adequate zinc levels can enhance libido, improve sperm quality, and support reproductive health in both men and women [130]. Moreover, oyster extract can help address ovarian dysfunction by reducing follicle stimulating hormone receptor levels in the ovaries of female rats treated with bisphenol-A. As a result, oysters are increasingly recognized for their potential health benefits [131].

10. Conclusions

Saccostrea cucullata, or the hooded oyster, holds significant economic and environmental importance. The Persian Gulf, with its unique environmental conditions, offers considerable potential for the exploitation of economically valuable bivalves, including *Saccostrea cucullata*. To fully harness this potential, foundational research is crucial to identify habitats, estimate populations, determine biomass, recognize existing species, and develop protocols for collecting and cultivating spat for breeding purposes. The artificial propagation and selective breeding of commercial species are among the essential goals for sustainable exploitation of the region's bivalve resources.

Continuous research and regulatory efforts are essential to ensure the long-term sustainability of *Saccostrea cucullata* cultivation. Effective management strategies, such as regulating harvest sizes, monitoring water quality, and promoting habitat conservation, are vital for maintaining healthy populations and maximizing the economic and environmental benefits associated with oyster farming.

Moreover, the adoption of innovative technologies, such as remote sensing, genetic improvement programs, and integrated multi-trophic aquaculture (IMTA), can significantly enhance oyster farming practices. Remote sensing techniques can monitor water quality parameters, detect harmful algal blooms, and optimize site selection for oyster farms. Genetic improvement programs focusing on selective breeding for desirable traits, such as growth rate, disease resistance, and shell strength, can lead to the development of superior oyster strains. Additionally, IMTA, which integrates oyster farming with other species like seaweed or finfish, can improve sustainability by utilizing waste nutrients and reducing environmental impacts.

By implementing these strategies and leveraging technological advancements, the cultivation of *Saccostrea cucullata* can be optimized, ensuring both ecological balance and economic viability. This integrated approach not only supports the sustainable growth of the oyster industry but also contributes to the overall health and resilience of marine ecosystems.

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