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Circular Bioeconomy in Aquaculture

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The world aquaculture industry that yields more than 120 tonnes of oceanic products yearly is at an important crossroad in its growth path. Although it still serves the protein demand needs of a growing population, traditional aquaculture businesses create extreme amounts of wastes including fish offal, shellfish shells, waste water, and processing plant by-products. The second-largest fish producer in the world, India has witnessed an exponential rise in its aquaculture sector with fish production rising 104% between 95.79 lakh tonnes in 2013 -14 to 195 lakh tonnes in 2024 -25. The extraordinarily of such growth has, however, increased the problem of waste production. Indian seafood processing industry generates more than 3 metric tonnes of fish-processing waste, and most of this is released to aquatic ecosystems without proper treatment, especially onto the coastal centers of Veraval and Cochin. In addition, the Indian aquaculture industries release waste water containing nitrogen, threatening the environment and key ecosystems in the aquaculture industry, particularly in the leading states of the aquaculture sector, such as Andhra Pradesh, West Bengal, and Karnataka. On the one hand, this is a daunting and very challenging task but, on the other hand, this is an excellent opportunity. Based on the concept of a circular bioeconomy, eco-innovation in aquaculture overtly changes the way that waste is perceived in the fisheries sector in India. Instead of portraying biological residues as a problem of disposal, the innovative Indian producers and research institutes are redefining them as useful feedstock in other domains of profit generation- nutraceuticals, cosmetics, bioenergy and new materials. This paradigm change does not only comply with the principles of the environment but also helps to affect the appearance of a competitive environment. The implementation of the circular bioeconomy by the Indian aquaculture facilities finds that waste valorization can be exploited to cut costs, boost profitability, and, at the same time, with a negative change in the ecological footprints.

Core values of Circular Bioeconomy are found to be as follows:

- **The Waste Valorisation Core Philosophy**

The principle of circular bioeconomy is supported by the simple and resolute rule: biological materials have an intrinsic value that can be fulfilled by proper valorization. Unlike the more conventional linear system, the circular bioeconomy does not see by-products as final outputs of the system and views them as intermediate products. The philosophy has led to the adoption of combined systems that have reduced wastage in the operations of aquaculture in India. As examples, waste processing in fish-processing is used as useful components in health supplements, shellfish shells used in a successful thriving shrimp-farming industry in India are processed to produce biodegradable biopolymers, wastewater treatment produces nutrients that can be used as fertilizers in agriculture, and sludge anaerobically digested creates clean energy. It has been the Indian Council of Agricultural Research (ICAR) institutions, such as the Central Marine Fisheries Research Institute (CMFRI) located in Kerala and Central Institute of Fisheries Technology (CIFT) located in Cochin, which pioneered these closed-loop methods and brought them to the increasing financial viability of large-scale undertakings in the Indian context.

- **India Policy Environment and Market Incentives**

The enabling factors to the aquaculture transition of circular have been achieved through regulatory frameworks and technological advancements, as well as in India. Though aquaculture development is still the core of the Pradhan Mantri Matsya Sampada Yojana (PMMSY) and its ₹20,050 billion of investment in 2020-25 there is a growing focus on waste valorization and environmental sustainability in new policy initiatives. India has the Coastal Aquaculture Authority (CAA) which has issued guidelines that include effluent-treatment systems and pollution-control providing a fundamental change of the aquaculture-waste economics. In addition to compliance, operation system circles also strengthen the viability of Indian aquaculture practice through minimizing the use of external resources like power, manure, and food. They also create various income outlets of the materials that would have been sent to landfills or dumped in the oceans. The value of ₹60,523.89 India's seafood exports come to be a major part of global fish production (7.7%) which with its growing value is put into the market with increasing requirements of traceability and sustainability credentials, waste valorization is not only a responsibility of the environment but also a commercial necessity.

- **The Economic Revolution of Waste.**

The Indian aquaculture enterprises have changed the economic calculus fundamentally since it does not cost waste as the ultimate cost center but it actually becomes a profit center. This change is changing the business models and priority of investments in the inland as well as the marine aquaculture in India. Manufacturers have realized today that efficient waste-management facilities would not only demand a large amount of capital up-front but also pay off big in terms of saving on costs and creating new revenues; in essence, fully changing the bottom-line figures of financial sustainability in aquaculture activities.

- **IMTA Systems Incorporate Multi-trophic Systems of Aquaculture.**

One of the most outstanding technological changes that are revolutionizing the field of Indian aquaculture is the Integrated Multi-Trophic Aquaculture (IMTA) platform that has been successfully tested in the coastal states in India by the Indian Council of Agricultural Research -Central Marine Fisheries Research Institute (ICAR-CMFRI). This system develops plurality of organisms (finfish, shellfish, seaweeds, and microalgae) both in harmonised matrices. In such a set-up the release of one population groups up as the food supply of the others, thus, creating a biologically synergetic environment. The excess of nutrients and organic matter discharged by conventional fish farming is recycled to fertilize seaweed and kelps plantations, which independently yields related benefits to these ecosystems and the carbon sequestration and water quality, at the same time. Slightly newer IMTA trials using ICAR-CMFRI in Kerala, in which the fish fed in cages is combined with green mussels and seaweed, have proved highly efficacious: along the east coast of India the growth rate of seaweed in monoculture systems is about 50 times less than that achieved in these systems. Growth of native seaweed species like the Kappaphycus alvarezii in IMTA matrices has particularly been effective and through one experimental harvest; 600kg of seaweed was obtained on six rafts in three months which earned the project a revenue of approximately USD 220 dollars making this method commercially viable. This ecosystem symbiosis determines a self-governing ecosystem, which not only reduces the pollution but also diversifies yields between 30-50% in comparison to although monocultural activities, enabling operators of Indian aquaculture a two-fold edge on environmental welfare and economic achievement.

- **Enzymatic Hydrolysis and Fish Waste Utilisation.**

Outside IMTA, using enzymatic hydrolysis and fermentation technologies, the Indian producers have been able to recover high-value compounds in the fish-processing wastes in a more cost-effective manner across the aquaculture industry. Indian manufactures are now incorporating fish bones, viscera and skin into the pharmaceutical, cosmetic and vitamin industries, which are full of proteins, omega-3 fatty acids, collagen, as well as bioactive peptides and minerals. Central Institute of Fisheries Technology (CIFT) in Cochin has been at the forefront in conducting researches that fish hydrolysates, produced by controlled biodegradation of fish protein waste, had a series of bioactive activities such as anti-inflammatory, anti-hypertensive and antioxidant activities creating new markets in India in the burgeoning functional-food and medical-nutrition markets. The abundance of bioactive compounds that could be obtained based on a single waste stream allows producing several products with different properties and selling qualities sequentially. All product groups are now aimed at one or another application: collagen as a cosmetic ingredient will be placed at a high price in the Indian cosmetics market, peptides will be sold as nutraceuticals to the expanding Indian health-conscious consumer segment, and other remaining proteins will be used as environmentally friendly animal feedstock, thus weaning on the use of wild-caught fish meal. Newer extraction techniques with enhanced aqueous extractions like the use of enzymatic pre-treatment and selective precipitation have demonstrated higher recovery rates of more than 85%, which makes it financially competitive to synthetic processes and can be scaled to large and small Indian fish-processing facilities.

- **Chitin and Chitosan Extraction from Crustacean Shells**

The shells of crustaceans contain peptidoglycan known as chitin and chitosan, which are utilized to extract mesenchymal stem cells during ridge repair. Utilizing shells is economically efficient and yields high-quality output.

Research work carried out in CIFT and various universities has significantly enhanced the extraction of chitin out of crustacean shells a by-product of the huge shrimp-farming sector in India. The effluents of the shrimp -processing plants yield a total of over 1.25 lakh tonnes of head and shell waste product every year, which is an enormous potential of valorization. CIFT has come up with its own protocols of extracting chitin in the shell of the shrimp, and it is capable of yielding close to 7000 tonnes of chitin in one year on what would have been illegal waste. Chitin and its derivative, chitosan, are examples of biodegradable biopolymers and have been used in several applications that include water treatment, soil remediation, wound healing and drug delivery systems. Once considered just a waste shell containing Indian shrimp, the shrimp-processed shell material is becoming commercially viable with market prices of between EUR 5000-10000 per tonne as long as it is converted into beneficial chitosan and this has been a great driving force in terms of developing processing infrastructure in the coastal areas of India. Modern extraction procedures can extract as much as 40 wt% chitin out of raw shells through an enzymatic and a chemical method, and further optimization efforts are currently aiming at extraction percentages even greater. Chitosan derived on the basis of Indian aquaculture waste has been proven to be effective in the binding of heavy metals and removal of pathogens in water hence proving to be significantly effective in treatment of heavy effluents in the aquaculture facilities prior to discharge, which is a key compliance requirement by environmental laws in India. Chitosan is used in agriculture as a biopesticide, growth control, and soil modifier; chitosan-based products are significantly pricier in the Indian organic-farming markets, and respond to the trends of creating sustainable agriculture on the governmental level.

- **Anaerobic Digestion and Biogas Generation**

An anaerobic digestion and biogas generation occur predominantly in hot regions via thermophilic digestion and thermal-driven biogas recycling. Its staples are mainly found in hot places through the process of thermophilic digestion and a thermal-biogas recycles.

Anaerobic fermentation of aquaculture sludge and wastewater is an implementation in the paradigm of the circular bio-economy of India. This technology does not only produce biogas that can be used to produce energy but also a nutrient rich digestate that could be used as a fertilizer in the agricultural fields in India. Most recent developments in the digestion plant make it possible to handle large volumes of sludge which then makes the waste-disposal exercise less expensive, reduces external acquisitions of energy and generates quality compost according to Indian systems of cultivations. Observations of academic centers all over India demonstrate that an average fish farm that produces 500 tonnes of fish per year has the capability to produce adequate biogas through anaerobic digestion to meet 30-40% of its energy needs, as well as, to reduce sludge volume by to suppress it by 70%. Deeply rooted in nitrogen, phosphorus and potassium which are key macronutrients in agricultural applications, the digestate is considered a perfect source of certified organic fertilizers meeting the organic-farming certification requirements in India. Several new plants have considered the zero-discharge approach, but they process the wastewater internally, and the biosolids are transformed into manure. The recirculated water is reused in closed loops or treated to reach the state environment requirements on discharge or discharge limits, therefore, drawing the Indian aquaculture activities into the strict regulatory frameworks, and at the same time, creating economic value. The industry 4.0 technologies of IoT sensors, artificial intelligence, and blockchain traceability systems further improve these innovations. All these tools optimize waste stream in the present time, reveal valorization opportunities and affirm sustainability assertions in high-market segments that require transparent supply chains. The waste composition is also monitored, the parameters of digestion forecasted and energy extraction optimized using monitoring systems, and predictive analytics to the best time to harvest products and sell in the market maximize value capturing in the processing chains.

❖ **Economic and Environmental impacts of Circular bioeconomy in Indian Fisheries:**

- **Economical Gains and Profit Making**

There are even more attractive economic advantages to the aquaculture of India as a result of the circular bioeconomy. The valorization of waste has a direct financial implications, decreasing the cost of operation by decreasing the disposal costs, decreasing the waste-management costs, and decreasing the environmental remediation costs. In a case of 10,000 tonne per annum salmon-farming facility the cost savings will be between ₹42,00,000 and

₹84,00,000 (roughly USD 50,000-100,000) per annum, depending upon local waste-management facilities and regulations. At the same time, valorization of by-products is creating new sources of revenues to the Indian aquaculture operators. Fish-oil extracts fetch high prices in the Indian market in the omega-3 supplement market number is able to hydrolyze gelatinous fish residues to yield bioactive peptide functional-food additives, seaweed a by-product may be used as a succession-fertilizer in organic agriculture, sludge biogas is made available as a competing renewable energy source, and chitosan itself is in the production of a high-valued specialty chemical. According to emerging evidence among various Indian companies, the percentage of by-products valorization is now 15-30% of the overall operating revenues; which radically alters the profitability metrics, as well as the profitability rates of investment. Besides, innovative operators have proved net-positive economics of waste management where the treatment process itself is profitable, which marks a paradigm change in the cost base of the aquaculture business.

- **Full benefits on the environment and health of the ecosystem.**

Environmental advantage is also a very important part of the transition of aquaculture in India. Closed-loop systems significantly eliminate aquatic contaminants such as nitrogen and phosphorus which enters water body hence alleviates eutrophication and hypoxia greatly experienced in most Indian aquaculture environments. Empirical research has shown that integrated multi-trophic aquaculture (IMTA) systems have a 40-60% reduction in nitrogen release compared to monoculture finfish operations and that integration of seaweed can sequester 5-10 kg CO2 equivalent/kg of seaweed biomass produced. As a result, the carbon footprints within aquaculture value chain in entire India are reduced, on-site production of biogas used in lieu of fossil fuels substitutes the fossil fuel use, closeness to recycling sites is enhanced and the total resource use is reduced. Circular aquaculture ensures the reduction of environmental impact by 40-60% in comparison with traditional approaches and at the same time biodiversity is increased by restoring the ecosystem. These regenerative processes are of special importance to the ecologically sensitive waters, including the East Kolkata Wetlands, which constitute an almost 4,000-hectares (nearly 1.9-square-mile) Ramsar site supporting almost 18,000 tonnes of carps each year among the uranium of integrated strategies. Therefore, circular systems deliver food-production urgency and conservation goals concurrently and satisfy the two-fold Indian agenda of enhancing the potential aquaculture and protecting aquatic resources.

- **Social Benefits and Creation of Employment**

Circular bioeconomy is not only about its social singularity. These solutions create jobs at any of the phases, such as waste collection, processing, product development, and marketing,

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specifically in rural and coastal regions where aquaculture is the main occupation with little alternative employment. Small-scale and increasingly cooperative led by women have become important sources of supply chains in waste-valorization in areas along the coast of India and have helped to strengthen local capacity and provide revenue. Where waste to value, projects have generated more jobs per tonne of product than primary aquaculture jobs, and in some areas are also providing the youth with access to technology related process jobs and on the digital platform, in line with the Digital India program.

The Indian Circular Aquaculture Scaling Problems

- **Logistics and infrastructure Barriers**

Although scaling circular bioeconomy has a transformative potential, it is faced with major challenges to which a collective action needs to be taken. The main problem is that the management of waste in India, due to the geographic dispersion, seasonal development of aquaculture, and the necessity to preserve the product in cold responses, is rather logistically complicated as it implies significant investments. The good waste-valorization requires having an aggregation infrastructure, homogenization of processing plants, as well as having an efficient distribution network through the Indian diversified coastal and inland regions. This type of investment cannot be resourced on an individual basis, but it requires strong public-private partnerships and governmental support structures. The existing waste-management systems in India are still disjointed and decentralized among the states of the coast with such a sharp disparity in processing capacity disproportionately impacting smaller and medium-scale operations in the rural aquaculture regions.

- **Acceptance in the market and Regulatory Fragmentation**

Another, and, in fact, quite significant obstacle is on the territory of market acceptance. Although the scientific merits of the aquacultural waste products as a safe and effective product are supported by scientific researches carried out by reputable institutions like Central Institute of Fisheries and Ocean Engineering (CIFT) and Central Marine Fisheries Research Institute (CMFRI), they face the challenge of consumer scepticism as well as a confusing regulatory environment in India. The legal system is still extremely disjointed, as the laws vary between Indian states and the jurisdiction between federal and state institutions is split. To illustrate, chitosan is either regulated as a food additive or an industrial chemical depending on its jurisdiction, hindering market access and making supply chain planning difficult, to producers looking to venture into market scale valorization ventures. Besides, hundreds of ingenious solutions are yet to face technical and economic constraints in implementation to the diverse aquaculture environments of India. Despite the success of their proven methods of operation, like chitin extraction and biogas digestion, when it comes to applying these projects to the entire spectrum of the Indian aquaculture system, both the small traditional shrimp pond and the large-scale recirculating system, the financial performance of their activities is yet to be equally profitable in all cases. This means that proprietary solutions, local area capacity building, and availability of cheap capital has to be developed to encourage mass adoption.

- **Gaps in knowledge and difficulties in implementation.**

Another similar problem exists in a high lack of knowledge among Indian manufacturers about the accessibility to technologies, market opportunities, and implementation channels. Numerous small and medium operators especially in the tier 2 and tier 3 coastal communities do not realise that waste valorization is an option or facilities that are necessary. The technical support and trainings are still inadequate even to those using the traditional methods of aquacultures. To overcome these impediments requires a massive, systematic approach that combines technical creativity and receptive policy, industry best practices and cooperative supply-chain building that is even more affordable to the Indian aquaculture environment.

Guidelines To the Future: Solutions and Success Patterns.

- **Policy Initiatives and Enabling Frameworks**

UK Forensic Science Policy Framework (2013-2017)

It is an issue that no one solution can solve on their own, and already there are several original methods to solve these dilemmas that have marked an efficient way out in India. Government policy and funding programmes are being used to enable environments in different areas. Circular practices and waste valorization in aquaculture are increasingly projected through the national strategy on the Blue Economy, which is conceived through a set of government programmes one of which is the Draft Blue Economy Policy Framework. Pradhan Mantri Matsya Sampada Yojana (PMMSY) with its allocation of crore Rs. 20,050 crore funds integrated aquaparks and aquaculture parks that automatically proclaim waste reduction and resource efficacy. There are several example case studies, which describe the targeted pathways: commercial-scaled operations with integrated multi-trophic aquaculture (IMTA) have been established by ICAR-CMFRI in Kerala where finfish cages were placed next to the employment of the green mussel and seaweed harvesting, resulting in a better financial and ecological performance than monoculture operations. Both the technical and economic viability in large scale: The introduction of the finfish farming and the integration of a seaweed farm with the *alvarezii* species along the east coast of India with an achievement rate of 50% increment in seaweed production has proven collaborative in technicality and economically viable. Similarly, the chitin separation procedures that were validated by CIFT of the shrimp shell waste powder have formed the foundation of several processing businesses in the coastal states. The aggregation of nascent waste is beginning to form in areas like Tamil Nadu and Karnataka which enable supply of shell and co- products to processing plants and thus create specialized supply chains that stabilize the markets.

- **Knowledge Sharing and Technology Transfer.**

The digital platforms and industry efforts are speeding up the process of sharing knowledge and minimizing redundant research spending and the implementation of circular practices among aquaculture enterprises spread across different geographical locations. Research institutes, such as CIFT and CMFRI, are also leaning toward spreading proven technologies and procedures via strategic partnership and training program to individual manufacturers and cooperatives. Introduction of long-term contractual models among producers of aquaculture and waste processors and downstream producers of value-added products are gradually stabilizing the market of the valued by-products. This has been a major trend that has removed the uncertainties that discouraged investments in circular infrastructure in the aquaculture sector in India.

- **Market Innovations and Financial Premiums.**

Financial innovation keeps reshaping the economic scene to favour the shift of India into the circular aquaculture. Green bonds, sustainability-linked lending, carbon credit initiatives, and venture-capital investments aimed at the answers to the circular-economy problems are increasingly becoming larger components in the capital base of the processes previously inviable to the view of conventional financial markets. The high mark up of sustainably produced and traceable seafood, at present costing between 15-30% more than the same products produced on conventional production methods, has not only been used to cover the cost of infrastructure incurred in the process of waste-to-value recovery but also has had the side benefit of encouraging the practice by an increasing number of Indian aquaculture firms, as well as supporting sectoral innovation.

Future Direction and Development of the Industry.

- **Female Genetic Engineering: Technological Development and Innovation.**

A new form of eco-innovation in the fish industry is on a path of transforming India fisheries sector to a significantly redefined structure in the coming ten years. The possibility of technological advancement can considerably enhance waste-to-value efficacy in an Indian environment. High-tech biorefining methods will permit extraction of various streams of values step-by-step out of a single waste stream, and reform the maximal yield and economic benefits out of aquaculture residues. Precision fermentation could help bring rare bioactive compounds to by-products, and, therefore, new markets in the pharmaceutical and nutraceutical sectors. Co-located electronic platforms will streamline transfers throughout the regional value communities on near real-time optimization, defining the just in time delivery channels, which would result in a lower cost of storage and product decay, a concern that is especially topical given the tropics of India.

- **New Future in Seaweed and Alternative Proteins.**

Expansion in the development of seaweed and macroalgae farming is set to provide the Indian marine ecosystems with unparalleled growth, providing not only carbon storage and capture of nutrients, but also a truly regenerative end-to-end aquaculture model that feeds itself, and does not need the external feedstock or arable land. Alternative protein manufacturing is another relevant avenue of valorization innovation that involves the use of insect farming on the basis of fish waste and mycoprotein production (using aquaculture by-products), and thus provides new avenues to use aquaculture waste streams.

- **Market Maturity and Competitive Urges.**

With the widening policy backing towards the aquaculture industry in India in form of declining technological costs due to economies of scale and the spread of the technology into a larger network of innovations, the circular bioeconomy is coming out of its niche position and into a larger model of innovations. In the next ten years, Indian aquaculture companies that do not implement the holistic waste-valorization modes will enjoy a significant competitive risk, first and foremost because of their higher operation costs and limited market opportunities, which are controlled by the retailers and institutional buyers in the market whose supply chains are increasingly growing to warrant circulatory compliance. Primary players in the Indian industry and export-based aquaculture businesses are already setting standards of circularity, defining minimal waste recovery and resource efficiency standards, and competitive pressure on extending these demands across aquaculture value chains in India.

Conclusion: Sustainability as Strategic Imperative

The concept of eco-innovation in the aquaculture is not confined to environmental virtue signaling or regulation under Indian environment. It is a business strategy that makes profit goals aligned with the sustainability requirements, thus developing business models where environmental stewardship is directly involved in improving financial performance. India bioeconomy models yield higher revenue, save money and expenditures and at the same time raise brand value among consumers who are environmentally conscious and ecological footprints in aquatic ecosystems are minimized since waste streams are transformed to reusable products and energy.

This radical change cannot be a voluntary choice in an industry where producers have to, at the same time, both increase production to support the growing needs of a one billion plus population and at the same time satisfy the high-level environmental regulation and customer demands on responsible sourcing; otherwise, sustainability in the long term will be not just unattainable, but also the wrong approach to take. During technology maturity via continuous innovation of the Indian research institutions, markets start to formalise on new supply chains and the convergence of policy regime under programs like the Blue Economy Strategy, the aquaculture industry finds that the most profitable business is in the hitherto considered wastes.

The future of the aquaculture in India is not all about increasing the production of seafood to meet the requirements of protein security but also the adoption of smarter growth plans especially in closed and integrated technology that make the most out of all biological inputs to create and regenerate value. Through the paradigm of commodification of waste instead of viewing it as a cost to the environment, India will be able to realize the true potential of eco-innovation in the area of fisheries, which is an industry that fertilizes the planet and makes ecological recovery possible, hence proving the fact that sustainability and economic success are self-affirming requirements to the blue economy path which the country is on.