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Echinoderm fisheries: their culture, conservation, bioactive compounds and therapeutic applications

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Abstract: The Indo-Pacific region, sometimes referred as the Indo-West Pacific, is considered to be the richest marine biodiversity hotspot comprising unique species of echinoderms, molluscs, shrimps, crabs and fishes. These bioresources provide excellent opportunities for the studies of breeding biology, reproductive ecology, aquaculture, conservation, population genetics as well as species and speciation mechanisms of many diverged taxa. However, this interesting area is quite new and yet to be fully explored and determined. In the bottom-dwelling sessile invertebrates, echinoderms belonging to phylum Echinodermata, have been considered as the high-valued marine bioresource, having profound biological, aquacultural, conservational, nutritional and pharmaceutical significance. Among them, the sea urchins and sea cucumbers are both commercially fished and heavily overexploited. In sea urchins, the harvested product is the gonad, commonly known as "Sea urchin Roe", which has been long traditions of consuming as a high delicacy food in Asian, Mediterranean and Western Hemisphere countries, and have long been using as luxury foods in Japan. The population of the Asian Pacific Region has been using it for long time as a remedy for improving general living tone and treatment for a number of diseases. In the sea cucumber, the principal product

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is the boiled and dried body-wall or 'bêche-de-mer' for which there is an increasing demand in many tropical and subtropical countries. Sea cucumbers are also believed to exert wound healing and reduce arthritis pain in humans, hence are widely used in Asian folk medicine. However, due to lack of proper management and conservation strategy in place, many sea urchin and sea cucumber fisheries are under threat. For this, cultivation of these species increasingly becomes a necessity, both for stock enhancement programs and as a means to meet the increasing market demand. Procedures for mass production of the tropical *Holothuria scabra* are now well established in China**,** India, Australia, Indonesia, the Maldives, the Solomon Islands**,** Philippine**s** and Thailand. Alike many other marine organisms, echinoderms have been, and continue to be, examined as a source of biologically active compounds with biomedical applications. Most recently, a number of important bioactive compounds have been isolated from sea cucumbers and sea urchins, having distinctive biological and pharmacological activities including anti-angiogenic, anticancer, anticoagulant, anti-hypertension, anti-inflammatory, antimicrobial, antioxidant, antithrombotic, antitumor and wound healing activities. However, development patterns of echinoderm fisheries are largely expectable, often unsustainable and frequently too rapid for effective management. Proper steps should be undertaken on the potential ecosystem and human community consequences, appropriate aquaculture management strategies, and urge for better monitoring and reporting of catch and abundance, proper scientific research for stock enhancement and consideration of international biodiversity and trade regulations to ensure sustainable development and utilization of high-valued echinoderm fisheries to a greater extent.

Keywords: Indo-Pacific, Echinoderm, Bioresource, Culture, Conservations, Bioactive compounds, Therapeutic applications

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1 Introduction

Sea cucumbers (class Holothuroidea) are elongated tubular or flattened soft-bodied marine benthic invertebrates, typically with leathery skin, ranging in length from a few millimetres to a metre (Lawrence, 1987; Rahman, 2014a). Holothuroids encompass 14,000 known species (Pawson, 2007) and occur in most benthic marine habitats worldwide, in temperate and tropical oceans, and from the intertidal zone to the deep sea (Hickman et al., 2006). The fisheries of sea cucumber have expanded worldwide in catch and value over the past two to three decades (Conand, 2004; FAO, 2008). Global sea cucumber production increased from 130,000 t in 1995 to 411,878 t in 2012 (Rahman et al., 2015). Among other aquatic animals, overall production of dried sea cucumbers has increased rapidly (Figure 1). However, sea cucumber fisheries in Asian countries (China, Japan, India, Philippines, Indonesia and Malaysia) have been depleted due to overexploitation as well as lack of proper management and conservation (Rahman et al., 2015).

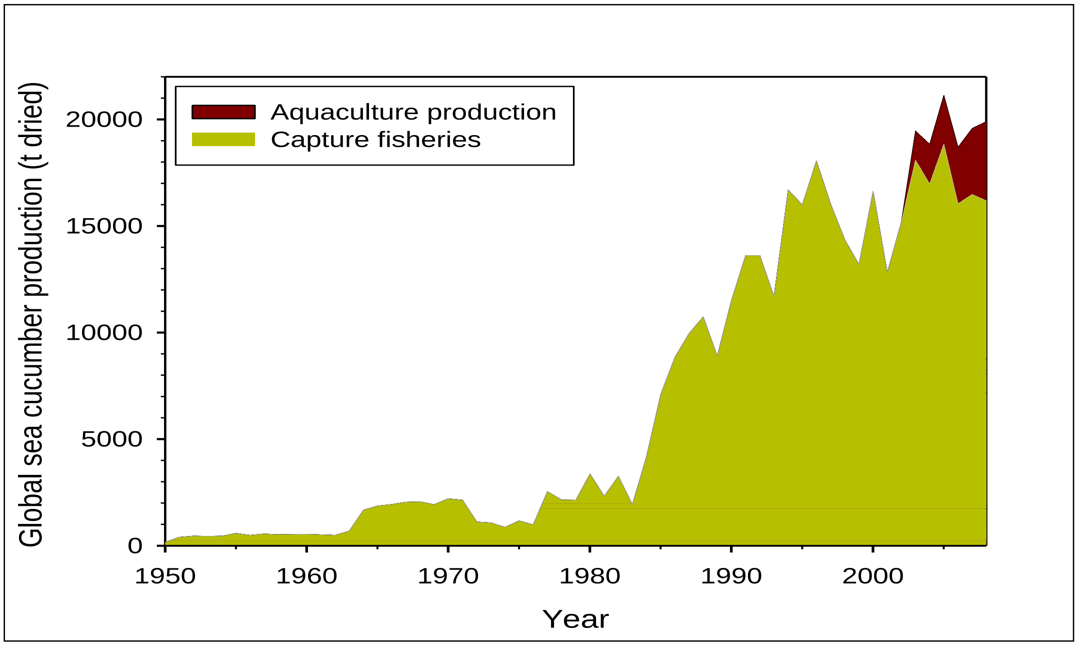

Figure 1: World sea cucumber fisheries production from 1950 to 2012.

Indo-Pacific regions have harvested and traded sea cucumbers for over one thousand years, driven primarily by Chinese demand (Conand and Byrne, 1993). Harvesters typically capture sea cucumbers by hand, spear, hook, or net while wading or diving with snorkel or SCUBA (Self Contained Underwater Breathing Apparatus) gear. In some regions and especially for less valuable species, sea cucumbers are trawled (Aumeeruddy and Payet, 2004; Kumara et al., 2005; Choo, 2008). They are consumed both reconstituted from a dried form (called trepang or bêche-de-mer) and in a wet form, with muscles cut in strips and boiled (Sloan, 1984).

In recent years, reports have documented both the rapid climb in value of traded sea cucumbers and the spread and increase in sea cucumber fisheries around the world (FAO, 2004; FAO, 2008). However, sea cucumber populations are particularly vulnerable to overfishing for at least two primary reasons. First, harvesters can easily and effectively capture shallow water holothurians (Uthicke and Benzie, 2000; Bruckner et al., 2003). Second, their late age at maturity, slow growth and low rates of recruitment make for slow population replenishment (Uthicke et al., 2004; Bruckner, 2005). Moreover, at low population densities, their broadcast spawning may induce an Allee effect (Courchamp et al., 1999; Uthicke et al., 2009), resulting in population collapse and inhibiting recovery (Uthicke and Benzie, 2000; Bruckner, 2005). Owing to these factors, overfishing has severely decreased the biomass of many sea cucumber populations (Skewes et al., 2000; Lawrence et al., 2005; Baum and Worm, 2009). Thus far, even with harvesting closures, sea cucumber stocks seem slow to recover (D'Silva, 2001; Uthicke et al., 2004; Ahmed and Lawrence, 2007). Other broadcast spawning invertebrate populations that have been severely depleted, such as pearl oysters in the South Pacific, have not recovered even 50–100 years far ahead (Dalzell et al., 1996).

The Sea cucumbers are important ecologically as suspension feeders, detritivores and prey. In kelp forests (Harrold and Pearse, 1989) and coral reefs (Birkeland, 1989), they consume a combination of bacteria, diatoms and detritus (Massin, 1982a; Moriarty, 1982). Their function as suspension or filter feeders can be substantial. For example, two species of holothurians alone represent nearly half of the filter feeding biomass in South African kelp. As suspension feeders, sea cucumbers regulate water quality by affecting carbonate content and the pH of the water (Massin, 1982b). Deposit feeding sea cucumbers change the size of ingested particles and turn over sediment via bioturbation, thereby altering the stratification and stability of muddy and sandy bottoms (Massin, 1982b). For example, on coral reefs, healthy sea cucumber populations can bioturbate the entire upper five millimetres of sediment once a year (4600 kg dry weight year/1000 m^2), significantly reducing the microalgal biomass in the sediment (Uthicke, 1999) and playing a substantial role in the recycling of nutrients in oligotrophic environments where nutrients would otherwise remain trapped in the sediment (Uthicke, 2001). Bruckner et al. (2003) noted that the extirpation of holothurians has resulted in the hardening of the sea floor, thereby eliminating potential habitat for other benthic organisms. Holothurians are also important prey in coral reef and temperate food webs (Birkeland, 1989; Francour, 1997) both in shallow and in deep water (Massin, 1982b), where they are consumed particularly by fishes, sea stars and crustaceans (Berkes et al., 2006).

In addition to the ecological importance of sea cucumbers, their fisheries are of great social and economic importance to many coastal communities. For example, just a few years after beginning in the Maldives, the sea cucumber fishery became the most highly valued fishery outside the tuna fishing season, representing 80% of the value of all non-fish marine products in 1988 (Joseph, 2005). Sea cucumber fisheries form the main source of income for many coastal communities in the Solomon Islands (Nash and Ramofafia, 2006) and for 4000–5000 families in Sri Lanka (Dissanayake et al., 2010). Perhaps most importantly, sea cucumber fisheries are economically decentralized. Whereas their total global value is low compared to other higher volume fisheries (Ferdouse, 2004), economic benefits are obtained immediately at the village level (Kinch et al., 2008). In contrast, other high-value fisheries, such as tuna fisheries, have higher initial cost and bring wealth to a more centralized group of people (Baum and Worm, 2009).

In spite of the ecological and social importance of sea cucumber populations, the assessment of their global status is challenging. There is generally a lack of abundance data; catch, import and export statistics are often incomplete; and the trade of sea cucumbers is complex (Baine, 2004; FAO, 2004; FAO, 2008). Nonetheless, reports such as FAO (2004, 2008) and the SPC Bêche-de-mer Information Bulletin (http://www.spc.int/coastfish/en/publications/bulletins/beche-de-mer.html) have assimilated much of the available knowledge on the status and management of sea cucumber fisheries around the world. So far, there has been discussion of country specific sea cucumber fisheries and insight into the dynamics of the global sea cucumber trade (Baine, 2004; Clarke, 2004; Ferdouse, 2004; Uthicke and Conand, 2005; FAO, 2008; Baum and Worm, 2009). However, we lack a quantitative analysis of the typical trajectory, potential drivers, and combined spatial and temporal dynamics of sea cucumber fisheries around the world.

Sea urchins are typical objects of research in different fields of biology, ecology, biodiversity, aquaculture and conservation. At the same time, they are used as raw material to produce foodstuff, in particular, the product of processing gonads known as "Sea urchin Roe", and is considered as a prized delicacy in Asian, Mediterranean and Western Hemisphere countries (Kaneniwa and Takagi, 1986; Lawrence et al., 1997; Rahman and Yusoff, 2010). The gonads of sea urchins either fresh or in the form of processed food have long been using as luxury foods in Japan (Shimabukuro, 1991). The peoples of the Asian Pacific Region has also long been using it as a remedy for improving general living tone, treatment for a number of diseases and strengthening of the sexual potency of men, especially the middle aged (Seifullah et al., 1995; Yur'eva et al., 2003). Although, sea urchin gonad has not yet been used as food in Malaysia, it is reported that in Sabah, an indigenous tribe known as 'Bajau Laut' eats sea urchin roe with rice after adding spices (Rahman and Yusoff, 2010; Rahman et al., 2012a; Rahman et al., 2014a; Rahman et al., 2014b). This delicacy is usually prepared for special events such as Lepa-Lepa Festival, wedding ceremony and other cultural events and is being treated as valuable fishery resources, especially by Bajau people (Rahim and Nurhasan, 2011). Thus, sea urchins play an important role in providing subsistence income to the local coastal communities. In Japan, sea urchin is known as "uni", and its roe can retail for as much as AU$450/kg (Richard, 2004). Sea urchin fisheries have expanded so greatly in recent years that the natural population in Japan, France, Chile, the Northeastern United States, the Canadian Maritime Provinces, and the west coast of North America from California to British Colombia have been overfished to meet the great demand (Lawrence et al., 2001; Rahman et al., 2005; Rahman et al., 2012b; Rahman et al., 2013; Rahman et al., 2014a; Rahman et al., 2014b; Rahman et al., 2014c). Trying to provide an overview about the world sea urchin production and trade, it should be noted that most of the harvest—specifically the gonads of both sexes called roe—occurs in temperate regions of the world. As can be seen in Figure 2, from 1950 to 2018, the trend of world sea urchin production followed two different performances. The first, growing, from 1950 to 1995, the year in which the harvest reached its peak with 117,039 tonnes of catch, and the second, on the other hand, is constantly decreasing, from 1995 to the most recent years.

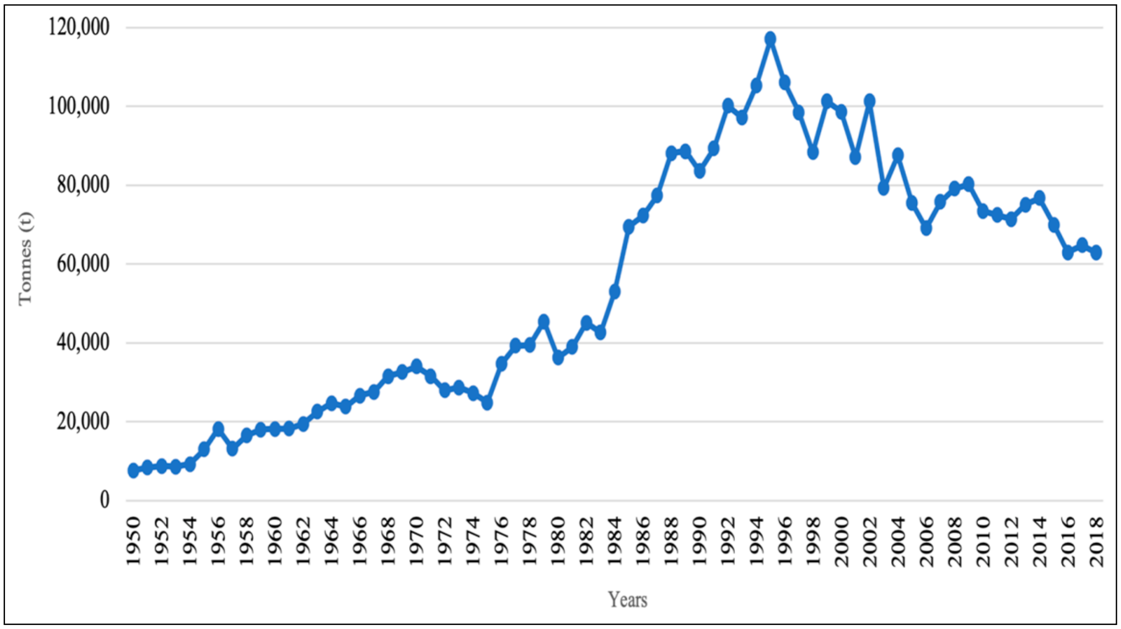

Figure 2: Total world sea urchin production (1950–2018), in tonnes value (FAO, 2021).

According to the latest available FAO data, indeed, the capture production of sea urchins in

2018, for the species included in the database and in all forms of sale-live, fresh, chilled or frozen, was approximately 62,828 tonnes (FAO, 2021). Specifically, considering the production by country shown in Figure 3, Chile is the dominant producer of sea urchin, although its production has dropped drastically over the last 18 years, from 54,097 tonnes in 2000 to 30,446 tonnes in 2018 (FAO, 2021). World landings of sea urchin, having peaks at 120,000 mt in 1995, are now in the state of about 82,000 mt (Carboni et al., 2012). These decreasing patterns clearly reflect the overexploitation of most fishery grounds and highlight the need for appropriate conservation policies, stock enhancement, fishery management and aquaculture development.

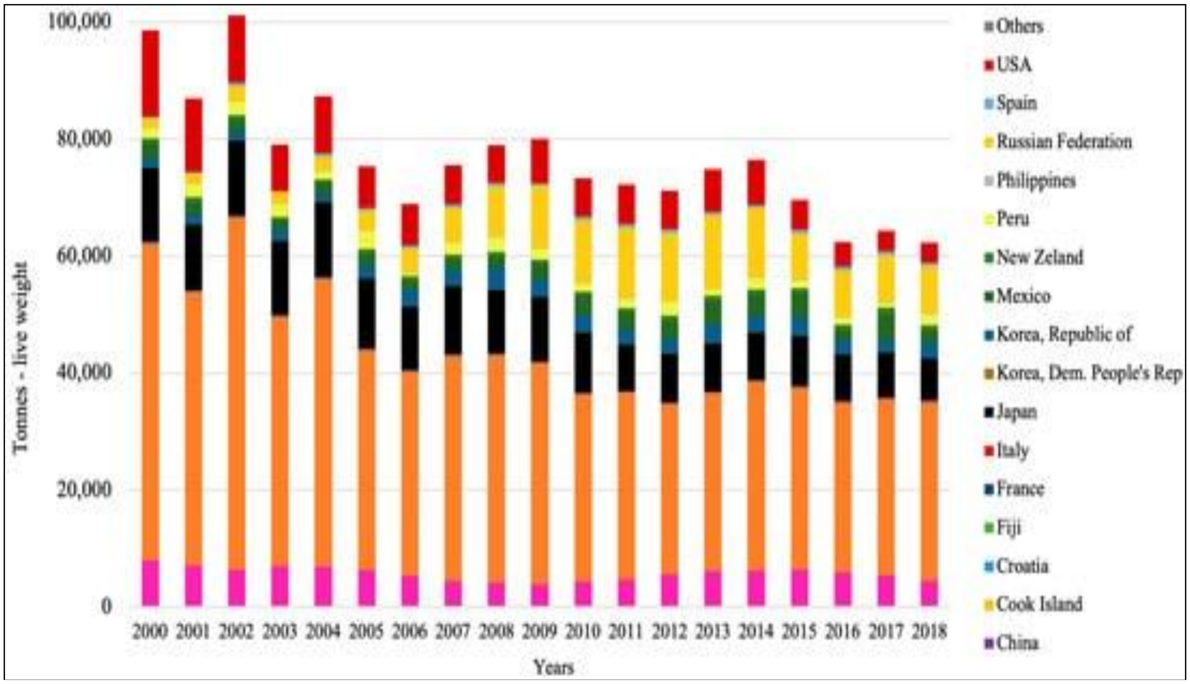

Figure 3: Global sea urchins harvest (production) divided by countries (2000–2018), in tonnes value (FAO, 2021).

2 Bioactive compounds from echinoderms

2. 1. Sea cucumber bioactives and therapeutic applications

Sea cucumbers are consumed predominantly by Chinese and other Southeast Asians such as Singaporeans, Vietnamese, Koreans, Malaysians, and Japanese. During the recent decades, sea cucumbers have been exploited with more than 50 commercially important species in 70 countries around the world in industrial, semi-industrial and small-scale fisheries that stretch from polar to temperate and tropical zones (Purcell et al., 2012). The important sources of sea cucumber in South-East Asia are Indonesia, the Philippines, Vietnam, Thailand and Malaysia, with Singapore and Hong Kong being major export destinations (Perez and Brown, 2012). The major product in the sea cucumber is the boiled and dried body-wall, commonly known as 'bêche-de-mer' or 'gamat', for which there is an increasing demand for food delicacy and folk medicine in the communities of Asia and Middle East (Yaacob et al., 1997; Huizeng, 2001; Bordbar et al., 2011; Mondol et al., 2017). There is also a trade in sea cucumbers for home aquaria and biomedical products (Bruckner et al., 2003). Sea cucumbers have been well recognized as a tonic and traditional remedy in Chinese and Malaysian literature for their effectiveness against hypertension, asthma, rheumatism, cuts and burns, impotence and constipation (Yaacob et al., 1997; Weici, 1987; Wen et al., 2010; Mondol et al., 2017). Nutritionally, sea cucumbers have an impressive profile of valuable nutrients such as Vitamin A, Vitamin B1 (thiamine), Vitamin B2 (riboflavin), Vitamin B3 (niacin), and minerals, especially calcium, magnesium, iron and zinc (Tian et al., 2005; Mondol et al., 2017). A number of unique biological and pharmacological activities including anti-angiogenic (Tian et al., 2005), anticancer (Roginsky et al., 2004), anticoagulant (Nagase et al., 1995; Chen et al., 2011), anti-hypertension (Hamaguchi et al., 2010), anti-inflammatory (Collin, 2004), antimicrobial (Beauregard et al., 2001), antioxidant (Althunibat et al., 2009), antithrombotic (Mourao et al., 1998), antitumor (Zou et al., 2003) and wound healing (San Miguel-Ruiz and García-Arrarás, 2007) have been attributed to various species of sea cucumbers. Therapeutic properties and medicinal benefits of sea cucumbers can be linked to the presence of a wide array of bioactive compounds (Bordbar et al., 2011; Rahman, 2014a; Rahman, 2014b; Rahman, 2014c; Rahman et al., 2015; Rahman et al., 2017a; Rahman et al., 2017b), especially triterpene glycosides (saponins) (Kerr and Chen, 1995), chondroitin sulfates (Vieira et al., 1991), glycosaminoglycan (Pacheco et al., 2000), sulfated polysaccharides (Mourao and Pereira, 1999), sterols (glycosides and sulfates) (Goad et al., 1985), phenolics (Mamelona et al., 2007), cerberosides (Sugawara et al., 2006), lectins (Mojica and Merca, 2005), peptides (Rafiuddin et al., 2004), glycoprotein, glycosphingolipids and essential fatty acids (Bordbar et al., 2011). However, the multiple biological, nutritional and therapeutic properties of sea cucumbers with respect to their potential and significant uses for functional foods, nutraceutical and pharmaceutical products and human health benefits have recently been well-documented (Rahman et al., 2015; Zulfaqar et al., 2016a; Zulfaqar et al., 2016b; Rahman et al., 2017a; Rahman et al., 2017b; Rahman et al., 2020). Sea cucumbers are also one of the delicacies of fine Chinese cuisine and are of cultural importance.

2. 2. Sea urchin bioactive and therapeutic applications

Similar to many other marine invertebrates, sea urchins have been examined as a source of bioactive compounds with biomedical applications (Kelly, 2005). Nevertheless, the potential of echinoids as a source of biologically active products are largely unexplored and undermined (Bragadeeswaran et al., 2013). The marine environment is an exceptional reservoir of bioactive natural products, many of which exhibit structural and chemical features not found in terrestrial natural products. Newly established modern technologies have opened vast areas of research for the extraction of biomedicinal compounds from ocean and seas to treat the fatal diseases. The number of natural products isolated from marine organisms increases rapidly, and now exceeds with hundreds of new compounds being discovered every year (Proksch and Muller, 2006). It is expected that some of the secondary metabolites may be pharmacologically active on humans and useful as medicines (Briskin, 2000). Majority of the pharmacologically active secondary metabolites have been isolated from echinoderms (Carballeria et al., 1996). There has been valuable information available for new antibiotic discoveries and give new insights into biologically active compounds in sea urchins; their shells are containing various polyhydroxylated naphthoquinone pigments, spinochromes (Anderson et al., 1969) as well as their analogous compound echinochrome A, which was found to have significant bactericidal effect (Service and Wardlaw, 1984). The phenolic hydroxyl groups in these molecules also suggested that they could participate in antioxidant activity as was observed in other well-known antioxidant polyphenols such as tea catechins. The similar structured compounds were also found in the shells of sea urchins and thus suggesting that they as well as echinochrome A would act as antioxidant substances similar to other polyphenolic antioxidants in edible plants (Chantaro et al., 2008). Squaric acid ester-based methodology was also used in a new synthesis of echinochrome A pigment, commonly isolated from sea urchin spines (Pena-Cabrera and Liebeskind, 2002). The gonads of sea urchin contain echinochrome A, which have potential antioxidant activity (Lebedev et al., 2001). Sea urchin gonads are also rich in valuable bioactive compounds, such as polyunsaturated fatty acids (PUFAs) and β-carotene (Dincer and Cakli, 2007). PUFAs, especially eicosapentaenoic acid (EPA, C20:5) (n-3)) and docosahexaenoic acid (DHA C22:6 (n-3)), have significant preventive effects on arrhythmia, cardiovascular diseases and cancer (Pulz and Gross, 2004). β-Carotene and some xanthophylls have strong pro-vitamin A activity and can be used to prevent tumour development and light sensitivity (Britton et al., 2004). The composition of these valuable components, however, varies greatly among different urchin species and is influenced by their natural diet and physiological processes i.e. reproductive stage (Fernandez, 1998; Lawrence, 2007). On the other hand, the high levels of AA and EPA recently detected in *Diadema setosum* and *Salmacis sphaeroides* supported the development of aquaculture of sea urchins (Chen et al., 2011), since PUFAs are important for human nutrition (Lawrence, 2007).

3 Breeding, rearing and culture of echinoderm fisheries

3. 1. Sea cucumber breeding, seed production and aquaculture

Usually, the cultivatable species of sea cucumbers are dioecious, broadcast spawners, the fertilized eggs developing into planktonic larvae in the water column before undergoing settlement induction and metamorphosis to the juvenile sea cucumber. The average life span of a sea cucumber is documented to be 5–10 years and the most species attain their sexual maturity at 2–6 years. Cultivation of sea cucumbers initiated in Japan in the 1930s and juveniles of the temperate species *Stichopus japonicus* (Figure 4A) were first produced in 1950 (Battaglene et al., 1999). During the last 15 years, commercial production in Japan has enhanced, where annually an estimated 2.5 million juveniles are released (Rahman, 2014a; Rahman, 2014b). In China, cultured rather than fished *S. japonicus* now account for around 50% of the country's estimated annual production of dry sea cucumber (Kelly, 2005; Rahman, 2014b; Rahman, 2014c). Procedures for mass culture of the tropical *Holothuria scabra* (Figure 4B) are well established and practiced in Australia, India, Indonesia, the Maldives and the Solomon Islands (Battaglene et al., 1999, Rahman, 2014a; Rahman, 2014b). Other tropical species in culture include *Actinopyga mauritiana* (Figure 4C) and *H. fuscogilva* (Figure 4D), with the focus of the research effort centered on the production of juveniles in hatcheries for the restoration and enhancement of wild stocks (Ramofafia et al., 1996; Ramofafia et al., 2000; Rahman, 2014a; Rahman, 2014c; Rahman et al., 2015). However, in the last decade, only a few commercial holothurians have been successfully reared to settlement, including some tropical and temperate species.

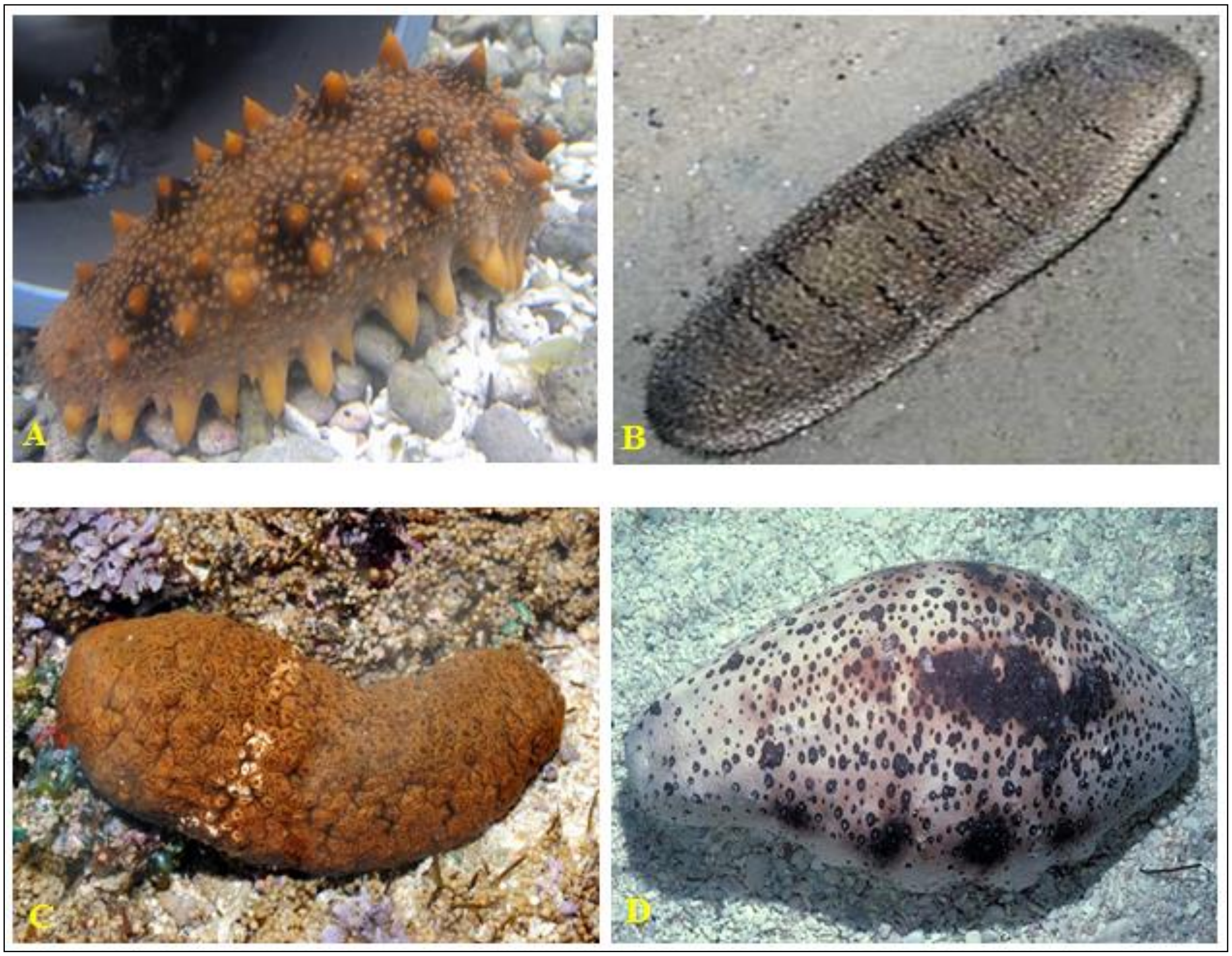

Figure 4: Commercially important species of sea cucumbers in aquaculture: A) *Stichopus japonicas*, B) *Holothuria scabra*, C) *Actinopyga mauritiana* and D) *Holothuria fuscogilva*.

Sexually matured brood stock of *Holothuria scabra* is usually collected from the wild and maintained in the hatchery in a bare 1 t polyethylene tank. The water in the broodstock tank is changed daily. Animals are fed with an extract of *Sargassum* sp. and unicellular algae (*Chaetoceros* sp. and *Isochrysis* sp.) (Dabbagh and Sedaghat, 2012). The broodstock is most commonly induced to spawn through thermal stimulation, by increasing the seawater temperature in holding tanks by 3–5 °C for 1 h. Generally, *H. scabra* has a bi-annual peak in gonadosomatic index, indicating two spawning periods a year, but closer to the equator, a proportion of the population spawns year-round (Battaglene et al., 1999; Kelly, 2005). After females spawned, eggs are left for one hour to be fertilized. The collected eggs are washed in fresh seawater to remove excess spermatozoa. Eggs are then transferred to three larval rearing tanks that are stocked at a density of 0.7-1.0 eggs/ml. The temperature in the larval tanks is maintained at 26 °C. Larvae are usually fed with phytoplankton, including *Isochrysis* sp., *Chaetoceros muelleri*, *C. calcitrans* and *Pavlova lutheri*. The algae are given twice daily, at gradually increasing concentrations of 20,000 cells/ml to 40,000 cells/ml. Complete water changes (100%)

are carried out every second day until the late auricularia stage is reached. At the start of the metamorphosis from late auricularia to doliolaria (Figure 5), preconditioned polyethylene plastic sheeting or rough-surfaced tiles added to the tanks. When settlement plates are placed into the tanks, the pentactula larvae are fed with spirulina powder and Algamac Protein Plus at a concentration of 0.25 g/m^3. Newly metamorphosed juveniles are fed with Spirulina powder and Algamac Protein Plus. When juveniles reached 2 cm, they are fed with *Sargassum* and *Padina* extract. The water in juvenile tanks is changed daily. A fine layer of sand is added to tanks as soon as juveniles reached 4 cm. Throughout the juvenile stage it is necessary to periodically detach the juveniles from the substrate for grading, transfer between tanks or to supply fresh substrates. After a 4-6-month, on-growing nursery phase, and at a length of 2–8 cm, juvenile sea cucumbers are released to managed areas of the seafloor or ponds for advanced rearing and grow-out culture (Rahman, 2014a; Rahman, 2014b).

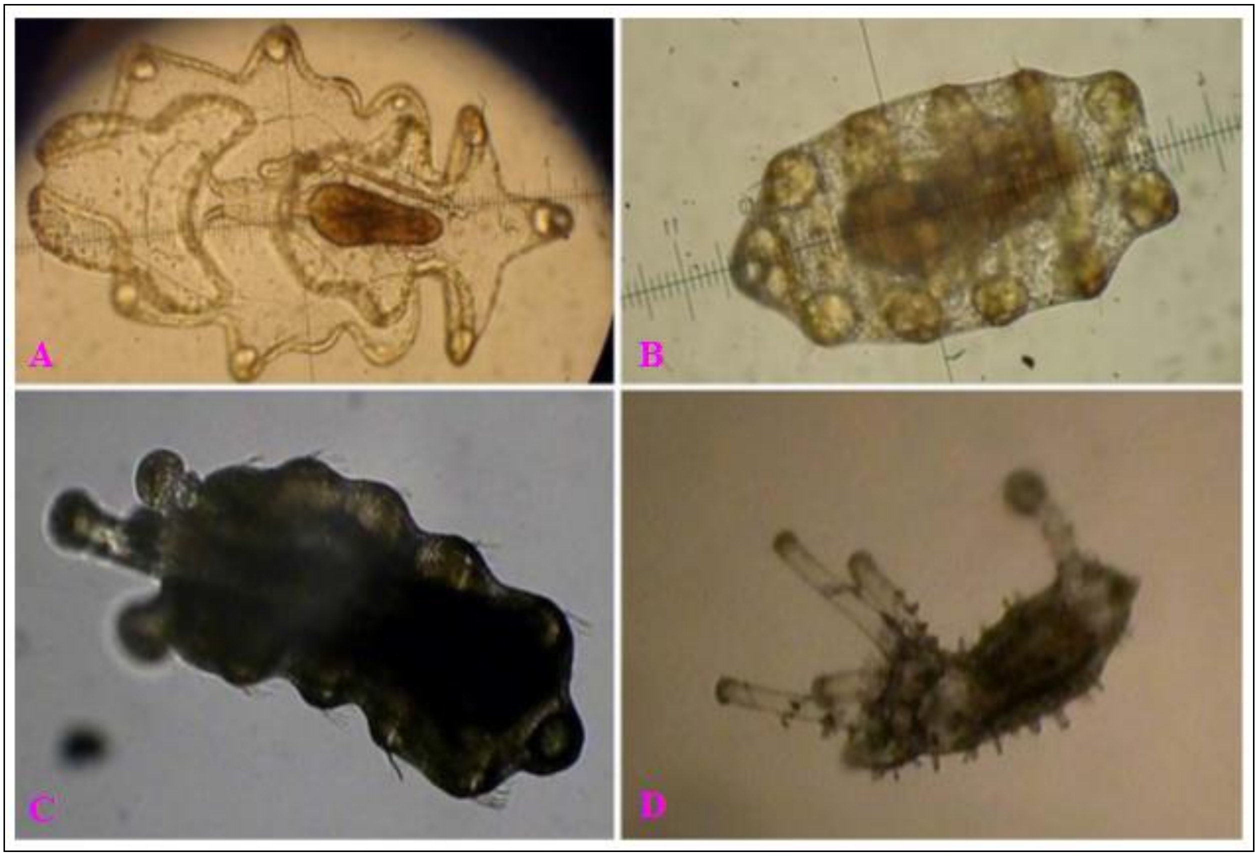

Figure 5: Larval developmental stages of *Holothuria Scabra*: A) Auricularia, B) Doliolaria, C) Pentactula and D) Early Juvenile (Dabbagh and Sedaghat, 2012; Rahman, 2014a; Rahman, 2014b).

Aquaculture, sea ranching and restocking has been evaluated as possible solutions to wild sea cucumber overexploitation (Rahman, 2014a). Currently, China is successfully producing an estimated 10,000 tons, dry weight, of *S. japonicus* from aquaculture, mainly to supply local demand (Rahman, 2014a; Rahman, 2014b). Because of the outbreak of prawn diseases in 1990s, lots of prawn ponds were unused and therefore, the farmers started pond culture of sea cucumber in Shan Dong province and Dalian and obtaining higher production with lesser costs and risks (Figure 6). In the Asia Pacific region, aquaculture is still in the early development stages, with one species of sea cucumber (*H. scabra*) in trials to ascertain the commercial viability of culture and farming options. Many additional threats have been identified for sea cucumber populations worldwide, including global warming, habitat destruction, unsustainable fishing, the development of fisheries with little or no information on the species, and lack of natural recovery after overexploitation. The critical status of sea cucumber fisheries worldwide is compounded by different factors including i) the lack of financial and technical capacity to gather basic scientific information to support management plans, ii) weak surveillance and enforcement capacity, and iii) lack of political will and socio-economic pressure exerted by the communities that rely on this fishery as an important source of income. The pervasive trend of overfishing, and mounting examples of local economic extinctions, urges immediate action for conserving stocks biodiversity and ecosystem functioning and resilience from other stressors than overfishing (e.g. global warming and ocean acidification), and therefore sustaining the ecological, social and economic benefits of these natural resources (Toral-Granda et al., 2008; Rahman, 2014a; Rahman, 2014b).

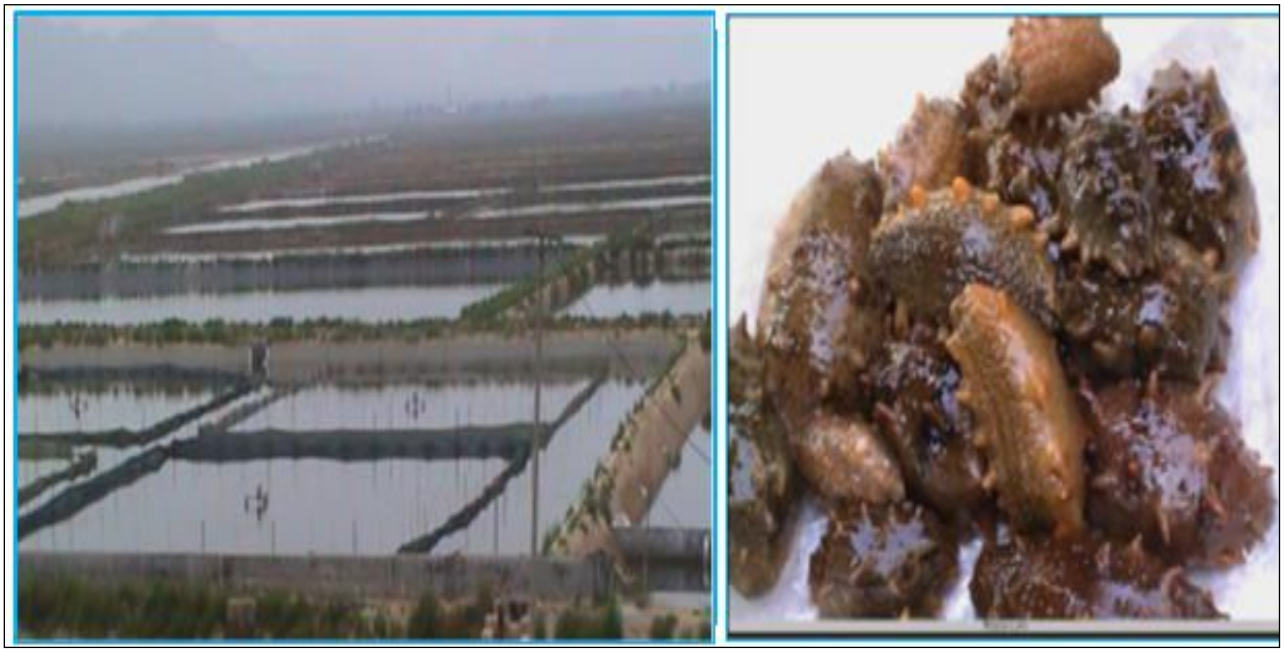

Figure 6: Current successful aquaculture practices of sea cucumbers (e.g., *Stichopus japonicas*) in earthen ponds in China, obtaining higher production with lesser costs and risks (Rahman, 2014a).

3. 2. Sea urchin breeding, seed production and aquaculture

There are around 40 edible sea urchin species within which more than 900 species that exist worldwide. Among them, 11 Indo-Pacific species have recently been documented in Malaysia's coral reef communities (Figure 7). These are: *Diadema setosum, D. savignyi, Echinothrix diadema, Salmacis sphaeroides, Parasalenia gratiosa, Toxopneustes pileolus, Astropyga radiata, Echinometra mathaei, Echinothrix calamaris, Salmaciella dussumieri* and *Tripneustes gratilla* (Rahman and Yusoff, 2010; Rahman et al., 2012a; Rahman et al., 2012b). However, some systematic works have been done on the abundance, distribution and population growth patterns of *D. setosum* and *S. sphaeroides* in Malaysia (Rahman et al., 2012a; Rahman et al., 2013) but few published information on their breeding, nursing, seed production and culture techniques are available. Due to the higher nutritional values of sea urchin gonad, it is very important to develop appropriate techniques for breeding and nursing. In view of this, two projects have been undertaken: (i) to develop a viable methodology for breeding, seed production and culture of *D. setosum* and *S. sphaeroides* in captivity and (ii) to determine the biochemical composition of gonads in a view to develop nutraceutical and pharmaceutical products.

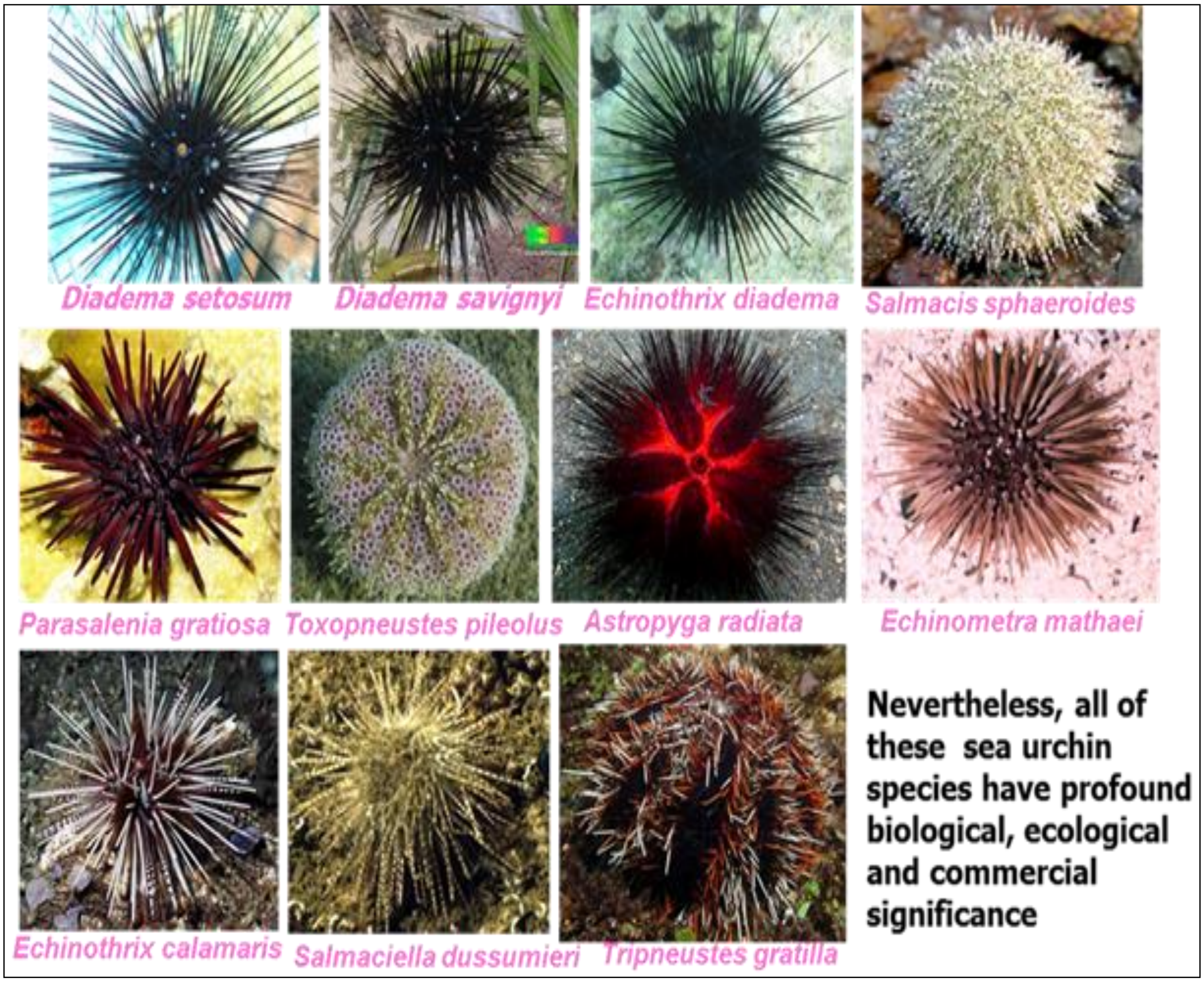

Figure 7: Eleven Indo-Pacific species of sea urchins documented in Malaysia's coral reef communities (Rahman et al., 2014c).

Sexually matured adults of the sea urchins, *D. setosum* (Figure 8A) and *S. sphaeroides* (Figure 8B), weighing from 100 to 150 g, were collected from Pulau Pangkor, Perak and Tanjung Kupang, Johor, respectively, at low tide during their natural breeding season from April to September, 2011. Immediately after collection, the live sea urchins were transported to the Laboratory of Marine Biotechnology, Institute of Bioscience, Universiti Putra Malaysia, where they were maintained in aerated aquaria before used for breeding trials.

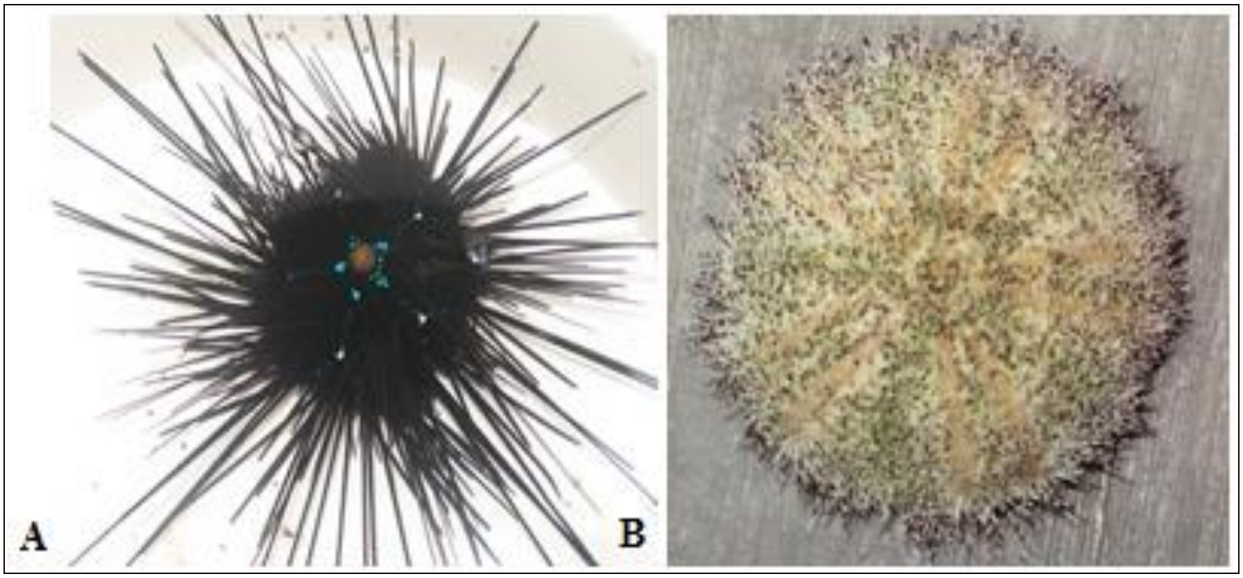

Figure 8: Matured adults of tropical sea urchins: A) *D. setosum* (Rahman et al., 2012b), B) *S. sphaeroides* (Rahman et al., 2012b).

Gametes from both female and male urchins were obtained by injecting 0.5 M KCl into the coelomic cavity. Eggs were collected by inverting female urchins over a glass beaker filled with filtered sea water (FSW). Fertilization was done at limited sperm concentration and the resulting embryos and larvae were reared. When the larvae attained feeding stage (four-armed pluteus), they were cultured in glass bottles on a rotating roller with a larval density of 1-2 individual/ml. Larvae were supplemented with a cultured phytoplankton, *Chaetoceros calcitrans* at concentrations of 4,000-8,000 cells per ml of medium daily until attaining metamorphic competence within 1 month post-fertilization (Figure 9 and 10).

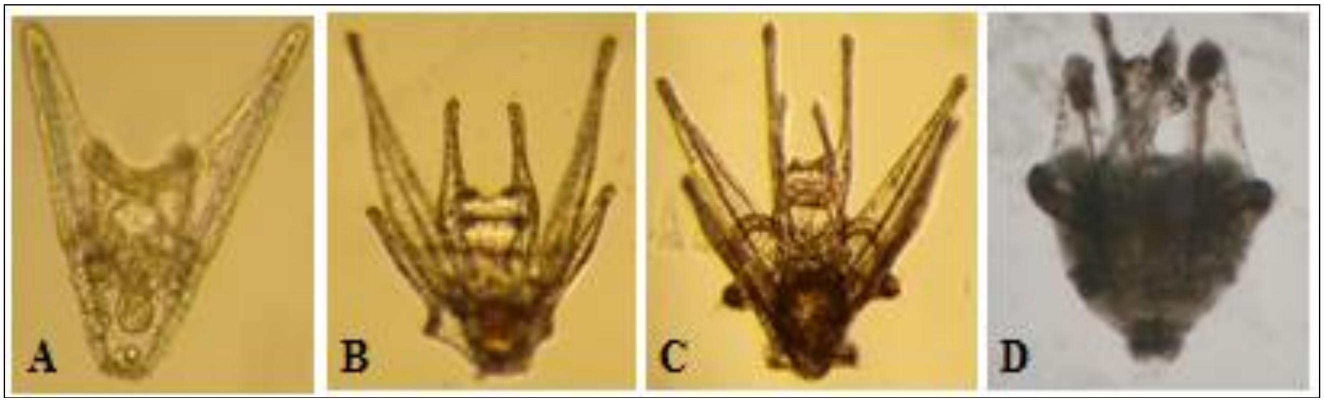

Figure 9: Larval developmental stages of *S. sphaeroides*: A) 4-arm pluteus, B) 6-arm pluteus, C) 8-arm pluteus, D) Competent larva with complete rudiment growth (Rahman et al., 2012b).

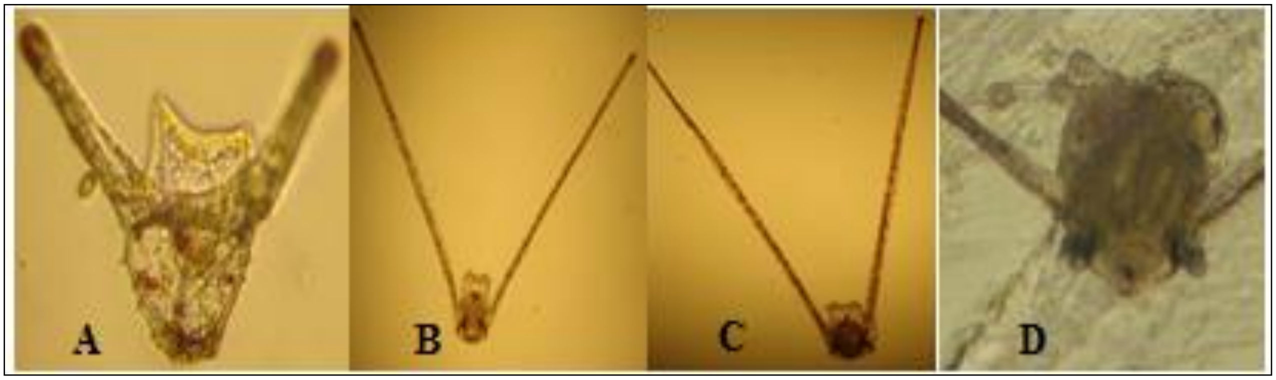

Figure 10: Larval developmental stages of *D. setosum*: A) 4-arm pluteus, B) POA (Postoral arm)-elongated stage-1, C) POA-elongated stage-2, D) Competent larva with complete rudiment growth and development (Rahman et al., 2014c).

Induction of metamorphosis was performed on coralline red algal extracts + *Chaetoceros* diatom (50:50) in petri dishes (9.0 x 3.0 cm) containing FSW. Majority of the competent larvae were metamorphosed to young juveniles within 1 day post-settlement and then cultured on coralline algal stones in aerated aquaria for three months by which time they attained appropriate juvenile sizes (Figure 11 and 12) for stocking in grow out culture aquaria.

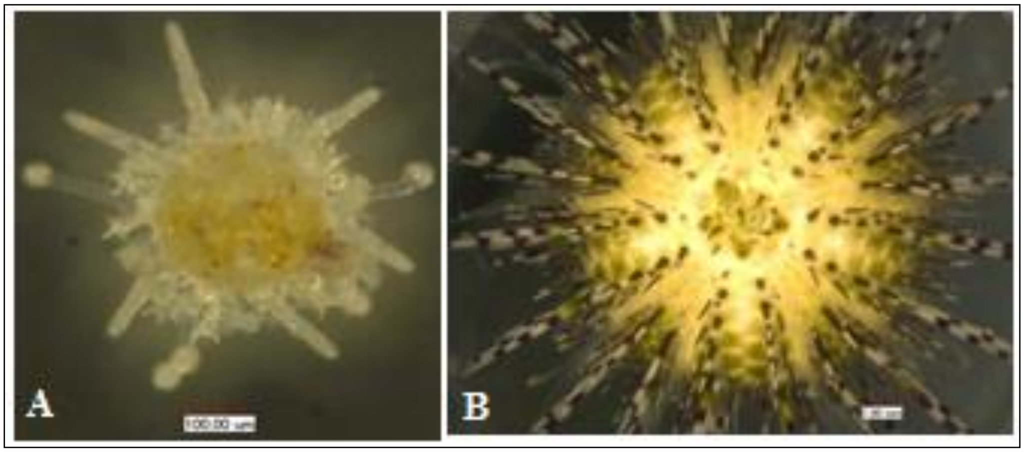

Figure 11: Juveniles of *S. sphaeroides*: A) 1-day-old juvenile, B) 3-month-old juvenile.

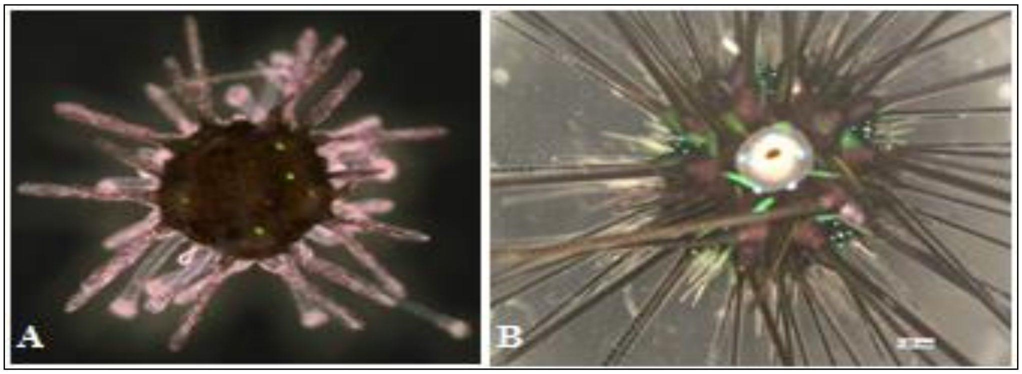

Figure 12: Juveniles of *D. setosum*: A) 1-day-old juvenile, B) 3-month-old juvenile.

In order to develop the appropriate aquaculture techniques, the 3-month old juvenile urchins are reared in aquaria (46 x 30 x 30 cm) at different stocking densities and algal feeding regimes. After two years of rearing in captive condition, all the urchins attained adult sizes with adequate matured gonads for harvesting (Figure 13).

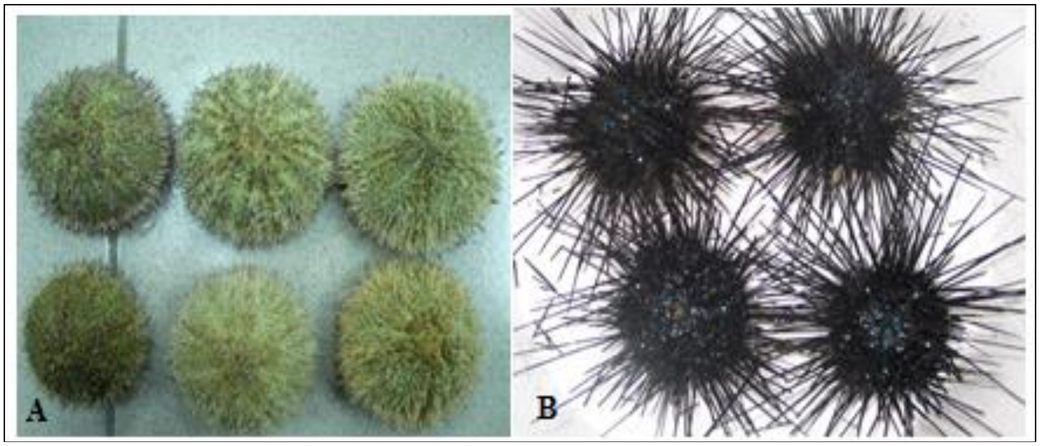

Figure 13: Sexually matured adult sea urchins after the culture period of two years in captive aquaria-rearing condition: A) *S. sphaeroides*, B) *D. setosum*.

This study demonstrates the first successful culturing of *S. sphaeroides* and *D. setosum* through the detailed larval development, metamorphosis and juvenile rearing in captivity. Therefore, the results obtained from the designated project will immensely be helpful towards the development of breeding, seed production and culture techniques of commercially important sea urchins and other marine invertebrates, which are yet to be fully determined and explored in the Indo-Pacific coral reef communities. In addition, development of appropriate rearing and culture techniques would immensely be helpful to produce adequate quantities of nutraceutical and pharmaceutical products from these high-valued Echinoderms. In contrast to the Japanese systems where hatchery-reared juveniles are mainly released to managed areas of seafloor (Hagen, 1996; Sakai et al., 2004; Kelly, 2005), researchers in other countries have experimented with a wide range of grow-out systems for juvenile and adult urchins, ranging from relocation from poor to good feeding grounds (Moylan, 1997) to the ranching of urchins caged on the seafloor (Cuthbert et al., 1995). Wild-collected adults of many species have been held in a variety of tank and sea-cage systems for roe conditioning (Lawrence et al., 1997; Cook et al., 1998; McBride et al., 1998; Fernandez and Boudouresque, 2000; Hammer et al., 2000; Kelly et al., 2001; Kennedy, 2002; Pearce et al., 2002; Kelly, 2005). Hatchery-reared juveniles have been grown in suspended culture (Kelly, 2002; Kelly, 2005) in closed recirculation systems (Grosjean et al., 1998) and in dammed rock pools in southern Ireland. A sea-cage cultivation system of stacking baskets suspended from a ladder-like structure over which a work barge or raft can operate is being developed by Norwegian researchers (Aas, 2004). The juveniles of most sea urchin species usually reach to marketable size within the culture period of 1–3 years.

Systems that accelerate growth to marketable size while producing a uniform size class would give an economic advantage. One possible route in obtaining sustainable and environmentally friendly systems for sea urchin culture is to further examine their potential in integrated aquaculture systems. They have already been shown to thrive in polyculture with the Atlantic salmon (Kelly et al., 1998) and to have a role in land-based integrated systems (Shpigel et al., 2004). However, many species are true omnivores, so the potential for their integration into systems where natural prey items, for example, mussels, are already produced should be fully explored, determined and utilized (Kelly, 2005; Rahman et al., 2014c) in a sustainable manner.

4 Conclusion and Recommendations

4. 1. Sea cucumbers

South-East Asia is a major source of sea cucumber supplied to the world market. However, the fishery is mostly artisanal, carried out by low-income households. Sea cucumber is generally an incidental catch in finfish fishing, although fishery activities where it is targeted are becoming more significant. The hotspot case studies show for instance that, despite the adoption of management plans in some countries, the lack of enforcement capacity poses considerable constraints on the effectiveness of adopted management measures, besides exacerbating illegal, unreported and unregulated fishing and trade. Prior to the enforcement of the sustainable management measures, it is vital that stocks are allowed to recover to a near pristine biomass level. Only then can management regimes such as TACs, closed seasons, restricted areas and size limits, be effective in achieving maximum benefits from the resource. Sea cucumber populations have been overexploited, which calls for immediate closure of the fishery to enable stocks to recover to levels where they can be managed sustainably. Whatever management measures are officially enacted; the underlying success of management will depend on effective enforcement. The area where sufficient governance exists, two important steps to manage existing and future holothurian fisheries have been suggested, such as: (i) the expansion rate of new sea cucumber fisheries had best be reduced to a level where management has time to react to early warning signs of resource depletion and (ii) lacking changes in regulation, the catch trajectory and patterns of serial spatial, species and size expansion or depletion are largely predictable. Knowledge of the impending sequence of events can therefore be pre-emptively incorporated into the management of new and existing high-valued sea cucumber fisheries. In general, this review highlights the urgent need for better monitoring and reporting of harvesting and abundance data, proper scientific stock enhancement and ecosystem impact assessment and appropriate aquaculture and conservation strategies to ensure more sustainable management and effective utilization of global sea cucumber fisheries.

Due to the declining catch from the wild, a number of possibilities have also been proposed by Perez and Brown (2012), Rahman and Yusoff (2017a) and Rahman and Yusoff (2017b) that can be explored to meet the ever-increasing demand, as follows:

- promoting aquaculture involving technically established protocols that can be explored to address;
- demand and supply gaps establishing direct market linkage between producers and exporters to reduce market inefficiencies;

- expanding research to develop culture protocols for other high-value species;
- improving support for efforts designed to generate new products from sea cucumbers;
- exploring new export destinations, especially in countries with significant Chinese populations;
- establishing regularly updated statistics and information systems for sea cucumbers;
- formulating and implementing official grades and standards;
- improving village-level small-scale primary processing;
- exploring strategies that could lead to the achievement of economies of scale in large-scale modern processing methods/facilities that observe international standards for processed food products.

The lack of capacity to gather the basic information needed for management plans, weak enforcement, the high demand from international markets and the pressure exerted from resource-dependent communities figure as important factors responsible for the critical status of sea cucumber fisheries. It should therefore need to undertake immediate actions to stop the trend of sequential depletion of sea cucumber production if we are to conserve stocks biodiversity and sustain the ecological, social and economic benefits of this high-valued marine bioresource to a greater extent.

4. 2. Sea urchins

To summarize the views, reports and publications of other scientists/researchers, it is apparent that sea urchin fisheries have a poor record of sustainability, as evidenced by the declines recorded in Japan, Maine, California and South Korea among others, as well as by the ad hoc and/or ineffective management in many sea urchin fisheries. Very few stocks have been formally assessed, meaning it is near impossible to qualify declines as the fish-down of accumulated biomass, which does not arrest the productivity of the stock, or as a case of over-fishing in which case its productivity may be forced into permanent decline. Small scale management is mentioned time and again as offering the most promise for ensuring long term sustainability. The strong and consistent spatial structure inherent in sea urchin stocks combined with excessive effort from mobile fleets and inappropriately large scale, and therefore ineffective management all contribute to declining production in many of the world's sea urchin fisheries. This is particularly the case for the world's largest sea urchin fishery in Chile where the risks of collapse cannot be discounted (Rahman et al., 2014c). Given that this fishery alone contributes upwards of 55% of the global harvest, a significant decline in Chile's fishery would likely lead to structural realignment in the market and higher prices for mid-range products until aquaculture production ramped up. There is also general agreement that some form of exclusive access as a prerequisite condition to promote meaningful enhancement and intelligent harvesting to maximize roe value will provide the best hedge against uncertainties in fisheries productivity and market stability. In order to make sea urchins fisheries profitable, the following actions are suggested:

- Complete the life cycle in culture;
- Improve larval diets and shorten larval life;
- Provide suitable settlement substrates that maximize survival at metamorphosis and of

the post-larval stages;

- Refine artificial diet formulations for juveniles and adults to maximize growth rates and survivorship and produce gonads of the desired taste, texture, flavor and color;
- Optimize grow-out facilities for juveniles and adults either at sea (in containers or 'ranched') or land based;
- Attend to packing, food hygiene, transport and marketing requirements;
- Regulations regarding fishing methods, fishing areas and protection of company investments need to be developed;
- Better surveillance of sea urchin density to guarantee a steady flow of raw materials;
- Areas need to be thinned out to get the best possible product for the market, this is also necessary for the kelp forest to grow back;
- More capital needs to be directed towards investing in technology for processing to reduce labour costs and preserve product quality;
- Improved cooperation between fishermen and processors, when marketing and selling the sea urchins.

In the short term, it is likely that global production of sea urchin roe from wild fisheries will decline, with the major production being provided by those fisheries that have supported active management strategies to readjust effort and contain catches to levels that provide long-term sustainability. Given that demand is unlikely to decline; future production will be increasingly valuable. This will also open the new opportunities for alternative production methods such as on-growing and aquaculture under captive conditions.

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Conflict of interests

The authors have no conflicts of interests to declare that are relevant to the content of this article.

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