Journal of Coastal Research	SI	86	270–276	Coconut Creek, Florida	2019

Domestication and Genetic Improvement of Indian White Shrimp, *Penaeus indicus*: A Complimentary Native Option to Exotic Pacific White Shrimp, *Penaeus vannamei*

Koyadan Kizhakedath Vijayan*

ICAR-Central Institute of Brackishwater Aquaculture
Chennai, Tamil Nadu, India

www.cerf-jcr.org

www.JCRonline.org

ABSTRACT

Vijayan, K.K., 2019. Domestication and genetic improvement of Indian white shrimp, *Penaeus indicus*: A complimentary native option to exotic *Penaeus vannamei. In:* Jithendran, K.P.; Saraswathy, R.; Balasubramanian, C.P.; Kumaraguru Vasagam, K.P.; Jayasankar, V.; Raghavan, R.; Alavandi, S.V., and Vijayan, K.K. (eds.), *BRAQCON 2019: World Brackishwater Aquaculture Conference. Journal of Coastal Research,* Special Issue No. 86, pp. 270–276. Coconut Creek (Florida), ISSN 0749-0208.

Shrimp farming is the economic engine of Indian aquaculture, where the annual production touched 0.7 million tons in 2017-18, valued over ₹30,000 crores. However, the sustainability of shrimp farming and production raises serious questions due to its single species focus, where 90% of the production is of the exotic Pacific white shrimp. Of late, several issues of shrimp aquaculture in India with special reference to *Penaeus vannamei* farming have been reported and are being discussed. Although the introduction of *P. vannamei* revolutionized shrimp aquaculture in India since 2010, recently aquaculture of *P. vannamei* has shown several problems owing to multiple reasons *viz.*, a decline in the productivity, emerging pathogens and increasing trend in production cost. In this context, the potential of development of native penaeid shrimp, the Indian white shrimp, *P. indicus* was critically evaluated. Present and past research work carried out in India towards the domestication of *P. indicus* indicate comparative advantages of domestication of the Indian white shrimp. The use of native species has many physiological advantages while avoiding many risks related to environmental issues and the introduction of exotic pathogens. High genetic diversity of *P. indicus* improves the effectiveness of selective breeding programs and provides one more option for the shrimp farmers towards sustainable shrimp farming.

ADDITIONAL INDEX WORDS: Penaeus indicus, *domestication, genetic improvement, sustainable farming*.

INTRODUCTION

Modern shrimp farming is the most dynamic and one of the fast-growing food production systems, particularly in the developing world, also concerning its credibility related to sustainability. In India, shrimp farming has become a multibillion-dollar industry, and in 2018, frozen shrimp earned almost $US 5 billion, which is about 70% of the total seafood export earnings (Ravisankar *et al*., 2018). The growth of shrimp farming over the past three decades is impressive from almost less than 0.1 million tons (1990) to about 0.7 million tons (2018). Although the growth of shrimp farming from 1990 to 2010 was modest, an upsurge in the growth happened during the recent decade. This escalation in the farmed shrimp production is mainly due to the introduced exotic, *Penaeus vannamei*, which has been selectively bred for growth enhancement. Although aquaculture of the exotic *P. vannamei* revived the growth of Indian farming sector, the industry has been in stress during recent years due to the multiple issues *viz.*, susceptibility to disease-causing pathogens, poor larval survival, growth *etc*. In this context, the development of native shrimp, *Penaeus indicus* is found to be a viable option for the long-term sustainability of the industry (Rajeev Raghavan and Prasad, 2006; Vijayan *et al*., 2004; Vijayan and Balasubramanian, 2016). Diversification, as such, for stable and sustainable industrial development is not a radical idea; it has been a component of successful aquaculture development in many countries (Corbin and Young, 1997). However, diversification alone need not lead to a successful aquaculture industry, particularly in the case of penaeid shrimp, as seed stock generated from wild broodstock provides unresolvable issues in the management of diseases. Therefore, domestication and improvement of the germplasm of native farmed species are the essential prerequisites for the sustainable shrimp industry.

In this article, the need of domestication and popularization of native species, *Penaeus indicus* is described at the context of the introduction of exotic *P. vannamei*. This article also examines how domestication of native species would stabilize and diversify the shrimp aquaculture in India while ensuring the equitable distribution of benefits.

SHRIMP AQUACULTURE IN INDIA

Shrimp farming in India, in its earliest form, began in the first quarter of last century as a pond based capture system. Later, in recent aquaculture literature, this form of aquaculture is often referred to as fishery based aquaculture. In west coast of India, the rice fields are adapted for dry season production of

DOI: 10.2112/ SI86-040.1 received 8 March 2019; accepted in revision 31 May 2019
*Corresponding author: vijayankk@gmail.com

shrimp by raising the dyke and installing of weirs, the sluice gate, to prevent the escape of post-larvae/juvenile trapped during the high tide. In the early days, this entrapment was used only for a short period to catch young shrimp, which was exported to Burma (presently Myanmar) as "*chemmeen* / shrimp pulp". Later, with the advent of the frozen shrimp industry in India, the demand for large shrimp increased considerably, and, therefore, it was essential to growing shrimp in the farm to meet the demand of the export industry. Thus, the paddy field shrimp fishery evolved into a primitive form of aquaculture, where the naturally immigrating shrimp seeds from coastal waters were entrapped and prevented from returning to sea, and reared for few months without any feed or aeration. The first experimental shrimp aquaculture has been carried out by Central Marine Fisheries Research Institute, Cochin in 1963 (George, Mohamed, and Pillai, 1967), and these studies paved the way for brackishwater aquaculture research in India. Although extensive production system of shrimp started as early as the 1960s, the industry only really began to intensify in the early 1990s. As a first step, a commercial tiger shrimp hatchery was set up in the state of Andhra Pradesh, by The Andhra Pradesh Shrimp Seed Production, Supply and Research Centre (TASPARC). This successful initiative triggered the establishment of commercial hatcheries and shrimp farms in the private sector. However, this development has not happened in the already existing traditional shrimp farming regions; Kerala, West Bengal, Karnataka and Goa, and the modern shrimp aquaculture development largely occurred in the areas where shrimp aquaculture did not have any prior history, such as Andhra Pradesh (AP) and Tamil Nadu (TN). It may be attributed to the entrepreneurship of the AP and TN farmers in addition to the seasonal, climatic and geographical advantages.

Production Characteristics

The first recorded data for farmed shrimp production in India was 20 tons in 1970, and the first major change became obvious in 1991 when it reached 40,000 tons. Farmed shrimp production showed a remarkable growth during the early 1990s. The rapid growth of shrimp aquaculture induced an increase in area of shrimp farming to 65,000 ha in 1990, it increased up to 0.16 million ha in 1999, and again reduced to 0.12 million ha in 2014. Major reduction in area under farming was recorded in AP; from 85,000 ha in 1999, it reduced to 36,000 ha in 2014, whereas West Bengal and Gujarat showed a marginal increase. However, AP still contributed more than half of the farmed shrimp production in India. By early 2000, shrimp production also increased up to 1,00,000 tons in 2001. This growth occurred in spite of the setback caused by white spot syndrome virus (WSSV) in late 1994. The disease impacted the aquaculture industry severely, and it caused the exit of almost all corporate investors by 1997, due to repeated crop failures inflicted by WSSV. A recovery and moderate growth happened in the post WSSV-era, from 2000 to 2006, by adopting novel farming method such as zero water exchange, to prevent the entry of WSSV pathogen, and shrimp farming gradually increased and peaked with a maximum production of about 1.4 lakh tons in 2006, but production reduced drastically in 2008. However, by 2018, there was a remarkable upsurge of farmed shrimp production, largely due to the introduction of, the exotic specific pathogen-free American white shrimp, *P. vannamei* (Figure 1).

Introduction of Pacific White Shrimp, *Penaeus vannamei*

During the early phase of shrimp farming, farmers were less concerned with the use of genetically improved or domesticated stocks. This is mainly because of the most dominant species for shrimp farming in Asian countries, the giant tiger shrimp, *P. monodon*, which was widely distributed all along the coastal seas of shrimp farming countries. Therefore, the availability of wild spawners was less problematic, and most shrimp farms use the seed stock generated from the hatchery seeds produced from the wild- caught brooders. Conversely, many shrimp farming countries in the western hemisphere such as Brazil, Venezuela and United States, preferred *P. vannamei*, distributed along the southern Mexican coast, for the farming, though the availability of quality brooders was often unpredictable even within the countries where *P. vannamei wa*s naturally distributed. Subsequently, domestication of shrimps, particularly for *P. vannamei*, began in these countries owing to the logistical as well as biological reasons (Clifford and Preston, 2006).

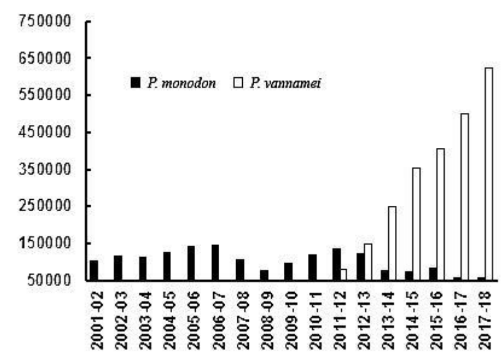

Figure 1. The status of the farmed shrimp production in India.

Later, farmers of Asian countries realized that the post-larvae of tiger shrimp generated from the wild broodstock often carry infective pathogens, and it was almost impossible to ensure biosecurity when wild broodstocks were used by the hatcheries for production of seeds. The only option left was the use of specific pathogen-free (SPF) stock in the production system, as the SPF seeds were not available for any Asian species, many Asian countries introduced SPF. In due course, SPF *P. vannamei* was also introduced in India, which revolutionized the shrimp aquaculture sector in India. Though SPF Pacific white shrimp created unprecedented success stories in shrimp farming across Asian countries, including India, this has certainly not been without problems. The production problems in Pacific white shrimp farming started showing up on serious levels after a decade of its introduction, and which has reminded the need of more SPF shrimp species preferably from the species which are native to the farming countries.

Issues in Current Brackishwater Aquaculture with Special Reference to the Introduction of *Penaeus vannamei*

The introduction of *P. vannamei* has made farm-raised changes in the production scenario of brackishwater shrimp culture in India. However, it faced the problems of emerging diseases, issues in larval rearing, low production in the grow-out, and problems in the marketing due to price fluctuation in the export markets. The presumed inbreeding depression due to the large-scale use of farm-raised broodstock was also reported as one of the problems for the lower performance in the rearing systems. Further, most of the broodstocks of *P. vannamei* were sourced from a single source based in the US, and this overdependence was found to impede the further growth of shrimp industry in general (Slater, 2018). It was also found that the productivity of Pacific white shrimp farming has been reducing drastically (Table 1). This drop-in production may be due to the high demand of SPF *P. vannamei* broodstock, and breeding companies have been forced to compromise on the quality of broodstocks. In this context, the development of native shrimp through selective breeding is found to be a viable option for the long-term sustainability of the shrimp farming industry in Asia, where complimentary shrimp species with potential for domestication are available (Rajeev Raghavan and Prasad, 2006; Vijayan *et al*., 2004).

Table 1. *Farming profile of* Penaeus vannamei *in India during 2010-2017.*

Year	Seed (billion)	Production (mt)	Productivity (mt/billion seed)
2010	2.2	47,000	21.4
2011	4.5	83,000	18.4
2012	9	1,45,000	16.1
2013	18	2,47,000	13.7
2014	28.5	3,26,000	11.2
2015	31.7	3,36,000	10.6
2016	36.5	3,85,000	10.5
2017	54	5,60,000	10.4

Domestication and Selective Breeding of *Penaeus indicus*

According to FAO (2014) data, about 600 species are being cultured worldwide; however, in reality, the production is limited to 30 species. Introduction of species from one geographical area to another is common, and over 4,000 introductions have been recorded in the FAO database for introductions. Although there are reports of few successful introductions without much recorded adverse effect, for example, the introduction of GIFT strain of Nile tilapia (*Oreochromis niloticus*) into many countries (Nguyen and De Silva, 2006), there are several documented cases of adverse environment effect of the introduction of exotic species. Owing to the highly publicized incidences of escaped culture population, there are widespread public concerns about the possibility of negative impact on native shrimp fauna. These impacts involve habitat destruction, introduction of pests and pathogens, competition of the feral exotic species with native species for food, space and displacement (Hulme, 2015). Therefore, many government agencies have taken keen interest in the development of native species as signatories of biodiversity engagements (Ross, Martinez Palacios, and Morales, 2008). Further, various stakeholders expressed increasing concern about the overdependence on exotic *P. vannamei* culture in India and the sustainability factor on a single species farming mode.

In this context, Indian white shrimp, *P. indicus* is found to be a better alternative for the development of specific pathogen-free stock for shrimp culture in India. The most important criteria for domestication and selective breeding of any species is complete control of reproduction under captivity. Although regulation of reproduction of penaeid shrimps has still been an elusive goal of shrimp culturists, some penaeid species are relatively easy to breed under captivity, for example, *P. vannamei* and *P. indicus* (Primavera, 1985). The relative ease of captive breeding of *P. vannamei* has helped, to a large extent, in its domestication and selective breeding. *Penaeus indicus*, is one of the first few penaeids whose breeding technology has been standardized. Further, initial experiments on the development of pond-reared broodstock also showed the potential of domestication for this species (Muthu and Laxminarayana, 1979).

Growth and production performance are important criteria for the candidate species for aquaculture. The tiger shrimp, *P. monodon*, received high popularity due to its higher growth performance; this species attains 25-30 g within 120 to 130 days. The growth and production performance of *P. indicus* is comparable or even slightly better to the pre domesticated *P. vannamei* (Table 2). For example, *P. indicus* attained 18.4 g within 114 days at a stocking density of 30 shrimps/m^2, whereas *P. vannamei* took 147 days to reach similar body weight even at a low stocking density of 12 shrimps/m^2. Similarly, gross production was higher in the case of *P. indicus* (Table 1). Moreover, Indian white shrimp is highly amenable to culture under high stocking densities with a high production of about 16-18 t/year in the early 1990s.

While formulating criteria for the development of native species for aquaculture (Ross, Martinez Palacios, and Morales, 2008) summarized basic requirements for the establishment of aquaculture of native species. The success of domestication largely depends on the previous degree of domestication of this species and core scientific knowledge generated on this species. It includes basic biology, environmental physiology, closing reproductive cycle in captivity, nutrition and husbandry. The generation of this scientific knowledge is an expensive and lengthy procedure. However, in the case of *P. indicus*, a large body of knowledge has already been developed in India, at the national research institutions such as Central Marine Fisheries Research Institute, Kochi and Central Institute of Brackishwater Aquaculture, Chennai.

Table 2. *Summary of pond culture performance of* Penaeus vannamei *(pre domestication period) in South Carolina and* Penaeus indicus *in Kerala, India.*

Characteristics	*P. vannamei*[#]	*P. indicus*[$]
Pond size (ha)	0.1-0.5	0.6
Stocking density (shrimp/m^2)	12	29.5
Initial mean weight (g)	0.01	<0.04
Final mean weight (g)	19.7	18.4
Days of culture	147	114
Daily weight gain g/day)	0.13	0.16
Production (kg/ha)	2477	2557
FCR	2.1	1.6
Salinity (‰)	28	11.1

[#]Sandifer *et al.* (1993); [$]Prasad (1999).

Table 3. *Comparative evaluation of* Penaeus indicus *and* P. vannamei.

Characteristics	*Penaeus indicus*	*Penaeus vannamei*
Growth rate	*Penaeus indicus* can grow as fast as up to 20 g size similar to *P. vannamei*.	SPF *P. vannamei* grow faster than *P. indicus* after 20 g size.
Stocking density	*P. indicus* could be cultured up to 45 PL/m^2.	SPF *P. vannamei* is easier to culture at higher stocking density as high as 60 to 150 PL/m^2.
Salinity tolerance	*P. indicus* is tolerant to a wide range of salinity (from 1 ppt to 50 ppt) similar to *P. vannamei.*	*P. vannamei* is less tolerant to very high salinity (>45 ppt).
Temperature tolerance	Highly tolerant to the tropical climate.	Tolerant to lower temperature than higher temperature.
Dietary protein requirements	Require low protein feed similar to *P. vannamei.*	Requirement of low protein feed.
Disease resistance	*P. indicus* is found to be less susceptible to emerging diseases such as EHP, white fecal disease *etc.*	*P. vannamei* is highly susceptible to, and a carrier of TSV, WSSV, YHV, IHHNV and LOVV; *P. monodon* is refractory to TSV and IHHNV.
Ease of breeding and domestication	Presently SPF stock is not available; however, recent and earlier research work indicates that this is possible. Broodstock rearing is not much complicated as *P. vannamei.*	Availability of pond-reared broodstock; Ability to conduct domestication and genetic selection work. Broodstock rearing and spawning more technical and complicated than use of wild P. monodon spawners.
Larval survival	Higher survival above 50% as *P. vannamei.*	Higher survival rates in hatchery of 50-60%.
Post-harvest characteristics	Remain fresh for a long time without melanisation, more appealing than *P. vannamei.*	Not as good as *P. indicus.*
Natural distribution and genetic variation	*P. indicus* has a wide natural distribution in Indo-West Pacific from Eastern Africa covering through India, Malaysia and Singapore to Southern China and Northern Australia. The wide distribution suggests genetic variation favourable character for selection.	Naturally, *P. vannamei* has very limited distribution in Eastern-Pacific of Central and South America which ranges from Sonora, Mexico at Northern end to Tumbes, Peru at Southern end. Limited geographic distribution is unfavourable for genetic improvement.
Origin	Native species. As *P. indicus* is a native species, all the quarantine measures to import *P. vannamei* could be avoided or minimize.	Exotic, all the potential adverse effect of non-native species would be there.

In the last fifty years, considerable advancements have been made towards the successful domestication of *P. indicus*. Control of reproduction of this species has been extensively studied (Muthu and Laxminarayana, 1980). Various aspects of reproductive endocrinology and vitellogenesis have been studied by Mohamed and Diwan, (1991a, 1991b, 1992, 1993, and 1994) and Diwan and Mohamed, (2007). Extensive studies on the basic physiology of moulting and its relation to growth have been studied by Diwan and Vijayan, (2007); Mohamed, Vijayan, and Diwan, (1993); Vijayan and Diwan (1995, 1996); Vijayan, Mohamed, and Diwan (1993, 1997). Nutritional requirements for *P. indicus* were studied by Ali (1982); Gopal (1986); Vijayagopal, Babu Philip, and Sathianandan (2008, 2009). The basic digestive physiology of *P. indicus* was studied by (Hemambika, 1989). Several growth experiments on *P. indicus* have been conducted (Prasad, 1999; Sivakami, 1988). Thus, ample core scientific studies have been published, and a solid platform has been laid for the development of the breeding program of Indian white shrimp.

Pilot Research Work Carried out by ICAR-Central Institute of Brackishwater Aquaculture for Facilitating *P. indicus* Domestication Program

To evaluate the farm level performance of *P. indicus*, 21 demonstration trials were carried out all along the Indian coast. The production ranged between 2 and 6.5 t/ha at a stocking density ranging from 15 to 45 PL/m^2 with survival ranging between 72 and 98%. The absence of emerging diseases such as hepatopancreatic microsporidiosis caused by *Enterocytozoon hepatopenaei* and running mortality syndrome is found to be an important advantage noticed during the farming of *P. indicus* (Panigrahi, 2018). Further, the growth rate of *P. indicus* up to 18-20 g in the initial phase is found to be similar to the growth trend in SPF *P. vannamei* (Figure 2, 3 and 4), though the latter species showed faster growth after 20 g size.

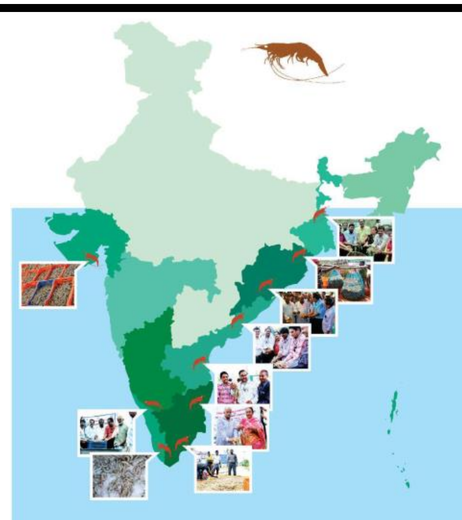

Figure 2. Demonstration trials of *Penaeus indicus* at different states of India.

Maturation and Larviculture Trials

To evaluate the reproductive and larval performance, several larval cycles were carried out using a large population of wild *P. indicus* brooders. A total of 2,164 wild-caught brooders were sourced from the broodstock fishery along the east coast of India. The experiment was carried out in two phases: In phase 1 brooders from Chennai coast alone was used, whereas, in the second phase, brooders from three stations, Odisha, Chennai and Kanyakumari were used. An ablated female had a latency period of 7-10 days to attain maturity stages with maximum successful spawning of 2-3 times per broodstock batch.

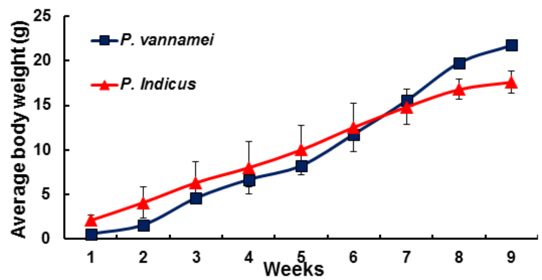

Figure 3. Growth patterns of *Penaeus indicus* and *Penaeus vannamei* cultured in semi-intensive ponds at Kakdwip research centre of CIBA. Up to seven weeks, *Penaeus indicus* undomesticated native stock shows a higher growth rate than the genetically improved exotic *Penaeus vannamei*.

Figure 4. Farm reared *Penaeus vannamei* (a) and *Penaeus indicus* (b).

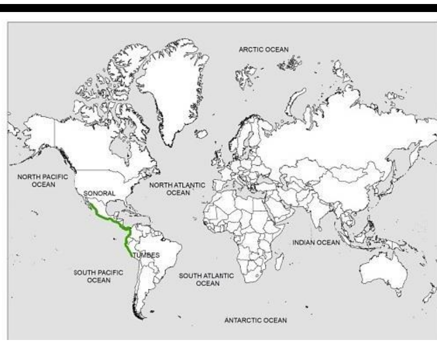

Figure 5. Natural distribution of *Penaeus vannamei*.

The average total fecundity of wild females was 2,20,000. Relative fecundity of the wild gravid females was 8,126±3,502 whereas, wild ablated females had only 1,481±863 eggs per gram body weight. The egg hatchability was 80% for wild spawners, whereas ablated spawners recorded 50-70% hatchability with a progressive reduction during successive spawning. Larval performance study indicated that zoea conversion problem was 33-58.6% and conversion of mysis to PL was about 15-27% in different stock of *P. indicus*. The average survival of postlarvae (PL12) from successful hatchery cycle of *P. indicus* was 25%, while some private hatcheries who produced the seed, reported 40-60% survival in Pl stage (personal communication). The study provides a deeper understanding of the decline of broodstock quality and hatchery performance of wild brooders through several decades. Further this study provides unique analysis of native *P. indicus* broodstock performance, which will be a reference database while developing breeding programs (Shyne Anand *et al.*, 2019).

Mitochondrial Genome of *Penaeus indicus*

The whole mitochondrial genome of Indian white shrimp has been deciphered for the first time. Phylogenetic analysis based on all protein coding genes among the shrimp species, including the sequenced *P. indicus* revealed a close relationship between banana shrimp and red-tail shrimp. This study unravelled the reclassification of genus *Penaeus*, and a full genome study at CIBA-Chennai is in advance stages of deciphering the full genome of *P. indicus*.

Advantages and Disadvantages of Indian White Shrimp, *Penaeus indicus*, over Pacific White Shrimp

The major advantage of *P. vannamei* over the native *P. indicus* is the ready availability of specific pathogen-free (SPF) genetically improved stock. However, when we evaluate the pre domesticated *P. vannamei* production with undomesticated *P. indicus*, it is indicated that Indian white shrimp outperforms exotic *P. vannamei* (Table 2). The recent studies conducted by CIBA further confirm the advantages of native *P. indicus* over exotic *P. vannamei* (Table 3).

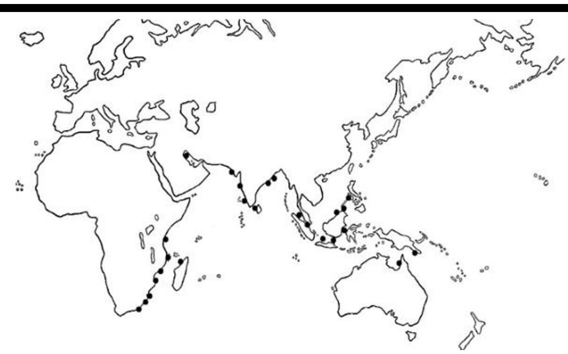

Figure 6. Natural distribution of *Penaeus indicus*.

When we evaluate both native species, *P. indicus* and exotic *P. vannamei*, there are advantages and some disadvantages, although comparatively more merits than demerits.

The Indian white shrimp, *P. indicus* is a native and promising species to consider for genetic improvement in India. Naturally, *P. vannamei* has very limited distribution in Eastern-Pacific of Central and South America, which ranges from Sonora, Mexico at Northern end to Tumbes, Peru at Southern end (Figure 5). On the contrary, *P. indicus* has a wide natural distribution in Indo-West Pacific from Eastern Africa covering through India, Malaysia and Singapore to Southern China and

Northern Australia (Figure 6). Culture trials on *P. indicus* in India during 2015-2018, yielded a harvest of about 2.5 tons per hectare, which is comparable to the harvest yield of *P. vannamei*. Being a native species of India, *P. indicus* is expected to have more adaptive capabilities and perform on par or even better than *P. vannamei*, when subjected to a selection program. Further, maturation, breeding and larval production trials on *P. indicus* showed comparable results with *P. vannamei.* Although many R&D efforts on breeding and production technology for *P. indicus* were carried out in 1980s, higher growth performance of *P. monodon* influenced farmers to opt for this tiger shrimp over the Indian white shrimp. Preference of tiger shrimp over Indian white shrimp was also due to the availability of technology in terms of feed and culture methods from foreign countries such as Taiwan, who are the pioneers in the scientific farming of shrimp. Currently, as the industry and the processing sector are comfortable with medium-sized shrimp of 12-20 g offered by *P. vannamei*, and considering all the listed advantages of *P. indicus,* it is the obvious species of choice for developing an improved variety of shrimp through selection program.

CONCLUSION

In the present context of the shrimp aquaculture scenario in India, it is worthwhile to relook into the candidate shrimp species used for aquaculture for long term sustainability of brackishwater shrimp farming. Promotion of a candidate native species for aquaculture has always been advantageous, as most of the scientific knowledge has already been generated. The present analysis indicates that native Indian white shrimp is similar to *P. vannamei* in all the aquaculture traits. In the case of *P. vannamei*, the greatest advantage, one can argue, is the ready availability of genetically selected stock. However, in the case of *P. indicus*, breeding program is the need of the hour, considering the overall benefits of genetically improved native species. This will bring in one more potential candidate shrimp species to the farming basket, and help in achieving sustainable aquaculture development in the Asian region including India.

ACKNOWLEDGMENTS

This work was supported by ICAR-CIBA through inhouse funded project (FISHCIBASIL201500200119), and National Fisheries Development Board, Hyderabad (FNO /NFDB/2113/CA/4/2013, Govt of India.

LITERATURE CITED

Ali, S.A., 1982. Effect of carbohydrate (starch) level in purified diets on growth of *Panaeus indicus*. *Indian Journal of Fisheries*, 19 (1&2), 201-208.

Clifford, H.C. and Preston, N.P., 2006. Genetic improvement. *In:* Boyd, C.E., Jory, D.E., and Chamberlain, G.W. (eds.), *Operating Procedures for Shrimp Farming*, Global Aquaculture Alliance, St. Louis, Missouri, USA, pp. 8-18.

Corbin, J.S. and Young, L.G.L., 1997. Planning, regulation and administration of sustainable aquaculture. *In:* Bardach, J.E. (ed.), *Sustainable Aquaculture,* John Wiley & Sons, New York City, New York, USA, pp. 201-233.

Diwan, A.D. and Mohamed, K.S., 2007. Neuroendocrine system. *In: Physiology of Marine Shrimp Fenneropenaeus indicus*. Narendra Publishing House, Delhi, pp. 202-225.

Diwan, A.D. and Vijayan, K.K., 2007. Moulting and growth**.** *In*: *Physiology of Marine Shrimp Fenneropenaeus indicus*. Narendra Publishing House, Delhi, pp. 59-92.

FAO, 2014. The State of World Fisheries and Aquaculture-2014 (SOFIA). Rome, Italy.

George, M.J., Mohamed, K.H., and Pillai, N.N., 1967. Observations on the paddy-field prawn filtration of Kerala, India. *FAO Fisheries Report*, 57 (2), 427-442.

Gopal, C., 1986. Nutritional studies in juvenile *Penaeus indicus* with reference to protein and vitamin requirements. Center of Advanced Studies in Mariculture, CMFRI, Cochin, Ph.D. thesis, 306 p.

Hemambika, M., 1989. Studies on the digestive enzymes of the Indian white prawn *Penaeus indicus* H. Milne Edwards. Cochin University of Science and Technology, CMFRI, Cochin, Ph.D. thesis. 276 p.

Hulme, P.E., 2015. Invasion pathways at a crossroad: Policy and research challenges for managing alien species introductions. *Journal of Applied Ecology,* 52 (6), 1418-1424.

Mohamed, K.S., 1993. Spawning congregations of Indian squid *Loligo duvauceli* (Cephalopoda Loliginidae) in the Arabian sea off Mangalore and Malpe. *Indian Journal of Marine Sciences*, 22, 172-175.

Mohamed, K.S. and Diwan, A.D., 1991a. Effect of androgenic gland ablation on sexual characters of the male Indian white prawn *Penaeus,* H. Milne Edwards. *Indian Journal of Experimental Biology*, 29, 478-480.

Mohamed, K.S. and Diwan, A.D., 1991b. Neuroendocrine regulation of ovarian maturation in the Indian white prawn *Penaeus indicus* H. Milne Edwards. *Aquaculture*, 98, 381-393.

Mohamed, K.S. and Diwan, A.D., 1992. Biochemical changes in different tissues during yolk synthesis in marine prawn *Penaeus indicus* H. Milne Edwards. *Indian Journal of Marine Sciences,* 21 (1), 30-34.

Mohamed, K.S. and Diwan, A.D., 1993. Spermatogenesis and spermatophore formation in the Indian white prawn *Penaeus indicus* H. Milne Edwards. *Journal of the Marine Biological Association of India*, 35 (1&2), 180-192.

Mohamed, K.S. and Diwan, A.D., 1994. Vitellogenesis in the Indian white prawn *Penaeus indicus* (Crustacea: Decapoda: Penaeidae). *Journal of Aquaculture in Tropics*, 9, 157-172.

Mohamed, K.S., Vijayan, K.K., and Diwan, A.D., 1993. Histomorphology of the neurosecretory system in the Indian white prawn *Penaeus indicus* H. Milne Edwards. *Bulletin of the Institute of Zoology*, 32 (1), 39-53.

Muthu, M.S. and Laxminarayana, A., 1979. Induced breeding of the Indian white prawn *Penaeus indicus*. Marine Fisheries Information Service, Technical and Extension Series No. 9, 6 p.

Muthu, M.S. and Laxminarayana, A., 1980. Induced maturation of penaeid prawns-A review. *Proceedings of the Symposium on Coastal Aquaculture*, (Cochin), pp. 16-27.

Nguyen, T.T. and De Silva, S.S., 2006. Freshwater finfish biodiversity and conservation: An Asian perspective. *Biodiversity and Conservation*, 15 (11), 3543-3568.

Panigrahi, A., 2018. *Upgradation of breeding and culture technology of Indian white shrimp* Penaeus indicus *through stock evaluation and culture demonstration*, National Fisheries Development Board, India, 175 p.

Prasad, G., 1999. Growth and production of *Penaeus indicus* in a low saline semi-intensive culture system of Kerala. *Indian Journal of Fisheries*, 46 (1), 25-32.

Primavera, J.H., 1985. A review of maturation and reproduction in closed thelycum penaeids. *Proceedings of the First International Conference on the Culture of Penaeid Prawns/Shrimps*, *Southeast Asian Fisheries Development Center*, *Aquaculture Department* (Iloilo City, The Philippines), pp. 47-64.

Rajeev Raghavan, P. and Prasad, G., 2006. A needless diversification: A perspective on the unregulated introduction and culture of the Pacific white shrimp, *Litopenaeus vannamei*, in India. *World Aquaculture*, 37 (1), 8-12.

Ravisankar, T., Geetha, R., Sairam, C.V., Vinoth, S., and Vijayan, K.K., 2018. *Aquastat India 2018*, Central Institute of Brackishwater Aquaculture, Chennai, 210 p.

Ross, L.G., Martinez Palacios, C.A., and Morales, E.J., 2008. Developing native fish species for aquaculture: The interacting demands of biodiversity, sustainable aquaculture and livelihoods. *Aquaculture Research*, 39 (7), 675-683.

Sandifer, P.A., Hopkins, J.S., Stokes, A.D., and Browdy, C.L., 1993. Preliminary comparisons of the native *Penaeus setiferus* and Pacific *Penaeus vannamei* white shrimp for pond culture in South Carolina, USA. *Journal of the World Aquaculture Society*, 24 (3), 295-303.

Shyne Anand, P.S.; Balasubramanian, C.P.; Francis, B.; Panigrahi, A.; Aravind, R.; Das, R.; Sudheer, N.S.; Rajamanickam, S., and Vijayan., K.K., 2019. Reproductive performance of wild brooders of Indian white shrimp, *Penaeus indicus*: Potential and challenges for selective breeding program. *In:* Jithendran, K.P.; Saraswathy, R.; Balasubramanian, C.P.; Kumaraguru Vasagam, K.P.; Jayasankar, V.; Raghavan, R.; Alavandi, S.V., and Vijayan, K.K. (eds.), *BRAQCON 2019: World Brackishwater Aquaculture Conference. Journal of Coastal Research*, Special Issue No. 86, pp. 65-72.

Sivakami, S., 1988. Observations on the effect of fertilizer and feed applications on the growth of *Penaeus indicus*. H. Milne Edwards. *Indian Journal of Fisheries*, 35 (1), 18-25.

Slater, M.J., 2018. Whiteleg shrimp post larvae supply in Europe: The risk of single sources of supply of fundamental Inputs. *Journal of World Aquaculture Society*, 49 (5), 802-804.

Vijayagopal, P., Babu Philip, M., and Sathianandan, T.V., 2008. Evaluation of compounded feeds with varying protein: Energy ratios for the Indian white shrimp *Fenneropenaeus indicus*. *Journal of the Marine Biological Association of India*, 50 (2), 202-208.

Vijayagopal, P., Babu Philip, M., and Sathianandan, T.V., 2009. Nutritional evaluation of varying protein: Energy ratios in feeds for Indian white shrimp *Penaeus* (*Fenneropenaeus*) *indicus*. *Asian Fisheries Science*, 22 (1), 85-105.

Vijayan, K.K. and Balasubramanian, C.P., 2016. Brackishwater aquaculture: Status, transitions and way forward. MPEDA Newsletter, pp. 27-35.

Vijayan, K.K., Balasubramanian, C.P., Alavandi, S.V., and Santiago, T.C., 2004. Introduction of exotic penaeids in India and its implications to shrimp farming and biodiversity. *In*: Abidhi, S.A.H., Ravindran, M., Venkitesan, R., and Vijayakumaran, M. (eds.), *Proceedings of Nineteenth National Seminar on New Frontiers in Marine Bioscience Research*, National Institute in Ocean Technology, Chennai, India, Allied New Delhi, pp. 117-126.

Vijayan, K.K. and Diwan, A.D., 1995. Influence of temperature, salinity, pH and light on molting and growth in the Indian white prawn *Penaeus indicus* (Crustacea: Decapoda: Penaeidae) under laboratory conditions. *Asian Fisheries Science*, 8, 63-72.

Vijayan, K.K. and Diwan, A.D., 1996. Fluctuations in Ca, Mg and P levels in the hemolymph, muscle, midgut gland and exoskeleton during the moult cycle of the Indian white prawn, *Penaeus indicus* (Decapoda: Penaeidae). *Comparative Biochemistry and Physiology*, 114 (1), 91-97.

Vijayan, K.K., Mohamed, K.S., and Diwan, A.D., 1993. On the structure and molt controlling function of the Y-organ in the prawn *Penaeus indicus*. *Journal of the World Aquaculture Society*, 24 (4), 516-521.

Vijayan, K.K., Mohamed, K.S., and Diwan, A.D., 1997. Studies on moult staging, moulting duration and moulting behaviour in Indian white shrimp *Penaeus indicus* Milne Edwards (Decapoda: Penaeidae). *Journal of Aquaculture in Tropics*, 12 (1), 53-64.