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The Biology and Culture of Mussels of the Genus *Perna*

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J.M. Vakily

Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), GmbH

International Center for Living Aquatic Resources Management

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Cover: Harvesting of *Perna viridis* from bamboo poles, Chumporn, Thailand. Photo by J.M. Vakily.

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Contents

Abstract 1

Introduction 2

Taxonomy and Geographical Distribution 4

Biology and Ecology of *Perna*
- Hydrological Factors 8
  - Depth 8
  - Salinity 9
  - Temperature 10
  - Currents 10
- Nutrients 10
- Feeding 11
- Growth 11
  - Environmental Factors 12
  - Length/Weight Relationship 14
  - Condition 15
  - Population Parameters 17
- Reproduction 19
  - Sexual Dimorphism 19
  - Gonad Development 20
  - Larval Development 20
- Predators 20
- Parasites and Diseases 21
- Pollution 21

Culture Practices
- Spat Settlement Phase 22
  - Spat Collectors 22
  - Spat Transfer 25
- Grow-Out Phase 25
  - Fixed Culture 26
    - Stakes and poles 26
    - Rope-web method 28
    - Rack method 29
  - Suspended Culture 29
    - Rafts: basic design and materials 30
    - Longline systems: basic design and materials 33
- Hatchery Techniques 35

Postharvest Handling
Live Mussels 37
Processed Mussels 38
Fresh Shucked 39
Sun Dried 39
Pickled 40
Marinated 40
Frozen 41
Smoke-Cured 41

Public Health Aspects
Bacterial Contamination 42
Paralytic Shellfish Poisoning 43
Trace Elements 43
Pollution Monitoring 44

Economics of Mussel Culture 46

Research Needs
Biology and Ecology 49
Culture Technology 49
Pollution and Diseases 50
Postharvest Handling 50
Economics 50

Prospects and Constraints 51

Policy Implications 54

Acknowledgements 56

References 56

The Biology and Culture of Mussels of the Genus *Perna*

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Abstract

In the tropics many bivalve species represent a source of inexpensive animal protein of high nutritional value. Mussels of the genus *Perna* are extensively farmed in Thailand, the Philippines and New Zealand. Experimental culture in many other countries in Asia, and to some extent also in Africa and along the Atlantic coast of Latin America, has demonstrated the good potential of this mussel as a candidate for coastal aquaculture. This review covers the biology and ecology of the three genera of *Perna*, namely *P. viridis*, *P. canaliculus* and *P. perna*. An overview is given of the technological status of culture systems with emphasis being laid on the description of advanced culture techniques such as raft and longline systems. Postharvest handling aspects for preservation of live and processed mussels are presented in detail. Finally, public health and economic aspects of the mussel culture industry are described. In general, prospects of mussel culture in tropical countries are considered good. The major constraint is the often low economic status of the mussel culture industry, hindering technological innovations and improvements in sanitary standards. This results in a poor image of mussel products, reinforcing again the economic constraints.

Introduction

In Europe, mussel culture is said to date back to the year 1235, when an enterprising Irish sailor faced the problem of surviving a shipwreck on the inhospitable shore of the southern Atlantic coast of France. He discovered that poles set out in the tidal mudflats were very attractive to mussels, and that these mussels grew much more rapidly than those living on the bottom. His discovery and further experimentation became the basis of the "bouchot" mussel culture system still practiced today in France with only slight modifications.

It was only in this century that the potential for mussel culture was extended to full-scale commercial operation. Culture activities were largely confined to Europe and based almost exclusively on the two species *Mytilus edulis* and *Mytilus galloprovincialis* (Bardach et al. 1972).

In many parts of Asia, bivalves have been long recognized as a valuable food resource. Collected from the wild or obtained as by-products from other culture operations, bivalve resources were, and still are, widely exploited at a subsistence level. Major target species are oysters (*Crassostrea* sp. reviewed by Angell 1986), cockles (*Anadara* sp. reviewed by Broom 1985), and mussels (*Perna* sp.). However, the increasing demand for food production and the alarming decrease in some of the traditional finfish fisheries has readily supported the development of commercial shellfish farming.

In 1950, the Philippines was one of the first countries outside Europe to explore the possibilities of intensive mussel culture. Mussels had in fact been present in Philippine bivalve farming for quite some time: as a "nuisance" to oyster farmers. The farmers' complaints eventually led to the "discovery" that the mussels by themselves were also a primary protein source. In 1955, the first commercial mussel farm started operation, marking the beginning of a mussel industry that has proved to be at least as lucrative as the oyster industry (Yap et al. 1979; Guerrero et al. 1983).

The only other two countries where *Perna* is being cultured on an intensive commercial scale are Thailand (Saraya 1982) and New Zealand (Cameron 1982). Table 1 gives an overview of the status of exploitation of *Perna* in various countries in the tropics and subtropics.

India is the sole country in Asia with a substantial mussel industry that is not based on culture. Its estimated annual production of 3,000 tonnes is landed by a traditional fishery exploiting natural stocks (Alagarswami et al. 1980). Production from culture is small, being limited to demonstration and technology transfer programs (Rao 1974; Silas et al. 1982).

Outside Asia (and with the exception of New Zealand) exploitation of *Perna* for human consumption is very rare. There are reports of mussels being collected from wild stocks along the South African coast (Villiers 1977; Siegfried et al. 1985), and of experiments with suspended culture of mussels in the P.R. Congo (Cayre 1981), Mozambique (Ribeiro 1984), Brazil (Brasileiro-Rafael 1982) and Venezuela (Iversen 1976).

The number of countries with experimental mussel culture (Table 1) clearly demonstrates a broad interest in mussel culture in the Asian and Pacific region. Extraordinary growth performance, natural abundance, adaptability to new environments and fairly simple culture

Table 1. Exploitation of mussels of the genus *Perna*.

Country	Species	Method of exploitation	Status of culture	Authority
Brunei	*P. viridis*	raft	experimental	Beales and Lindley (1982)
Fiji	*P. viridis*	raft, racks	experimental	Navakalomana (1982)
India	*P. viridis*	artisanal fishery, raft	experimental	Narasimham (1980)
India	*P. indica*	artisanal fishery, raft	experimental	Appukuttan and Nair (1980)
Indonesia	*P. viridis*	subsistence fishery; raft, stakes	experimental	Unar et al. (1982)
Malaysia	*P. viridis*	raft	experimental	Ng et al. (1982)
Philippines	*P. viridis*	poles, stakes	highly developed	Young and Serna (1982)
Singapore	*P. viridis*	raft	small-scale	Cheong (1982)
Tahiti	*P. viridis*	racks and iron bars	experimental	Coeroli et al. (1984)
Thailand	*P. viridis*	poles, stakes	highly developed	Saraya (1982)
Brazil	*P. perna*	raft	small-scale	Brasileiro-Rafael (1982)
Mozambique	*P. perna*	longline	experimental	Ribeiro (1984)
P.R. Congo	*P. perna*	raft	experimental	Cayre (1981)
South Africa	*P. perna*	artisanal fishery	-	Siegfried et al. (1985)
Venezuela	*P. perna*	raft	small-scale	Iversen (1976)
New Zealand	*P. canaliculus*	raft, longline	highly developed	Hickman (1987)

techniques make *Perna* appear well suited to become the principal shellfish crop in many of these countries.

In order to help governments to assess potential and limitations of mussel culture in their coastal waters, exchange of information and interaction between scientists involved in bivalve culture is needed. This review is an attempt to summarize the present state of knowledge on the biology and culture of *Perna*. It might appear that little has been published on this subject compared to the wealth of literature that exists for *Mytilus* or other bivalve families, such as oysters. It is, however, very likely that especially in Southeast Asia much valuable information exists, which is not readily available to the international scientific community, because it forms part of the so-called "gray" literature. This review, therefore, is also meant to encourage scientists to present their findings concerning the biology and culture of *Perna* in order to fill the gaps of knowledge still existing in this vast field.

Taxonomy and Geographical Distribution

Many representatives of the family Mytilidae are exploited commercially worldwide; those belonging to the genera *Mytilus* and *Perna* have proven very successful in mollusc culture. However, for a long time the taxonomic status of these two species has been confused, chiefly because of the general variability in the morphological features of Mytilids. Siddall (1980) has to be credited for finally bringing clarification into the general systematics and geographical distribution of *Perna*. His historical review which is partly summarized in Table 2 clearly reflects the general confusion that has reigned in the literature dealing with *Perna*. The most common synonyms for *P. viridis* were *Mytilus smaragdinus* and *Mytilus viridis*.

It might be of some consolation to the many authors who became caught in the taxonomic jumble to know that the confusion over *Perna* extends far back into the history of natural science. The Roman author Pliny is reported to have used the common Latin name *"Perna"* (which means "ham") to describe a species that is now the well-known *Pinna* (Cotte 1944).

The major characteristic by which the adults of *Perna* and *Mytilus* can be distinguished is the pattern of the scars left at the area of muscle attachment on the shell (Fig. 1). In *Mytilus*, the

Table 2. Taxonomy of *Perna* species: summary of synonyms (source: Siddall 1980).

	Perna viridis (Linnaeus) 1758	
1758	*Mytilus viridis*	Linnaeus, Syst. Nat., Ed. X
1785	*Mytilus smaragdinus*	Chemnitz, Conch. Cab. VIII
1819	*Mytilus opalus*	Lamarck, Anim. s. Vert. VI
1855	*Mytilus viridis* L.	Hanley, Ipsa Linn. Conch.
1936	*Mytilus (Chloromya) viridis* L.	Lamy, Rev. Mytilidae, J. Conchyl. LXXX
1950	*Mytilus viridis* L.	Suvatti, Fauna Thailand
1952	*Chloromya viridis* L.	Dodge, Bull. Amer. Mus. Nat. Hist., 100
1968	*Mytilus viridis* L.	Cheriyan, Symp. Mollusca 3
1974	*Perna viridis* L.	Dance, Encyc. of Shells
	Perna perna (Linnaeus) 1758	
1758	*Mya perna*	Linnaeus, Syst. Nat., Ed. X
1780	*Mytilus pictus*	Born, Test. Mus. Caes. Vindob.
1785	*Mytilus africanus*	Chemnitz, Conch. Cab. VIII
1791	*Mytilus afer*	Gmelin, Syst. Nat., Ed. XIII
1819	*Mytilus perna* L.	Lamarck, Anim. s. Vert. VI
1919	*Mytilus (Chloromya) perna* L.	Lamy, Bull. Mus. Hist. Nat. XXV
1952	*Chloromya perna* L.	Dodge, Bull. Amer. Mus. Nat. Hist., 100
1955	*Perna perna* L.	Soot-Ryen, Allan Hancock Pac Exped. 20(1)
1965	*Mytilus (Chloromya) venezolanus*	Andreu, Inst. Invest. Pesq. Barcelona 5
1969	*Perna picta picta* (Born)	Nordsieck, Die Europäischen Miesmuscheln
1976	*Perna (Perna) picta* (Born)	Buccheri and Palisano, Conchiglie 12
	Perna canaliculus (Gmelin) 1791	
1784	*Mytilus canaliculus*	Martyn, Univ. Conch. II
1785	*Mytilus latus*	Chemnitz (non Lamarck), Conch. Cab. VII
1791	*Mytilus canaliculus*	Gmelin, Syst. Nat., Ed. XIII
1873	*Mytilus smaragdinus*	Hutton (non Chemnitz), Cat. Mar. Moll.
1959	*Perna canaliculus* Martyn	Fleming, Trans. Roy. Soc. N. Zealand 87

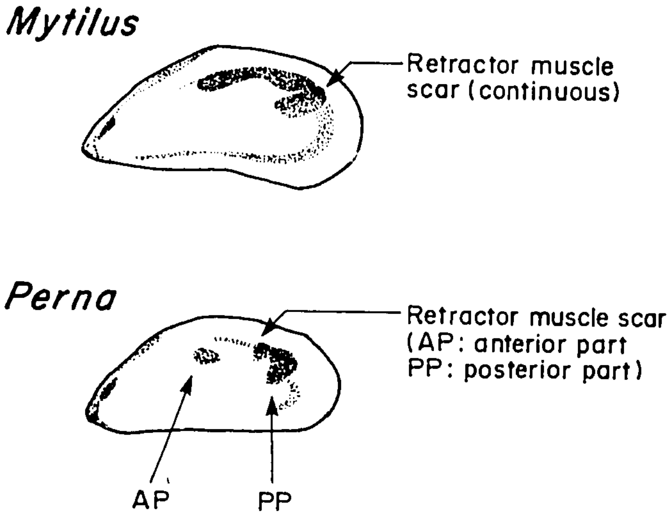


Fig. 1. Differences in muscle scar pattern on right valves of *Mytilus* and *Perna* (after Siddall 1980, modified).

anterior and posterior components of the retractor muscle are united forming a continuous band of myostracum along the dorsal margin of the pallial line. In contrast, these two components attach separately on the shell in *Perna,* resulting in a discontinuous muscle scar (Siddall 1980).

Another less clear characteristic that distinguishes the adult *Perna* from at least *M. edulis* is the anterior adductor muscle which is present, although small in *Mytilus* but absent in all *Perna* species (Siddall 1980).

Differentiation of the juveniles of the two genera requires more elaborate techniques such as the examination of the structure of the hinge line with a scanning electron microscope. Siddall (1980) investigated the development and fate of lateral hinge teeth. He states that "the presence of lateral hinge teeth which develop after metamorphosis are unique and consistent criteria for distinguishing juvenile mussels of the genus *Perna*" from those of the genus *Mytilus,* where these "primary" lateral hinge teeth are missing.

Siddall (1980) lists three species belonging to the genus *Perna: P. viridis, P. canaliculus* and *P. perna.* He concedes that the three species can hardly be differentiated other than by their geographical distribution (see below). Outer appearance of the shell is of little taxonomic value because "variations in shell coloration and patterns are considerable in all material; however, light colored zigzag markings are most common in young *P. canaliculus* specimens. *P. perna* adults are typically brown to red-maroon with irregular areas of light brown and green. Brilliant green and blue-green predominate in *P. viridis* juveniles, while adult shells are less brilliant and have a greater proportion of brown" (Siddall 1980). Martinez (1967) discusses a method of indirectly identifying mussel larvae and gives a description of the larvae of *P. perna* in order to differentiate it from other bivalve larvae found off the Venezuelan coast. Late stages of the larvae of *P. canaliculus* and their seasonal occurrences in the plankton are described by Booth (1977) and set in comparison to larvae of other Mytilids found in New Zealand waters.

An apparent exception to the taxonomic scheme presented by Siddall (1980) is a "brown mussel" found confined to a limited area around the southern tip of India (Rao 1974; Kuriakose 1980a; Appukuttan and Nair 1980; Silas et al. 1982), which Rao (1974) referred to simply as *Mytilus* sp., and was later described as *Perna indica* (Kuriakose 1980a). Though no proof exists, there is some evidence that this species might actually be *Perna perna.* Given the difficulty of reliably distinguishing *P. viridis* from *P. perna* because of the great morphological variation within the genus *Perna* (Siddall 1980), it is interesting to note that the major characteristics listed by Kuriakose (1980a) to differentiate *P. indica* from *P. viridis* are identical with those given by Siddall (1980) to distinguish *P. perna* from *P. viridis*. These are: shape and external coloration (brown vs. green) of the shell and the existence of enlarged sensory papillae (Siddall 1980) or tentacles (Kuriakose 1980a) along the mantle margins which are absent in *P. viridis*. A further indication that *P. indica* might actually be *P. perna* is its restricted distribution along the southern tip of India just opposite and in close geographical proximity to Sri Lanka where *P. perna* is reported to occur naturally (Sadacharan 1982).

Another species of the family Mytilidae sometimes confused with *Perna* is the brown mussel of the genus *Modiolus*. Even though widely distributed in the Indo-Pacific region, it is considered unsuitable for farming as it is not known to attach to the usual culture substrates such as ropes or bamboo, but lives in dense mats on the muddy bottom (Yap et al. 1979).

As mentioned previously, the geographic distribution of *Perna* has - to a certain extent - taxonomic value, since the three species have nonoverlapping geographic ranges (Fig. 2). The only exception to this is the occurrence of *P. perna* together with *P. viridis* in Sri Lanka (Sadacharan 1982).

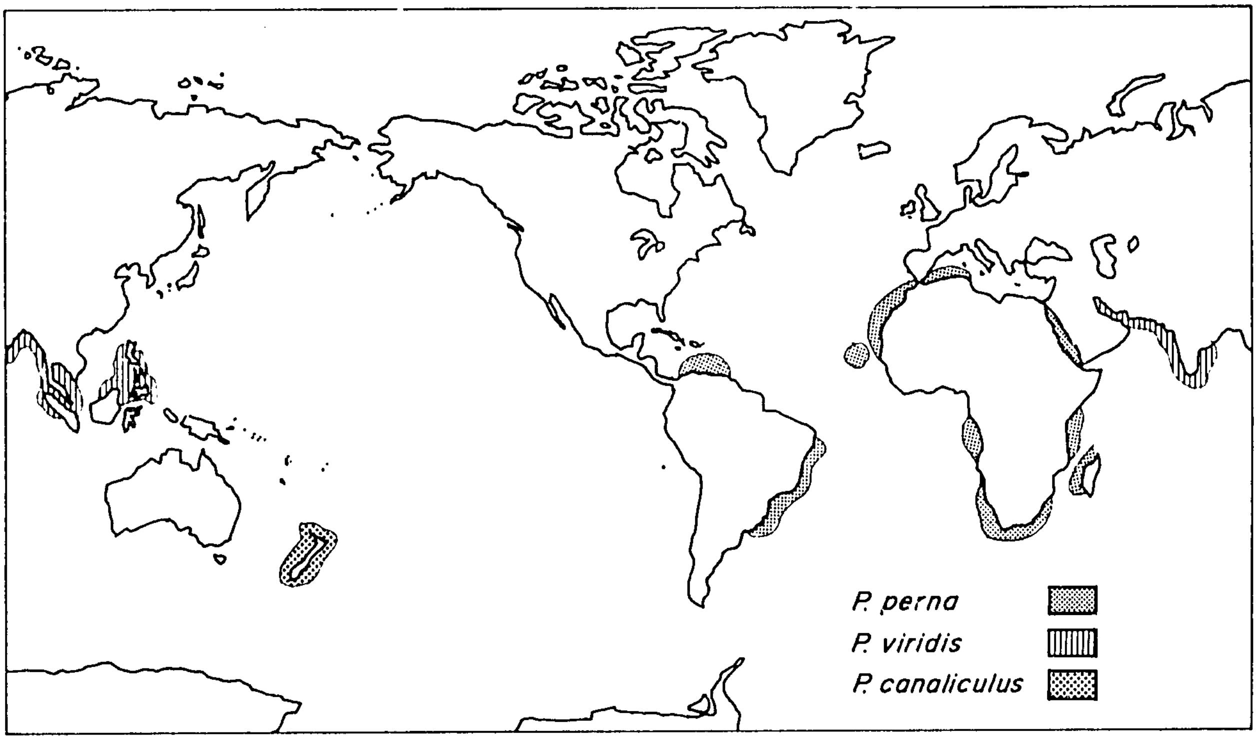


Fig. 2. Geographic distribution of the three species of the genus *Perna* (updated from Siddall 1980).

P. canaliculus, the "green-lipped mussel", is restricted to New Zealand. The "green mussel", *P. viridis*, is widely distributed throughout the Indo-Pacific area, extending to the north as far as Hong Kong (Lee and Morton 1985), the southern provinces of Guangdong and Fujian in China (Zhang 1984; Cai and Li 1986) and southern Japan (Habe 1976). The east-west distribution ranges from the Persian Gulf to the Indonesian coast west of New Guinea (Siddall 1980), and to some of the Pacific islands, where *P. viridis* has been experimentally introduced (AQUACOP and de Gaillande 1979; Coeroli et al. 1984; Glude 1984). Beside the already mentioned occurrence of *Perna perna* in Sri Lanka (Sadacharan 1982), the major area of distribution of the "brown mussel" is along the coasts of the African continent (Siddall 1980) up to Morocco (Shafee 1989) and in South America where it occurs in Venezuela (Chung and Acuña 1981) and along the Atlantic coast from Recife, Brazil, to the Rio de la Plata (Siddall 1980). Siddall (1980) also mentions reports of *P. perna* being found along the coasts of Argentina even as far south as the Straits of Magellan, but leaves this open to question.

Biology and Ecology of *Perna*

The natural habitats of *Perna* are littoral and sublittoral waters that are rich in plankton and organic matter and carry low loads of suspended sediments (Bardach et al. 1972; Korringa 1976).

Because of its capability to adapt to a wide range of different environmental conditions, *Perna* is found both in brackish estuaries and in open, though not very exposed, waters. The mussel attaches itself by means of byssal threads to a large variety of substrata, such as rocks, stones, piers, dead shells and even compact mud or sand. Mangrove mudflats represent a major potential habitat for the tropical mussel (Macintosh 1982). In contrast, lagoons and bays with primarily oceanic seawater - as is typical of most of the Pacific islands - are considered inadequate for mussels because of the poor nutrient content of the water (Glude 1984; Coeroli et al. 1984).

Hydrological Factors

DEPTH

As for most species whose biotope extends into the intertidal zone, the upper limit of the vertical distribution of *Perna* is defined by its ability to survive physical stress, caused by desiccation and reduced filtering time (Lee 1985a). The energy requirement of basal metabolism is probably the principal limiting factor (Baird and Drinnan 1957). With increasing water depth, light penetration plays a major role in limiting the mussels' lower limit of vertical distribution, as the loss in light intensity causes a general reduction in food availability.

Tan (1975b) investigated the settlement of *P. viridis* on stationary coconut coir ropes that were suspended from wooden poles and reached 12 m down to the sea bottom. He found that spat settled at all levels between 1.5 m and 11.7 m below High Water Spring Tide (HWST), and were absent only at the upper intertidal levels and immediately above the sea bottom. Settlement started at a water depth about half way between HWST and LWST (Low Water Spring Tide) where the mussels remained submerged for about 60% of the time (Fig. 3). However, settlement density was not evenly distributed over the depth range. Fig. 3 shows a distinct pattern that is dependent on two factors with opposite trends: percentage of time the spat remains submerged, and water depth. Only limited settlement occurred at depths with less than 80% submersion. Peak of settlement occurred at shore levels where the spat remained submerged almost constantly (98% submersion). Settlement density then decreased significantly with increasing water depth. Similar ranges were observed by Yang (1970) and Lee (1985a).

Investigating the settlement of *P. viridis* in raft culture, where exposure is practically excluded, Cheong and Chen (1980) reported a similar tendency of the spat to settle more densely on the upper 2 m of the culture ropes with a (nonlinear) decrease in spat density at greater depths. The settlement distribution pattern is related to the survival of the spat at the higher shore levels. Tan (1975b) showed that duration of submersion had a crucial impact on the survival of

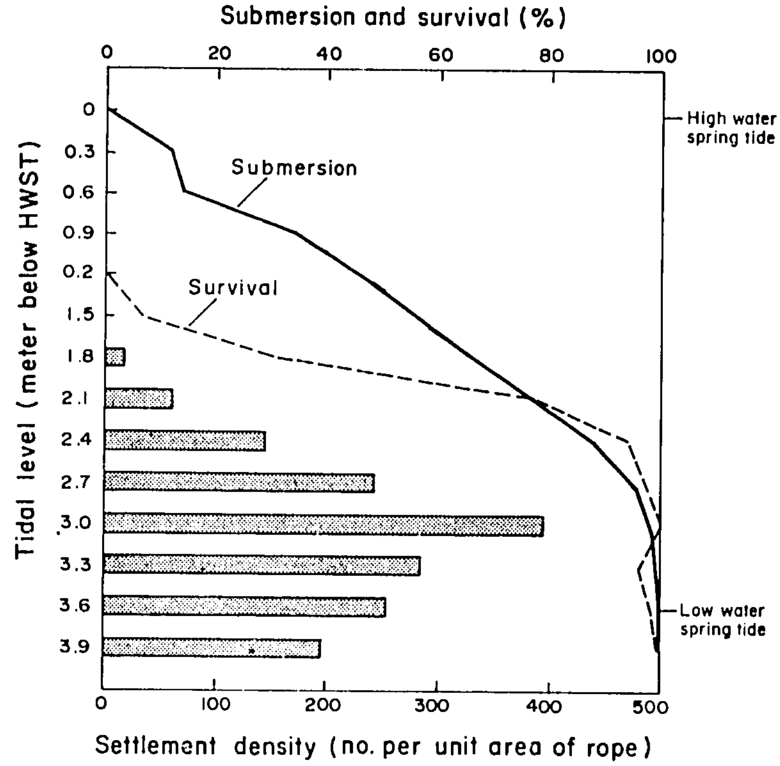


Fig. 3. Settlement density and survival of *Perna viridis* spat on fixed ropes in relation to tidal level and duration of submersion (adapted from data of Tan 1975b).

spat of *P. viridis* (Fig. 3). The mortality rate rose dramatically from around 10% to almost 100% within the 1 m above the optimum settling depth. On the other hand, with increasing water depth the availability of food becomes a factor limiting settlement since the phytoplankton on which the mussel spat feed tends to aggregate near the surface. (Dietrich et al. 1980). Cheong and Chen (1980) also reported that the planktonic larvae of *P. viridis* were most abundant near the water surface. Johns and Hickman (1985) found that the larvae of *P. canaliculus* in New Zealand had a preference for settlement in the depth range 2-5 m, independent of the actual distribution of the larvae in the water column. This somewhat larger range of spat distribution - compared to *P. viridis* - is also substantiated by the findings of Meredyth-Young and Jenkins (1978) who could not trace any depth preference in the settlement of *P. canaliculus* on suspended ropes of 4 m length. It most probably reflects the fact that the eutrophic zone of the waters around New Zealand extends to a greater depth than in most tropical waters.

SALINITY

Perna seems to tolerate fairly well large fluctuations in salinity. The salinity of the natural estuarine habitats of *P. viridis* usually ranges from 27 to 33 ppt (Korringa 1976; Sivalingam 1977; Lee 1985a). This is well within the lower and upper tolerance limits reported by Sivalingam (1977) who found 50% survival of *P. viridis* after two weeks exposure at salinities of 24 ppt and 80 ppt, respectively. *P. perna* can adapt well to salinities ranging from 19 to 44 ppt. Lower salinities will affect survival (Salomao et al. 1980). AQUACOP and de Gaillande (1979) considered the optimum salinity for *P. viridis* to be 30 ppt but it will survive salinities as low as 20 ppt, which can occur after heavy monsoon rainfalls (Korringa 1976) for short periods of time.

Salinity below 5 ppt is lethal to *P. viridis* if exposure exceeds two days (Coeroli et al. 1984). Huang et al. (1985) also mention this salinity level to be the major factor limiting the distribution of *P. viridis* in Hong Kong waters.

TEMPERATURE

Apart from a few exceptions, *Perna* lives - in contrast to its cold-water relative *Mytilus* - in an environment characterized by a rather uniform water temperature ranging from 26-28°C during winter to 31-32°C in summer (Korringa 1976; Sivalingam 1977; Chonchuenchob et al. 1980).

Investigating upper and lower limits of temperature tolerance of *P. viridis*, Sivalingam (1977) reported 50% survival at 10°C and 35°C, respectively. Chung and Acuña (1981) tested the upper temperature tolerance limits of *P. perna* under different heating rates. They found that in general the mussels survived rapid temperature increase better than slow heating rates, with 50% survival at 37-42°C, depending on the size of the mussel. Though such extreme temperatures will hardly occur under natural conditions, these upper temperature limits may be relevant to the culture of *Perna* on trays in shallow ponds where temperatures might reach 40°C (AQUACOP and de Gaillande 1979; Coeroli et al. 1984).

CURRENTS

Good water exchange is a necessary prerequisite for mass culture of *Perna* (Yap et al. 1979; Cheong and Lee 1984). It plays a crucial role in providing the mussel with food. Currents are important in respect to the distribution of the larvae and in controlling the excessive build-up of pseudofaeces and silt in the culture area.

Cheong (1982) indicates that suitable currents for culturing green mussel are 0.17-0.25 m/s at flood tide and 0.25-0.35 m/s at ebb tide. Currents of more than 0.5 m/s negatively influence spat settlement and food availability. It also can lead to mooring problems in floating culture systems (Johns and Hickman 1985).

Nutrients

Glude (1984) stressed the point that successful mollusc culture requires careful site selection. Based on his experience in the Pacific islands, he noted that tropical waters often are so low in nutrients that there is insufficient phytoplankton to support mollusc farming. Waters reserved for mussel culture should, therefore, exhibit a net primary production of 27-100 µg C/m^3/hour. Such areas are typically bays, estuaries or large landlocked water bodies like the Gulf of Thailand that receive enough nutrients from land run-off to promote adequate growth of phytoplankton. A further possibility would be a coastal area with a natural upwelling system that brings nutrient-rich deep oceanic water to the surface.

Cheong (1982) reports suitable phytoplankton concentration for green mussel culture of 17-40 µg chlorophyll a per liter seawater. However, even 5.2 to 3.5 µg chlorophyll/l was considered sufficient for green mussel culture in Malaysia (Sivalingam 1977). In Tahiti, an average phytoplankton concentration of 10^4 cells/ml supported a rapid growth of *P. viridis* (AQUACOP and de Gaillande 1979).

Feeding

Perna is a ciliary-mucoid filter feeder. It has 4 rows of gills which serve as both respiratory organ and filter-feeding apparatus. Gill structure and morphology of the digestive system of *Perna* are very similar to that of *Mytilus* which has been extensively reviewed by Bayne et al. (1976).

Perna feeds on phytoplankton, zooplankton and detritus (Korringa 1976; Sivalingam 1977; Yap et al. 1979). Berry and Schleyer (1983) investigated the filtration rate and efficiency of *P. perna* and found it was able to retain particles down to at least 0.46 μm in diameter.

The suggestion by Sivalingam (1977) that *P. viridis* is a selective feeder seems doubtful since the only species he found in the stomach *(Coscinodiscus nodulifer)* was also the major species (99%) present in the waters where the mussels were raised.

Growth

Growth is probably the most important aspect of mussel biology to the mussel farmer for assessing the success of his culture system. Most markets demand a certain size mussel to achieve optimum price. It is, of course, in the interest of the farmer, that his mussels reach this "marketable size" in the shortest possible time, since additional culture increases operational costs and risk of losses.

Growth of *Perna* is most commonly measured as increase in length. "Length" in this context is the maximum distance along the anterior/posterior axis of the animal (Fig. 4). Increase in weight might be of equal interest in describing growth, but recording of length data is usually easier and causes less stress to the animals in field experiments where the animals are allowed to continue growing after measurements are taken. Hickman (1979) tested the effect of taking regular length measurements on the growth rate of *P. canaliculus*. He found a slight tendency

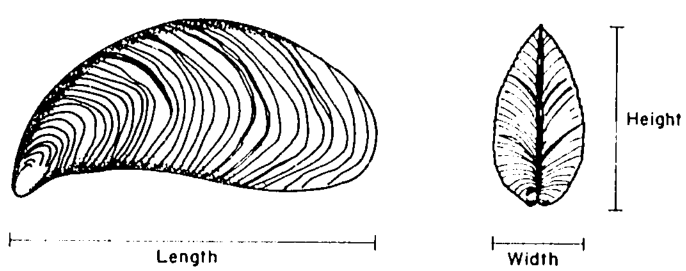


Fig. 4. Definition of shell dimensions in *Perna*.

towards higher growth on control ropes which were not disturbed for regular measurements, but concluded that the handling procedure did not produce biologically significant differences in growth.

Perna has a generally better growth rate than its cold-water relative *Mytilus* because of its predominantly tropical distribution, where elevated water temperatures and less prominent seasonality in food supply favor continuous growth throughout the year. Under average culture conditions, *Perna* can attain a length of 70-80 mm in the first year, and 110-120 mm in the second year. This compares well with average lengths of 40 mm and 70 mm for one- and two-year-old *Mytilus* edulis in Europe (Seed 1976). Impressive growth rates in *Perna* were reported from Singapore (Cheong and Chen 1980), where *P. viridis* cultured on experimental ropes increased in length at a rate of 10.6 mm per month during the first six months. Growth rates from various locations are summarized in Table 3.

Table 3. Growth rates for different species of the genus *Perna* (compiled from published data).

Location	Investig. size range (mm)	Average growth per month (mm)	(g)	Temp. (°C)	Remarks	Authority
				Perna viridis		
Brunei	20-100	9.0	8.6	-	rope	Beales and Lindley (1982)
Brunei	20- 67	5.2	2.2	-	rope, polluted waters	Beales and Lindley (1982)
Hongkong	32- 74	8.3	-	20-31	rope, summer growth	Lee (1986)
Hongkong	32- 86	4.4	3.5	12-31	rope	Lee (1986)
Hongkong	32- 86	2.3	1.9	12-31	cage	Lee (1986)
India, Goa	14- 86	7.2	4.2	26-30	rope	Parulekar et al. (1982)
India, Goa	5-107	5.0	-	25-30	rope	Parulekar et al. (1984)
India, Goa	8- 89	7.4	-	28-32	rope, in tanks	Chatterji et al. (1984)
Malaysia, Johore	20- 70	8.3	-	-	rope	Choo (1983)
Malaysia, Penang	30- 48	6.7	-	29-30	net cage	Sivalingam (1977)
Malaysia, Penang	18- 78	5.7	3.8	-	plastic cage	Choo and Speiser (1979)
Philippines	0- 70	8.8	-	25-30	rope	Walter (1982)
Philippines	> 70	6.5	-	25-30	rope	Walter (1982)
Singapore	3- 72	10.6	2.0	-	rope, "thinning-out"	Cheong and Chen (1980)
Tahiti	0- 70	9.7	2.5	27	rope	AQUACOP and de Gaillande (1979)
Thailand, upper Gulf	21- 57	5.9	1.3	28-33	rope	Choi chuenchob et al. (1980)
Thailand, upper Gulf	44- 73	6.1	-	-	pole, 1st-yr growth	Tuaycharoen et al. (1988)
Thailand, upper Gulf	73- 91	2.2	-	-	pole, 2nd-yr growth	Tuaycharoen et al. (1988)
Thailand, upper Gulf	56- 96	4.2	-	-	net cage	Vakily, unpublished data
				Perna canaliculus		
New Zealand, north	16- 80	5.0	3.3	18.1	rope	Hickman (1979)
New Zealand, south	24- 50	2.3	0.7	12.2	rope	Hickman (1979)
New Zealand, Te Kaha	1-110	5.1	-	13-24	rope	Johns and Hickman (1985)
New Zealand, Te Kaha	49- 80	2.1	-	13-24	cage	Johns and Hickman (1985)
				Perna perna		
Mozambique	-	7.0	-	-	-	Ribeiro (1984)
South Africa	0- 75	6.3	-	-	bottom, subtidal	Berry (1978)
Venezuela	3- 81	4.5	-	21-30	asbest collector	Carvajal (1969)
Venezuela	26-110	4.6	-	24-28	rope	Acuña (1977)

ENVIRONMENTAL FACTORS

The considerable fluctuations in recorded growth rates indicate that the mussels' growth is the result of the combined effects of a number of environmental factors, such as water temperature, availability of food, setting density, currents, exposure, and pollution. Because of the obvious complexity of the influence of multiple factors, it appears difficult to quantify the apparently existing relationships between growth and environmental factors (Wilbur and Owen 1964).

The effect of temperature on the growth of *Perna* has been investigated in a number of field experiments in areas with marked seasonality in water temperature, primarily in Hong Kong and New Zealand, which represent geographical extremes of the north-south distribution of *Perna*.

Lee (1986) reported a rapid growth of *P. viridis* from August to December in Hong Kong waters. This was followed by a three-month period of much reduced growth, during which water temperature ranged between 20° and 12°C. Growth resumed in April when the water temperatures exceeded 20°C. Using a graphic method, he estimated 17°C to be the lower temperature threshold for the growth of *P. viridis* in Hong Kong.

Similar influence of temperature on growth was observed in *P. canaliculus* from New Zealand, both in terms of absolute size and seasonal changes in growth rate during the course of a year. Hickman (1979) compared mussels grown on ropes at various locations throughout the country. Those grown in the north with a mean water temperature of 17-18°C increased twice as much in length as those grown in the south, where the mean water temperature was only 12°C. In addition, growth rate was, at least in the first year of culture, closely related to water temperature.

Growth data for *P. perna* from the northern coast of Venezuela show a clear decrease in growth during the months November to January (Acuña 1977), which is usually the period of lower water temperature (Salaya et al. 1977).

It has been demonstrated for *Mytilus edulis* and various other mussel species that growth is inversely related to age, and, hence, initial size (see review by Jorgensen 1976). This explains why attempts to relate growth and temperature usually fail to produce convincing results once the mussels have reached a size of approximately 60-70 mm (Hickman 1979; Lee 1986). The relationship between growth and temperature becomes increasingly veiled by the influence that size has on growth increments. *P. canaliculus* from the northern part of New Zealand reached on average a length of 73 mm (= 6.1 mm/month) in the first year and 113 mm at the end of the second year. This represents a growth rate of only 3.3 mm per month in the second year of culture (Hickman 1979). *P. viridis* grown in the Gulf of Thailand with its uniform water temperature throughout the year showed the same tendency of reducing its growth rate in the second year to about half that of the first year (Tuaycharoen et al. 1988).

Accessibility to food plays as important a role on the growth of *Perna*, as it does for *Mytilus* (Boje 1965). Hickman (1979) observed better than expected growth rates in *P. canaliculus* at two locations in New Zealand, where high nutrient contents of the water due to domestic wastes probably offset the effects of low water temperature. Velez and Epifanio (1981) found the growth of *P. perna* to be positively correlated with food availability at 21°C and 28°C, while effects of temperature and interaction of temperature and ration were insignificant. Qasim et al. (1977) investigated the growth of *P. viridis* raised in natural beds and on ropes off Goa, India. They reported a minimum growth rate for length during monsoons, which coincided with relatively low phytoplankton concentrations.

The importance of nutrient availability is also evident in the observation that raising *Perna* in cages usually results in a noticeable reduction in growth rate when compared to mussels grown on culture ropes in the same area (Johns and Hickman 1985; Lee 1986). It is likely that the limited water flow within the cages leads to reduced nutrient supply and accumulation of faeces. In growth experiments with marked animals, *P. canaliculus* averaged only 2.1 mm increase in length per month when grown in cages, while rope-grown mussels of similar initial size achieved a growth of 5.4 mm per month during the same period (Johns and Hickman 1985).

The same striking difference in growth rate can be observed when comparing the increase in size of mussels grown in suspended culture with mussels from intertidal banks. Hickman (1979) showed that *P. canaliculus* under intertidal conditions only gained 2.5 mm per month in the first year, compared to 6.0 mm per month for mussels raised on ropes. *P. viridis* in India recorded an average growth of 5 mm per month as against 8 mm per month on ropes (Qasim et al. 1977). Limited food supply due to overcrowding or exposure have to be considered the main factors for the obvious decrease in growth efficiency of wild populations. Shafee (1976a) showed in controlled experiments with *P. viridis* that the rate of oxygen consumption increased significantly during exposure to air. This effect continued even into the post-exposure period. The author reported that it took the mussels another 1.5 hours to reach metabolic normalcy equal to that of nonexposed mussels.

LENGTH/WEIGHT RELATIONSHIP

The length/weight relationship in *Perna* has been investigated by a number of authors (Shafee 1976b; Hickman 1979; Cheong and Chen 1980; Parulekar et al. 1982; Lee 1986). The objective is to obtain the necessary constants that allow the transformation of length into weight, a dimension that - for previously mentioned reasons - is usually more difficult to measure in growth experiments. With the parameters of the length/weight relationship known and sufficiently reliable information available on numbers of mussels per unit of culture area, estimates of potential yield of marketable size mussels in terms of weight can be attempted.

The allometric relationship between length and weight is usually described by the equation

$$W = aL^b \qquad \text{... 1)}$$

where W and L are measures of weight and length respectively, while "a" and "b" are constants. In its linearized transformation, Equation 1) becomes

$$\log_{10}W = \log_{10}a + b \log_{10}L \qquad \text{... 2)}$$

In this form, the least-square regression technique can be applied to determine the constants "a" and "b". It should be noted that the logarithmic transformation introduces a systematic bias which requires the constant "a" to be multiplied with a correction factor (see Sprugel (1983) for the computational procedure and Vakily et al. (1988b) for more detailed information).

Length/weight relationships are an important factor in growth and production comparisons. Like many other bivalve species, mytilids are known to display large phenotypic plasticity in shell dimensions under different environmental conditions (Seed 1968; Lee 1986). Hickman (1979), for example, compared raft-grown mussels with those of a wild, intertidal population of *P. canaliculus*. He found differences in both the length/width and the length/weight relationships. Mussels from the wild were in general slightly heavier per unit length because of thicker shells. Mussels transferred from the wild population to ropes gradually changed dimensions from the shore-grown to the raft-grown form. He speculated these differences to be density-dependent.

Lee (1986), therefore, is right in cautioning against the exclusive use of shell length as a measure of growth and, hence, production. He emphasizes that "mussels growing at a high linear rate are not necessarily more productive, i.e., they do not always achieve higher overall (shell plus soft tissue) growth". This is clearly demonstrated in the variation of "W_{70}" (Table 4), which is the computed (theoretical) weight of a mussel at a common marketable size of 70 mm, if it had grown in accordance with the corresponding coefficients "a" and "b" of the length/weight relationship.

Table 4. The coefficients "a" and "b" of the allometric length/weight relationship in Perna from various locations (compiled from published data)

Species	Location	a	b	W_{70}[1] (g)	Unit of length measurement	Authority
P. viridis	Hong Kong	1.12E-03	2.37	26.43	mm	Lee (1985a)
	India, Goa	5.13E-04	2.50	21.03	mm	Parulekar et al. (1982)
	India, Kakinada Bay	1.63E-04	2.86	30.84	mm	Narasimham (1981)
	Malaysia, Penang	2.22E-04	2.76	27.47	mm	Choo and Speiser (1979)
	Singapore	9.81E-02	2.79	22.36	cm	Cheong and Chen (1980)
	Thailand, upper Gulf	7.07E-02	2.78	15.80	cm	Chonchuenchob et al. (1980)
	Thailand, upper Gulf	2.22E-04	2.70	21.29	mm	Vakily et al. (1988b)
P. canaliculus	New Zealand, Ahipara	2.14E-04	2.80	31.38	mm	Hickman (1979)

[1]Computed weight of a mussel of 70-mm length.

Table 4 lists coefficients of the length/weight relationship in *Perna* derived from various sources in the literature. Values of "b" commonly range between 2.5 and 2.8. The only distinct exception to this is a value of b = 1.3007 for *P. viridis* given by Chatterji et al. (1984). Judging, however, from the graph presenting the computed length/weight relationship, this extreme value might actually be a typographic error.

All authors used "TOTAL WEIGHT" as the unit of recorded weight. In bivalves, however, total weight tends to be a somewhat imprecise variable. Most bivalves, and mytilids are no exception, will retain a certain amount of water within their shells when collected for measuring. This "cavity water", which can represent 40-50% of the total weight in *P. viridis* (Vakily et al. 1988b), gradually seeps out of the shell, thus introducing a methodological error the magnitude of which depends on the time elapsed between removal of the mussels from the water and the actual weighing. Vakily et al. (1988b) concluded that a unit "FLESH & SHELL" - which is the weight of the mussel with the cavity water drained off - would best serve as a standard unit of weight.

Table 5 summarizes the relationship between length and various weight units in *P. viridis* as presented by Vakily et al. (1988b). If "total weight" includes the cavity water, the value of "b" is 2.70. If, on the other hand, the weight only includes shell and flesh, the value of "b" decreases to 2.55. This range is quite similar to the one presented in Table 4, thus indicating that the differences in the observed values of "b" might primarily originate from differences in sampling procedure.

Table 5. Length/weight relationships of *Perna viridis* (adapted from Vakily et al. 1988b).

Function			$Y = a \cdot X^b$		
X-variable:	Length	Length	Length	Length	Length
Y-variable:	Wt. total	Wt. flesh + shell	Wt. flesh wet	Wt. shell	Wt. flesh dry
a	2.22 E-4	2.41 E-4	2.17 E-4	0.69 E-4	0.89 E-4
b	2.70	2.55	2.37	2.72	2.18
S_b	0.0196	0.0250	0.0349	0.0274	0.0465
S_y	0.0552	0.0701	0.0986	0.0764	0.1315
r^2	0.916	0.856	0.725	0.850	0.555
n	1744	1747	1754	1743	1754

Authors testing the growth of *Perna* for isometry (Hickman 1979; Vakily et al. 1988b) found "b" to be significantly different from 3 in all cases that involved "length" as unit of size. Vakily et al. (1988b) reported, however, a "b" of 2.98 ($r^2 = 0.905$, n = 1744) for the relationship height and total weight (i.e., shell + flesh + cavity water), which was not significantly different from 3 (P = 0.01).*

CONDITION

Mussel culture production based on "total weight" might be of limited use for estimating meat yield, when looking at it in terms of food or nutritional value. The wet or dry weight of the mussel meat, for example, reflects much better the mussel's general "condition". Vakily et al. (1988b) showed that on an average the wet and dry meat of *P. viridis* made up 24-41% and 4-8% of total weight respectively, depending on which unit is selected as total weight (Table 6).

* Since this review was prepared, a study on length-weight relationships in *P. viridis* from Xiamen Harbor, Fujian, China, has been published (Cai and Li 1988).

Table 6. *Perna viridis:* Relationship between weights of various body components (expressed as mean per cent of the heavier component ± standard deviation) (adapted from Vakily et al. 1988b)

	Total	FL and SH[1]	Flesh wet
FL and SH[1]	58.00 ± 7.65		
Shell	33.75 ± 4.32	58.55 ± 5.97	
Flesh wet	24.25 ± 5.73	41.45 ± 5.97	
Flesh dry[2]	4.40 ± 1.47	7.51 ± 2.04	18.02 ± 3.62

[1]Weight of flesh and shell combined
[2]Weight of flesh dried for 48 hours at 70°C

The rather extended range of values demonstrates that condition of mussels varies strongly. Seasonal changes "result from the complex interactions of a variety of factors including food temperature and salinity, on the metabolic activities of the mussel, most particularly the growth and reproductive processes" (Hickman and Illingworth 1980). Detailed information on the seasonal pattern of the annual condition cycle is necessary to assess the potential of *Perna* for cultivation and to develop appropriate farming practices.

A number of different "condition indices" are found in the literature which are basically some measurement of tissue weight against a total fresh weight or volume. Hickman and Illingworth (1980) recommend for biological studies a condition index

$$CI = \frac{\text{dry meat weight}}{\text{whole weight - shell weight}}$$

while in mussel farming practice they consider

$$CI = \frac{\text{wet meat weight}}{\text{whole (live) weight}}$$

to be more appropriate because of its simplicity in application. An often used condition index relating weight and volume (Hickman and Illingworth 1980; Cheong and Lee 1984) is calculated as

$$CI = \frac{\text{dry meat weight (g)}}{\text{whole mussel volume - shell volume (ml)}}$$

Lee (1985a) used the latter condition index to compare the growth performance of *P. viridis* at different locations in Hongkong waters. He found that compared to a natural population the condition index could be increased by a factor of almost 2 after the mussels were transplanted to a location with more favorable living conditions. Similar findings were presented by Qasim et al. (1977) for *P. viridis* in India.

Hickman and Illingworth (1980) investigated the condition of *P. canaliculus* from different sites in New Zealand. They found that raft-grown populations usually showed a higher (though in some cases only slightly better) overall condition compared to a site with shore-grown mussels. On the other hand, analysis of the annual cycle in chemical composition of *P. perna* carried out by Benitez and Okuda (1971) in Venezuela revealed the condition factor of mussels from natural populations being higher than in cultured mussel.

Irrespective of the method applied, most authors observed a seasonal pattern in the condition with usually two more or less prominent peaks. These peaks correspond to peaks in the reproductive cycle (Velez 1971; Acuña 1977; Appukuttan and Nair 1980; Hickman and Illingworth 1980; Narasimham 1980; Lee 1985b). Hickman and Illingworth (1980) also noted an inverse relationship between condition index and size (as whole weight), which is an interesting point in determining optimum harvest size.

POPULATION PARAMETERS

Seed (1976) reviewed the application of the von Bertalanffy model to the growth of *Mytilus* spp. He concluded that despite certain criticism the use of growth equations derived from the von Bertalanffy model is an acceptable technique to arrive at mathematical expressions of growth in mytilids. As with fish, the parameters of such growth functions can serve as input in various production models used in fish stock assessment (Ricker 1975; Gulland 1983; Pauly 1984).

The very few analytical growth studies for *Perna* documented in the literature deal exclusively with *P. viridis* (Choo and Speiser 1979; Narasimham 1981; Chatterji et al. 1984; Lee 1985b; Tuaycharoen et al. 1988).

Growth is generally described by the von Bertalanffy growth equation, which - in its most common form - is usually written as

$$L_t = L_\infty (1 - e^{-K(t-t_0)}) \qquad \text{... 3)}$$

where

L_t is the length at age t

L_∞ is the asymptotic length

K is a growth constant indicating the rate at which the asymptotic length is approached, and

t_0 is the age of the fish at zero length, if it had always grown in the manner described by the function.

Table 7 summarizes values of the parameters L_∞, K and t_0 for *P. viridis* as published by various authors. The wide range of L_∞ - values is eye-catching and cannot solely be attributed to the fact that "each habitat ... (imposes), by its environmental conditions (physical and biotic), an upper size limit to the local mussels ..." (Seed 1976). They also reflect the influence of other factors, such as experimental design and the method of analysis applied. For example, in the case of Choo and Speiser (1979), the low L_∞ most probably results from the premature termination of the growth experiment (due to theft of the samples) at a point where the mussels were still growing at an almost linear rate.

The data of Tuaycharoen et al. (1988) who investigated the growth of cultured mussels in the Gulf of Thailand clearly demonstrate the effect that harvesting has on L_∞. The almost complete removal of large-size mussels at a certain time of the year leads to a rapid

Table 7. *Perna viridis:* Parameters of the von Bertalanffy growth formula (extracted from published growth data).

Location	L_∞ (mm)	K (year)	t_0 (year)	Method of analysis[1]	Authority
Hong Kong	101.9	0.30	-0.683	FWP	Lee (1985b)
India, Kakinada	184.6	0.25	-1.730	FWP	Narasimham (1981)
India, exp. tank	110.0	1.35	-0.007	FWP	Chatterji et al. (1984)
Malaysia, Penang	89.4	2.14	-0.012	VBP	Choo and Speiser (1979)
Thailand, upper Gulf	111.9	1.00	-0.010	IMPA	Tuaycharoen et al. (1988)

[1]Methods of analysis are: Ford-Walford Plot (FWP); von Bertalanffy Plot (VBP); Integrated Modal Progression Analysis (IMPA).

disappearance of larger specimens from the length-frequency distribution in the landings. This results in an artificially decreased and hence biased mean length in the samples.

P. viridis is characterized by considerable variation in growth performance and by extended periods of spawning activities. Both factors combined usually lead in any given sample, whether from wild or cultured populations, to length-frequency distributions which include various cohorts that are not clearly defined by modes. Any result, therefore, that originates from growth estimates based on the mean length in the sample (e.g., Ford-Walford plot, Gulland & Holt plot) has to be viewed with some skepticism. Similarly, the use of "modal class progression analysis" might be limited by uncertainties in the identification and/or attribution of peaks, especially of older animals (see Pauly (1983) for a comprehensive review of various approaches to the estimation of growth parameters).

As a consequence, growth studies of *Perna* generally require the use of more advanced methods that do not limit themselves to the mere estimation of mean lengths or the definitions of modes. These methods are available in the form of nonlinear procedures, as those presented by Fabens (1965) and Allen (1966), or in the form of computer-based methods, such as ELEFAN I (Pauly and David 1981). The extent to which growth parameter estimates of *P. viridis* can be influenced by the method of analysis is demonstrated in Table 8 which shows the results of three different methods applied to the same data set published by Tuaycharoen et al. (1988).

Table 8. Comparison of growth parameters obtained for *Perna viridis* by applying different methods of analysis to a given data set (source of data: Tuaycharoen et al. 1988)

Method	L_∞ (mm)	K (year)
Graphic simulation of integrated modal progression analysis[1]	111.9	1.000
Gulland and Holt plot	76.5	2.801
ELEFAN I[2]	111.0	0.800

[1]Results as published originally by Tuaycharoen et al. (1988)
[2]Results computed by M.L. Palomares (pers. comm.)

It is interesting to note that Narasimham (1981) reported a distinct seasonal pattern in growth performance for *P. viridis* reared in cages in Kakinada Bay, India, with a typical tropical climate. More along the line of expectation is the growth oscillation of *P. viridis* observed in Hong Kong waters (Lee 1985b) with its clear seasonality in water temperatures. Both authors, however, present growth parameters computed on the base of a Ford-Walford plot which does not provide a mean to account for seasonality. This might partly explain the rather unusual form of the growth curves derived from their growth parameters (Fig. 5) and emphasizes the need for more elaborate methods of growth analysis, such as those mentioned previously.

From the information available in the literature it is not possible precisely to define maximum length or longevity of any of the species of *Perna*. In his experiments with *P. viridis*, Narasimham (1981) had one specimen of 176 mm length that was still growing at a rate of 4 mm/year. His computed value of L_∞ = 186 mm, therefore, might still underestimate the potential maximum size *P. viridis* can attain. Korringa (1976) mentioned a maximum size of 250 mm for *P. viridis* grown in the Philippines. Mason (1976) even reports that *P. viridis* is known to exceed 300 mm in length. Lee (1985b) concluded from his data, that the observed average life span of three years of *P. viridis* in Hong Kong is delimited by ecological factors (mainly pollution) rather than being a result of senescence. Berry and Schleyer (1983) described *P. perna* as being very short-lived since only 0.1% of the population investigated off Durban (South Africa) survived into their third year.

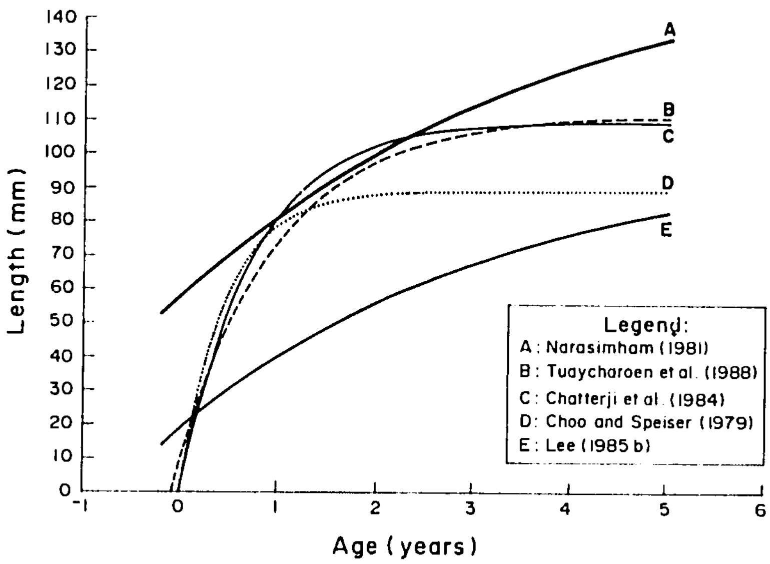


Fig. 5. Growth of *Perna viridis* (computed growth curves based on published parameters of the von Bertalanffy growth formula).

Reproduction

SEXUAL DIMORPHISM

Sexes in *Perna* are generally separate (Yap et al. 1979; Walter 1982). The occasionally reported occurrence of hermaphrodites (Anon. 1960) might result from misidentification (Lee, in press). Similar, observations of seasonally fluctuating sex ratio (Walter 1982) might simply reflect the limitation of the sex identification technique (Lee, in press).

There is no differentiation in the outer appearance of both sexes of *Perna*. The sexes of truly mature animals can often be determined by the color of the gonads: milky to creamy white in males, orange to red orange for females (Yap et al. 1979). Lee (in press), however, considers this method too unreliable, as immature or developing ovaries have a color very similar to the mature male gonad.

GONAD DEVELOPMENT

Perna living in the more stable environmental conditions prevailing in the tropics exhibit year-round spawning activities with usually two more or less prominent peaks (Parulekar et al. 1982; Walter 1982; Tuaycharoen et al. 1988). Larval surveys off the Venezuelean coast indicated even three spawning periods for *P. perna* (Carvajal 1969). In the almost temperate waters of Hongkong, peak spawning activities of *P. viridis* occur only once a year (Lee 1986). Temperature is generally considered the most influential single factor in determining reproductive cyclicity in bivalves at higher latitudes. Lee (in press) suggests that in *P. viridis* temperature is less significant in defining the reproductive cycle, but interacts with other environmental factors such as pollution and food supply. Velez and Epifanio (1981) cultured juveniles of *P. perna* at different combinations of temperature and ration. They found gametogenesis was generally inhibited at water temperatures of 28°C while gonad development at low temperature (21°C) was positively correlated with ration.

Perna viridis is sexually mature at 20-30 mm in length which is attained after 2-3 months. If the gonads are ripe, mussels can easily be stimulated to release eggs and sperms, which could make them suitable for use as transplants to increase natural spat production (Yap et al. 1979).

LARVAL DEVELOPMENT

Mussels release sperm and eggs freely into the water where fertilization takes place. Fertilized eggs develop into veliconcha larvae within 24 hours, with the formation of the morula at 1.5 hours, the trochophore at 6.25 hours, the veliger at 16 hours, and the umbo (= "D-shape" stage) at approximately 20 hours after fertilization (Sivalingam 1977; AQUACOP and de Gaillande 1979; Sahavacharin et al. 1984).

The larvae remain fee-swimming for 15-20 days. Locomotion is by means of the velum (Bayne 1976). As the larva approaches metamorphosis a pedal organ develops. Once this organ is functional, it is primarily used by the pediveliger larva in the search for a suitable substratum on which to settle. The larva attaches itself to a solid surface by means of byssal threads. Thereafter, metamorphosis takes place and secretion of the adult shell starts. The young postlarva, the "plantigrade", is commonly called "spat".

In contrast to oysters, mussels retain after metamorphosis and throughout their lifetime a limited mobility, which allows them to some extent to escape from unfavorable environmental conditions (Tan 1975b). Their ability to replace severed byssal threads is the reason for the relative ease with which thinning and transplanting operations can be carried out in mussel farming (Yap et al. 1979).

Predators

Generally seen, mussels grown in off-bottom culture are relatively safe from bottom-living predators, such as starfish (Barker 1979; Yap et al. 1979). They are, however, vulnerable to attacks by fish and octopus (Smale and Buchan 1981). AQUACOP and de Gaillande (1979) mentioned the need to protect newly seeded mussels from *Scylla serrata,* a crab which was also found to be the principle predator of both young and adult mussels in the Philippines (Yap et al. 1979) and in Malaysia (Choo 1983). Beales and Lindley (1982) reported from Brunei that mortality of *P. viridis* caused by *Scylla serrata* was especially observed during the first two months.

Johns and Hickman (1985) reported predation by fish, mainly snapper, on ropes which had been reseeded with spat of *P. canaliculus,* while in the same time ropes with mussels of similar size which had not been reseeded did not suffer noticeable predation.

A rather unusual and extreme case of predation on mussels *(P. viridis)* was described by Appukuttan (1980). In experimental raft culture in the Vizhinjam area (India), newly seeded ropes were attacked by a shoal of silver bream, *Rhabdosargus sarba* (Fam.: Sparidae). The fish completely destroyed the 250 culture ropes set out, preying even on large-size adult mussels. Attempts failed to control the predators by catching them with hook and line or by gill netting. Another sparid fish known to prey on *P. perna* is the blacktail *(Diplodus sargus capensis)* off the South African coast (Coetzee 1986).

Parasites and Diseases

Little has been reported on outbreaks of disease or manifestation of parasites in mussels. Appukuttan and Nair (1980) mention the existence of the pea crab *Pinnotheres* sp. as a commensal in *Perna viridis.* Both natural and cultivated *P. canaliculus* in New Zealand were found to be infested by *Pinnotheres novaezelandidae* and the trematode *Cercaria haswelli* (Jones 1977; Hickman 1978). However, infection rates were very low, ranging from 0.2% to 3.6%, and showed no significant effect on the condition of the mussels. Hickman (1978) concluded that mortality caused by these associate organisms was minimal. Pillai (1980) investigated the microbial load of mussel culture areas at Vizhinjam (India) and found potentially pathogenic bacteria such as *Pseudomonas, Vibrio* and *Micrococcus* to be part of the normal flora both in mussels and in the seawater. He is probably correct when stating that diseases and mortality among mussels of the genus *Perna* are unknown, "not because of the absence of the diseases but due to inadequacy of attention to this aspect."

Pollution

Various authors have investigated the toxicity of heavy metals to *Perna.* Krishnakumar et al. (1987) exposed *P. viridis* for 96 hours to different concentrations of copper (Cu), mercury (Hg), and zinc (Zn). LC_{50} values for 30-40 mm size group were 0.086, 0.155 and 3.9 mg/l, respectively. The order of toxicity to *P. viridis* was Cu > Hg > Zn. Tan and Lim (1984), reporting on the lead (Pb) uptake of a similar size group of *P. viridis,* found the LC_{50} at 168 h to be 4.46 mg/l Pb^{2+}. This shows an even greater tolerance of *P. viridis* to lead compared to the other three heavy metals. Toxicity of cadmium to *P. viridis* was reported with a LC_{50} of 2.5 ppm of Cd (Mohan et al. 1984).

In sublethal concentrations Hg, Zn, and Cd induce reduction in byssus production (Mohan et al. 1986), filtration rate (Watling and Watling 1982) and oxygen uptake (Baby and Menon 1986). Mathew and Menon (1984) reported a 50% reduction in filtration rate when exposing *P. viridis* to concentrations of 0.0017 ppm of silver (Ag), 0.068 ppm of Cu, and 0.6 ppm of Zn, respectively. It is interesting to note that the overall toxicity of a given metal is a function of the salt form of the metal in solution (Baby and Menon 1987). Experiments with *P. indica* showed that the sulfate form of copper was more toxic than the nitrate form. (Prabhudeva and Menon 1988). Prabhudeva and Menon (1986, 1988) also mention possible synergistic interactions between metals resulting in an enhanced toxicity of one metal in the presence of another metal.

Culture Practices

Mussel culture can be separated into two categories: bottom and off-bottom culture. Bottom culture consists of relaying mussel seed on the sea-bottom where they are left to grow until harvest. This method is commonly applied in the culture of the European mussel *(Mytilus edulis)*, particularly in the Netherlands (Chew 1986), but no mention of this method of culture has been found for *Perna.*

Off-bottom culture consists of providing a substrate to which the mussel can attach by means of its byssal threads. Harvesting is done by removing the culture substrate from the water and stripping off the mussels. Various modifications and improvements of the basic technique exist. They are mainly designed to increase the yield, taking advantage of local conditions and materials, and make the culture operation less labor intensive.

Off-bottom culture uses ropes or wooden material (stakes or bamboo poles) as substrate for the mussels to settle and grow. Its major advantage compared to bottom culture is the vertical orientation of the culture substrate, which results in a better utilization of the water column and makes the mussels less accessible to bottom living predators. On the other hand, culture areas can represent a considerable obstacle to other forms of activities commonly found in coastal waters (Appukuttan et al. 1980). Artisanal fishing and transportation/navigation will compete for space, making it usually mandatory to develop an extended coastal area management scheme (Silas 1980).

Mussel farming is characterized by two distinct phases: spat settlement and grow-out. Appropriate measures that take into consideration the specific requirements of the mussels during the two phases will result in optimization of yield and thus better utilization of capital investment.

Spat Settlement Phase

SPAT COLLECTORS

The success of commercial mussel farming depends heavily on reliable seed supply. In areas with existing mussel stocks natural spatfall is still considered the primary source of seed (Yap et al. 1979; Cheong and Lee 1984). Though the technology to produce spat of *Perna viridis* under controlled conditions in hatcheries has been successfully studied in Thailand (Sahavacharin et al. 1984, 1988) and elsewhere, its large-scale implementation is economically not yet viable (Yap et al. 1979) (see "Hatchery techniques", below).

Efficient spat collection requires accurate forecasting of the time of spatfall. There are many reports on spawning seasons of *P. viridis* from many different places throughout Southeast Asia. When summarized, they present a picture of continuous spawning activity in almost all *P. viridis* stocks with two peaks per year (Sivalingam 1977; Cheong 1982; Ng et al. 1982; Saraya 1982; Young and Serna 1982). These peaks, however, cannot be reliably assigned to a definite period of the year, since their position might shift from year to year (Cheong and Lee 1984).

Relating spawning to prevailing weather conditions, Cheong and Lee (1984) suggest that the onset of spatfall can usually be expected when the gonadal "ripeness" of the mussels coincides with an extended dry period being broken by a spell of heavy rains. They report the spawning season of *P. viridis* in Singapore to last two to three weeks. Spat densities range from 5,000 to 10,000 spat per square meter of collector surface, with 5,000/m^2 being the minimum density required for commercial operation (Cheong and Lee 1984).

A wide variety of spat collecting material is in use. In Thailand and the Philippines mussel farmers employ bamboo poles or wooden stakes to which the spat attaches easily. Another popular type of collector are ropes, mainly because of their relative ease of handling and the possibility of also using them for the grow-out phase. Ropes suitable for collecting mussel spat are manufactured from either natural fibers such as coir or sisal, or synthetic material such as polypropylene and polyethylene ropes (Choo 1979, 1983; Cheong and Lee 1984).

In the (more common) case where the same culture rope is used for both the collecting of spat and the ensuing on-growing of mussels to marketable size, the selection of appropriate rope material will largely depend on the evaluation of the following criteria:

a) efficiency as spat collector;
b) local availability of material;
c) durability of material;
d) initial cost of investment.

Ropes made of natural fibers have proven to be very successful in catching mussel spat because of their hairy and/or creviced nature (Tortell 1976). Mason (1976) mentions experiments with *Mytilus edulis,* where smoother synthetic ropes were found to acquire a poorer settlement of mussel spat than ropes of more hairy fibers such as coir. On the other hand, ropes made of synthetic materials can last several years, while those made of natural fibers usually have to be disposed off after a one-year culture period (Choo 1979).

Various authors have looked into the possibilities of devising culture ropes that combine the advantages of fibrous material with the durability of synthetic ropes. Tortell (1976) states that "a synthetic substitute attractive to mussel larvae, as well as being an improvement on natural fibers, would be of great value to the mussel farming industry."

A rather simple but seemingly effective step in this direction are ropes termed "polycoco" (Cheong and Lee 1984). They consist of a main polyethylene rope, 14 mm in diameter, to which are tied pieces of coconut coir rope, 40 mm in diameter and 30 cm long. These short rope offcuts are positioned at the middle of each meter of the main rope down to the maximum depth at which spat attachment can still be expected. Yap et al. (1979) mention the use of coconut husk in combination with synthetic ropes, a practice commonly found in the farming of *Perna viridis* in the Philippines (Fig. 6). The husk is stripped from the coconut shell and shredded. The sickle-shaped pieces are inserted at 20 cm intervals between the lays of a polypropylene or polyethylene rope. Yap et al. (1979) caution, however, that the coconut husk deteriorates rather fast when immersed in seawater. Additional bamboo crosspieces should be used to give more support to the on-growing mussels. Because of the buoyancy of the coconut husk such culture ropes need a heavy object tied to the end of the rope to prevent it from floating.

In the highly developed farming of *Perna canaliculus* in New Zealand, two interesting modifications of synthetic culture ropes are reported to have particularly good catching and retaining characteristics for mussel spat.

One is the so-called "Christmas tree" rope (Johns and Hickman 1985), a three-strand, 12 mm-diameter, carbon black polypropylene rope, which has one of the three lays covered in fibrillated sacking offcuts. Once this type of rope is immersed in water the effective surface available for mussel larvae to settle is increased several times.

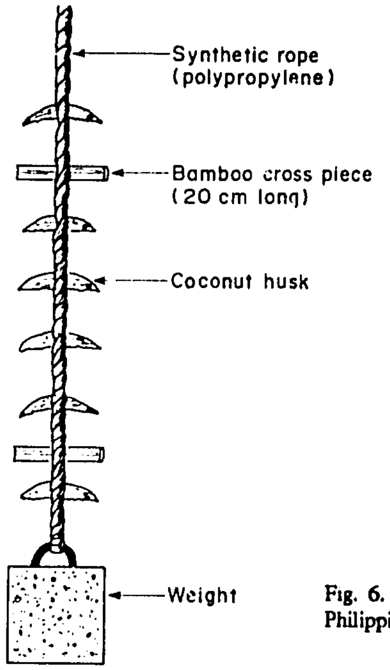


Fig. 6. Combined collector and growing rope for the culture of *Perna viridis* in the Philippines (after Yap et al. 1979, modified).

The second form of modification successfully applied at least on an experimental scale is a carbon black dyed polypropylene rope with crosspieces of the same material inserted at regular intervals (Tortell 1976). The crosspieces are different from the main rope insofar that they are made from a bundle of strips of polypropylene film. To obtain the desired filamentous character of the material, the strips are mechanically fibrillated by a series of blades which produces a syncitium of fibers of varying cross sections. Tortell (1976) reported that this type of rope required little or no "seasoning" in seawater and greatly reduced the settlement of competing organisms such as barnacles or tunicates. To achieve a more even distribution of the mussels along the culture rope at time of harvest he suggests keeping the distances between the single crosspieces fairly small, i.e., less than 20 cm.

Other material used for collecting spat are tiles suspended from rafts (Rangarajan and Narasimham 1980), polyethylene netting (Cheong 1982) and even used tyres (Cheong and Lee 1984). In New Zealand a "natural" spat collector was discovered when stranded seaweed was found to be heavily encrusted with minute seed of *Perna canaliculus* (Hickman 1976). Though the strandings occur irregularly, the prodigious quantities of seed "make this material an extremely valuable alternative to *in situ* spat catching" (Johns and Hickman 1985). A similar occurrence of *P. perna* on seaweed was reported from South Africa (Beckley 1979).

The need for "seasoning" the spat collecting material is mentioned quite frequently. It means that settling of young mussel larvae is successful only if the spat collector has been immersed for at least two weeks (Cheong and Chen 1980). "Seasoning" may be related to the attachment of other marine organisms to the substrate prior to the expected spatfall. Some authors conclude, though not very convincingly, that the presence of barnacles is critical for settlement (Korringa 1976; Krippene 1977,) while other authors consider the establishment of a film of primary settlers such as algae and hydroids to be necessary prerequisite for mussel spat to settle (Cheong and Chen 1980).

No attempt has apparently been made to analyze the mechanism behind this "conditioning" that triggers the larval settlement. It might therefore be interesting to note that Morse and Morse (1984) investigated a similar occurrence of substratum-specific settlement in the behavior of the gastropod *Haliotis*. They reported that the attachment and metamorphosis of abalone larvae was induced by molecules available at the surface of crustose red algae. Morse (1984) mentions that amino acid-derived molecules had been found to trigger settlement and metamorphosis in species of clams, oysters, mussels, nudibranchs and other molluscs.

SPAT TRANSFER

When a monitoring system (Cheong 1982) has indicated the onset of a spatfall, ropes or other appropriate spat collectors are placed in the water. Johns and Hickman (1985) suggest to double the 5 m long catching ropes, as this facilitates handling and permits the attachment of a weight to the loop which is necessary to sink the very buoyant rope. If the settlement of spat occurs in a clustered pattern and at high densities, transfer of spat ("thinning" or "reseeding") is required to ensure uniform and maximum possible growth of the mussels (Choo 1983; Johns and Hickman 1985).

Reseeding is done by stripping the mussels from the catching material and redistributing them onto (preferably) culture ropes. Ideally, this should be done when the mussels are no longer than 15-20 mm long (Rangarajan and Narasimham 1980; Johns and Hickman 1985). Cheong and Lee (1984) reported that the falling-off rate rises dramatically with increasing initial length at the time of reseeding. The detached spat are usually placed on cotton netting, e.g., mosquito netting (Kuriakose and Appukuttan 1980), and then bound around the culture ropes (Rangarajan and Narasimham 1980; Cheong and Lee 1984). Estimates of optimum seeding density in number of spats per meter of culture rope vary from 200-300 for *P. canaliculus* (Johns and Hickman 1985), and from 250-350 (Kuriakose 1980b) to 800-1000 (Choo 1983; Cheong and Lee 1984) for *P. viridis*. The cotton netting disintegrates in about two weeks by which time the spat have attached themselves to the culture rope. Cheong and Lee (1984) caution, however, that spat transfer is very laborious and time-consuming, and, therefore favor the use of the "polycoco rope" (see above). In their opinion, this rope does not require any thinning, because spat settle initially on the coconut coir pieces, then later migrate up and down the polyethylene rope section, resulting in a more or less even distribution over the entire "polycoco rope". In cases, where reseeding cannot be avoided, the use of a reseeding stocking stretched over a 300 mm PVC tube (Johns and Hickman 1985) might considerably speed up the operation.

One advantage of the spat transfer technique is the fact that it frees the farmer from growing his mussels only in areas with natural spatfall. Seed will remain viable for one (Kuriakose and Appukuttan 1980) to three days (Johns and Hickman 1985), if kept cool and damp. This allows transport of seed over quite some distance. This feature was successfully exploited in Thailand, when seed of *P. viridis* was transferred to new culture areas (Saraya 1982; Chaitanawisuti and Menasveta 1987) as well as in Fiji (Navakalomana 1982) and in Tahiti (AQUACOP 1982). Another example occurred in India where scientists, faced with the lack of sufficiently sheltered areas, experimented with spat collected in near-shore waters and transferred to rafts anchored in the open sea off Calicut. It was found that the mussels under open sea condition grew at a much better rate than the natural stocks from which the seed was collected (Kuriakose 1980b; Rangarajan and Narasimham 1980).

Grow-Out Phase

Basically, off-bottom culture can be divided into fixed and suspended culture with the principal difference being the "fixpoint" of the system. In fixed culture, the supporting structure is firmly anchored in the sea bottom (e.g., poles or racks). In suspended culture ropes are hung from a device floating at the surface of the water, e.g., rafts or longlines held afloat by buoys.

Fixed culture has the advantages of simplicity of the farming technique and low material and maintenance costs. It facilitates the introduction of mussel culture to coastal communities with little or no previous experience in shellfish farming. Disadvantages include the need for extensive areas to set out sufficient numbers of poles, periods of less favorable feeding conditions for the mussels in areas with large tidal fluctuations, difficulty in applying yield-increasing farming techniques such as thinning, and gradual deterioration of farming areas due to increased siltation. Potential hazards of diving to harvest the mussels or to remove entire poles for stripping should not be overlooked.

The primary advantage of suspended culture is the constant positioning (relative to the water surface) of the mussels in the nutrient-rich upper range of the water column. This provides optimum feeding conditions throughout all tidal periods. Further advantages are: no specific requirements regarding the sea bottom, suitability to various enhanced farming techniques (thinning, spat transfer, etc.), reduced risk of environmental deterioration. Major disadvantages are substantial initial investment cost and a certain minimum demand in technical know-how, bearing higher financial risks for potential mussel farmers than in fixed culture systems. Also, raft culture, at least, faces the dilemma that on the one hand relatively deep water is needed to keep the culture ropes off bottom during low tide, but that on the other hand the required water depth is primarily found in exposed areas with strong currents and/or rough sea conditions which have proven to be generally unsuitable for the operation of rafts.

FIXED CULTURE

Fixed culture systems comprise basically of stakes or poles; rope-webs; or racks.

The rearing of *Perna* on poles or stakes is primarily found in Thailand (where it is the only method applied (Saraya 1982)) and the Philippines (Yap et al. 1979). The rope-web method is practiced in the Philippines (Krippene 1977), while rack culture of *P. viridis* was successfully tried in shallow ponds in Tahiti (Coeroli et al. 1984).

Stakes and poles

Mussel farms in Thailand culturing *P. viridis* on bamboo poles or stakes are traditionally located along the coastline of the inner Gulf of Thailand. Towards the south with less sheltered waters, mussel farms are operated in the deeper parts of large estuaries where soft muddy substratum prevails. Depending on the material used for staking a water depth of 5 to 10 meters is required. (Sribhibhadh 1973).

Bamboo poles are 6-8 m long, depending on the water depth. Care is taken that the tips of the poles will be near the water surface during low tide without actually falling dry (Guerrero et al. 1983). The poles are sharpened at the base and holes punched at the upper end of each segment to reduce buoyancy (Torres and Lorico 1982; Young and Serna 1982). The prepared poles are brought on large rafts to the farms where they are staked into the bottom about half a meter deep and one meter apart. Space is left in regular intervals to facilitate navigation. A one-hectare mussel farm, therefore, requires up to 10,000 bamboo poles (Saraya 1982).

In shallow areas farmers also use stakes made from date-palms *(Phoenix paluposa)*. Very often, however, the primary purpose of planting these stakes is the setting up of fish traps for chub-mackerels (Sribhibhadh 1973). Harvesting of the mussels that have settled on the stakes is, therefore, more of a by-product.

After setting of the poles, there is hardly any further culture activity involved (Saraya 1982; Young and Serna 1982). Settlement depends on local spatfall and is usually no constraint in established farming areas. A major draw-back of all vertically oriented culture methods is the loss of a large portion of the originally settled spat. Drop-offs occur due to overcrowding and ensuing slippage of whole mussel clusters because of the increasing weight during growth. Saraya (1982) estimated the losses to be usually more than half the original number. He even cites an experiment where the initial number of 4,000 spat was reduced to a mere 500 mussels after a culture period of 11 months. Sribhibhadh (1973) mentions partial harvesting of young mussels in Thailand to reduce setting density on the poles. These young mussels are reported to be sold as animal feed (Wattanutchariya et al. 1985), especially as poultry feed (Saraya 1982). This seems to be, however, not a general strategy, as surveys of the marketing system of *Perna viridis* in Thailand (Tokrisna et al. 1985) did not reveal the existence of any established market channel through which *P. viridis* is sold as animal feed.

The culturing of *P. viridis* on stakes in the Philippines is very similar to the methods found in Thailand (Yap et al. 1979). Major culture areas are Sapian Bay in Capiz, the Maqueda Bay in Samar and the Bacoor Bay in Cavite (Young and Serna 1982). Preferred bamboo species for staking are *Bambusa vulgaris* and *B. blumeana*. In shallow waters *Schyzostachium lumampao* is used (Torres and Lorico 1982; Young and Serna 1982). In areas with strong currents, this basic system is sometimes modified such that rows of stakes are interconnected by horizontal poles or by using the "wigwam" method (Yap et al. 1979; Young and Serna 1982). This consists of arranging seven to ten poles in a 2 m radius around a central pole to which they are tied with their upper ends to form a "wigwam". The poles serve both as spat collector and grow-out medium.

Regular management practices are limited to inspection of the farm area to reinforce or remove weak or rotten poles. No thinning or transplanting is done during the culture period, but farmers may occasionally try to avoid the loss of oversized mussel clusters by tying thin ropes around the clusters to prevent them from falling (Young and Serna 1982).

Harvesting of mussels usually starts after about six months when the mussels have reached a marketable size of 60 to 70 mm. Hired divers wearing goggles or face masks assist in removing the poles by sawing them off near the base (Saraya 1982).

Operational activities of divers are very limited in free diving and, hence, harvesting of large quantities of poles is very time consuming. Mussel farmers in Thailand were observed using air compressors mounted on board small boats to provide divers working in shallow waters with a constant air supply through tubes loosely attached to the divers' masks (Vakily, pers. obs.). Similar practices are reported from the Philippines (Torres and Lorico 1982; Guerrero et al. 1983). The additional costs involved in the use of more sophisticated diving equipment, such as SCUBA tanks, are prohibitive.

Once the mussel-laden stakes are free, they are pulled into a boat where the mussel clusters are stripped off the stakes with sharpened iron bars. Young and Serna (1982) mention the practice of partial harvesting of stakes in the Philippines, if mussels attached to a pole are predominantly undersized. In such cases, divers will not cut off the poles, but simply remove selectively mussels of appropriate size.

Bamboo poles decay easily. In addition, boring organisms and crabs nesting inside submerged poles (Yap et al. 1979) can drastically reduce the number of poles still in good enough condition to be restaked after the first harvest. Generally, bamboo poles will last between one and two years (Torres and Lorico 1982).

Undoubtedly, culture of mussels using the stake method has its advantages: the cost of investment is low compared to other culture methods; the material (bamboo or date palms) is locally available; the farming operation is very simple and does not require specially trained personnel.

However, Yap et al. (1979) list a series of problems and disadvantages inherent in stake culture. These are:

- the necessity for sufficiently low water levels and good weather conditions for the maintenance and inspection of a farm, and also, of course, for the harvesting of the stakes;
- heavy dependence on supply of bamboo poles or date palm stakes;
- accessibility of the mussels to bottom-living predators;
- crowding of mussels at the upper part of the stakes because of more favorable living conditions;
- ineptness of the culture technique for the promotion of yield increasing methods such as regular thinning or transplanting of mussels.

A major constraint is the fact that stakes hinder the free flow of tidal currents when planted in large quantities and very close together. This situation, typically found in large and intensively used mussel farming areas, allows suspended organic and inorganic matter to settle, adversely affecting the ecology of the area where the mussels are cultured (Yap et al. 1979). Young and Serna (1982) suggest that the increased rate of siltation and the limited water exchange results in poor growth, thin, brittle shells and higher mortality rates of the mussels.

A way to circumvent this problem is the form of fixed suspended culture which is suitable for shallow waters with a small tidal range. Culture ropes are hung from horizontally fixed poles that rest on wooden supports driven into the substratum (Choo 1983; Guerrero et al. 1983). Without drastically increasing the cost of the operation this system improves on the traditional stake method insofar that the ropes provide better manageability and are not accessible to bottom living predators. However, frequent exposure due to changing water levels would result in poor growth and high mortality of the mussels.

Rope-web method

An interesting alternative to the stake culture method is the "rope-web" system, developed and successfully applied in the culture of *Perna viridis* in the Philippines (Yap et al. 1979; Young and Serna 1982; Guerrero et al. 1983). One unit consists of two strong bamboo poles firmly driven into the substratum 5 m apart. A parallel pair of 5-m ropes, positioned 2 m apart, is strung across the poles. These supporting ropes are connected at intervals of 40 cm in a zigzag pattern by a 40-m rope, preferably polypropylene rope 12 mm in diameter (Fig. 7). To prevent the slippage of large clusters of mussels, bamboo pegs, 20 cm in length, are inserted into the rope at 40 cm intervals. The units are positioned parallel to the current and 2 m deep at low tide, leaving a space of 5 m between units (Young and Serna 1982). The system is used for both collecting spat and growing the mussels to marketable size.

In harvesting, the rope webs are untied from the poles and lifted into a boat, where the mussels are detached manually. On land, dirt and encrustations are scraped off the ropes which are sun-dried to effectively remove algae and other organisms (Guerrero et al. 1983). Though more expensive in initial cost of purchase, polypropylene ropes have been found to be durable enough to last for several years (Guerrero et al. 1983).

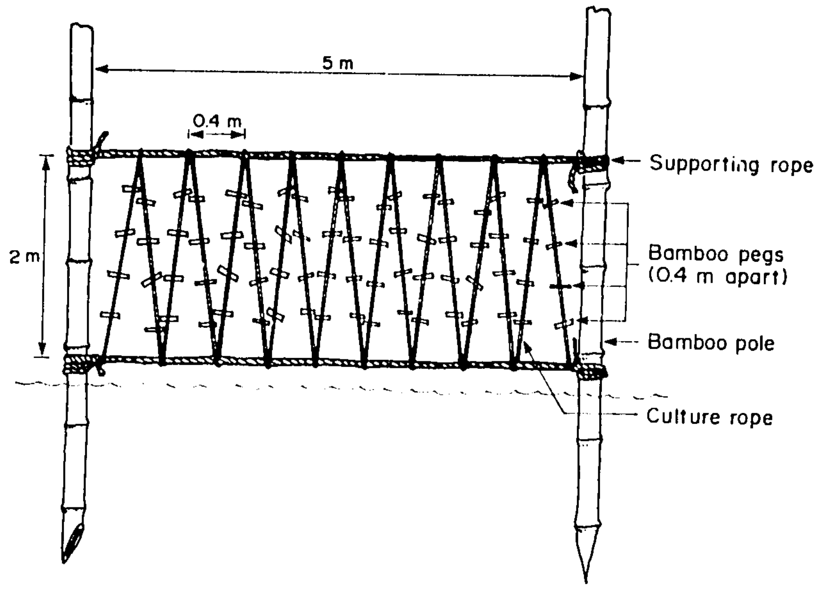


Fig. 7. "Rope-web" method for the culture of *Perna viridis* employed in the Philippines (after Yap et al. 1979, modified).

Rack method

Use of racks in the culture of *Perna* has so far only been tried in Tahiti (Coeroli et al. 1984) where several units were constructed in shallow ponds with 0.8 m maximum depth at low tide. The racks consist of wooden trays with mosquito-wire netting into which hatchery-reared spat of *P. viridis* is sown. In order to keep the mussels in tolerable conditions during the rainy season the trays are hung in the rearing structure by means of nylon cord that allows adjusting their level in the water.

SUSPENDED CULTURE

Exploitation of *Perna* in suspended culture on rafts or longlines is generally still in an experimental stage. The only exception is the longline culture of *P. canaliculus* in New Zealand which has been extensively reviewed by Jenkins (1985). Especially in Asian countries with good potential for culturing *P. viridis*, scientists and fisheries authorities have shown interest in this new technique in their efforts to establish mussel culture as an additional means of exploiting coastal resources. Though promising results exist, the transition from a purely experimental stage to a commercial-scale industry so far apparently has been achieved - apart from New Zealand - only in Singapore (Cheong 1982).

In Singapore, raft culture of *P. viridis* was introduced in 1975 (Chen 1977; Cheong and Chen 1980; Cheong 1982). Originally, the culture period was split into two phases: spat collection and grow-out. Coconut coir ropes were used for spat collection. They were 4 m in length and suspended from rafts at a density of 8 ropes per m^2. After two to three months the spat (then 2-3 cm in size) was transferred to polyethylene production ropes of the same length. Using the cotton netting technique spat was evenly dispersed at a rate of around 3,000 per 4 m rope. The production ropes were suspended from rafts at a density of 4 ropes per m^2. Marketable size (7 cm shell-length) was reached after 6-7 months total culture period. Later, the development of the "polycoco" rope (see above) allowed the labor-intensive transplanting procedure to be discontinued. Mussels are now left on the ropes for continuous growth until they have reached marketable size (Cheong and Lee 1984).

The mid 1970s also saw a major research input on raft culture in India (Nayar et al. 1980), involving both *P. viridis* and the brown mussel referred to as *P. indica*. Given the lack of suitable farming areas in sheltered waters, much of the experimental work had to be done in the open sea.

Experiments with *P. viridis* were carried out on the Indian west coast off Calicut (Kuriakose 1980b). Spat was collected from natural grounds and seeded onto culture ropes. The culture ropes, either coir or nylon, varied from 5 to 8 meters in length and were suspended 0.5 to 1 m apart from a raft. On average, the mussels grew from 25 mm to 80 mm within a five-month period (Kuriakose 1980b). Corresponding raft experiments with *P. viridis* on the Indian east coast off Kakinada showed similar good growth rates (Rangarajan and Narasimham 1980).

Appukuttan et al. (1980) reported on the culture of the brown mussel *Perna indica* both in a bay and in the open sea off Vizhinjam at the southern tip of India. Though the growth achieved in open sea raft culture was better than in bay-grown mussels, the loss of two-thirds of the open-sea rafts during the adverse weather condition of the monsoon period, clearly shows the limits of open-sea raft culture with conventional rafts.

Use of ropes in Thailand has been confined to a few experiments (Chonchuenchob et al. 1980; Chaitanawisuti and Menasveta 1987). Similarly, in Malaysia (Choo 1979; Ng et al. 1982; Choo 1983) and in Indonesia (Unar et al. 1982) suspended culture has not yet reached beyond a primarily experimental stage.

Rafts: basic design and materials

A raft culture system consists of four basic components:

- culture ropes;
- a rigid framework to accommodate the ropes;
- buoyant material to keep the raft afloat;
- a mooring system to prevent the raft from drifting.

Selection of appropriate equipment and the final design of a raft will depend on the availability of materials and capital costs.

The material considered to construct the framework of a raft has to satisfy two requirements with, unfortunately, opposite trends. On the one hand it should be strong enough to support the increasing weight of the on-growing mussels. On the other hand, it should be light to minimize the buoyancy used just to keep the system itself floating (Yap et al. 1979). Materials commonly used are bamboo and lumber. Bamboo has the advantage of being light, cheap, and widely available throughout many tropical countries (Yap et al. 1979).

The basic design of a bamboo raft is very simple. A lattice work is made either entirely of bamboo poles (Yap et al. 1979) or of an outer hardwood frame and connecting bamboo poles (Kuriakose and Appukuttan 1980). The poles are up to 8 m long and lashed together at their crosspoints using nylon rope (3-4 mm diameter). Even though ropes are subject to wear and tear, they are preferable to galvanized wire, the sharp ends of which can cause considerable injuries to those working on the raft during maintenance and harvesting.

The major constraint regarding the utilization of bamboo is its limited durability. The cost of material and labor needed to regularly replace parts (or, in the worst case, the whole) of a raft, can make the long-term cost of operation high in comparison to the initial materials cost. While rafts made entirely of bamboo can be appropriate during an experimental phase, more durable material should be employed when expanding raft culture to a commercial scale. Iversen (1976) cites the drastic case of the introduction of rafts for the culture of *Perna perna* in Venezuela. The step from promising experiments to a large-scale farming venture ended as a complete failure because the material used, bamboo and lightwood lumber, became riddled by marine borers and fell into the sea.

A more durable raft can be built from hardwoods such as those used for bridges and piers. Based on their experience with raft culture in Singapore, Cheong and Lee (1984) gave recommendations for the construction of rafts. The main frame consists of wooden beams of the mixed medium or heavy hardwood variety, with the cross-section measuring 10 cm by 7.5 cm. The frame is bolted into position by galvanized bolts 20 cm long and 1.3 cm in diameter. Onto this frame are nailed - at 60 cm intervals - cross-beams of the mixed light hardwood variety measuring 7.5 cm by 5 cm in cross-section. The length of the beams depends on the area intended to be available for hanging the culture ropes. Typically, these areas measure 5 x 5 m (25 m^2), 15 x 5 m (75 m^2) or 15 x 10 m (150 m^2), with the actual dimensions of the raft being slightly larger to account for the placement of the floats.

To minimize corrosion from seawater spray, all metal parts should be painted over with antirust paint (Cheong and Lee 1984). The treatment of all wooden parts of a raft with a marine antifouling paint as suggested by Yap et al. (1979) should not be considered without carefully evaluating the health hazard resulting from the mussels ability to accumulate potentially harmful chemical components of the paint that might get into solution in the seawater.

After a raft has been in use for some time the wooden framework tends to become very slippery, because of the attachment of algae, making work on the raft relatively difficult. Even though this can partly be controlled by providing floats with enough buoyancy to keep the wooden framework well above the water level, wooden planks should be placed atop of the raft to serve as walk-ways and working platforms (Cheong and Lee 1984). Sun shades made, for example, from the fronds of "attap" *(Nipa frutescens)* can be fitted to the raft (Cheong and Chen 1980). Andreu (1960) reported a negative effect of bright sunlight on the growth of *Mytilus edulis*. Though this theory was rejected by Cheong (1982) for *P. viridis,* Cheong and Loy (1982) reported a more uniform spat distribution along the collecting rope under shaded conditions when material other than the polycoco rope was used as spat collector.

The floats most commonly found in the raft culture of *Perna viridis* are used metal or plastic drums (Yap et al. 1979; Kuriakose and Appukuttan 1980; Cheong and Lee 1984). Styrofoam blocks or ferroconcrete buoys could also be used (Telosa 1979; Yap et al. 1979), but have proven less suitable because of high cost and limited availability of these materials.

Preparing drums for use as floats involves thorough cleaning (especially in the case of used oil barrels) and painting of the drums (Kuriakose and Appukuttan 1980; Cheong and Lee 1984). Caps should be firmly tightened and - if necessary - sealed with fiberglass prior to painting. Metal drums are painted first with red lead (primer) and finally with an anticorrosion paint. Cheong and Lee (1984) recommend that plastic drums should be coated, too, with antifouling paint to deter marine borers such as Teredo sp. The attack by Teredo seems to be, however a minor problem in the light of the previously made general reservations against the use of antifouling on marine farming structures.

Compared to metal barrels, plastic drums have the advantage of lasting much longer in the water, typically 2-4 years (Yap et al. 1979) and that their transport and handling outside the water is considerably facilitated by their light weight. Drums of 200-l capacity seem to be a convenient size (Kuriakose and Appukuttan 1980; Cheong and Lee 1984), since they can easily be slipped in-between two parallel beams of a raft or dislodged when they need replacing.

The buoyancy required to keep a raft afloat solely depends on the onset of a culture period on the material used for constructing the raft. Kuriakose and Appukuttan (1980) give a number of five 200-liter barrels needed for a raft 8 m x 8 m, while a raft of 150 m^2 would have to be provided with approximately 30 drums of the same size (Cheong and Lee 1984). From this can be concluded that a number of 3 drums per 10 m^2 raft surface for small to medium-sized rafts would be an acceptable first approximation of the needed buoyancy. Large rafts exceeding 100 m^2 require only 2 drums per 10 m^2 raft surface.

As culture progresses, the resulting increase in weight of the mussels growing on the ropes means that more buoyancy has to be added to the raft. Thus, a raft stocked at a density of 4 ropes per 1 m^2 and laden with market-sized mussels of 60-70 mm shell-length might require doubling the original number of drums (Cheong and Lee 1984). Raft design as described above is meant for use in mussel farms located in protected waters such as bays or small estuaries. However, in many places such sheltered areas are rare or already fully utilized. While in Europe methods are being developed to extend the controlled culture of marine organisms to the open sea, none of the solutions presented seem to be appropriate for application in developing countries because of the high costs involved. An apparently more practicable step into the utilization of the open sea for mussel farming is the use of submerged rafts which has been investigated in India by Rajan (1980).

The framework of a submersible raft need not differ much from a conventional raft. The one used in the experiments by Rajan (1980) consisted of a frame made of teak-wood poles with a center pole to provide sufficient rigidity. The poles were connected by cross halving joints and iron bolts. Onto this frame were lashed bamboo poles at intervals of 0.75 m. A raft of 81 m^2 surface (9 x 9 m) can accommodate approximately 150 ropes, if the ropes are spaced 60 cm apart (Rajan 1980).

The critical point of such a system is the shape of the floats which should exert little resistance to waves and currents, but keep the raft at the desired depth. Rajan (1980) found inverted conical floats to be better suited than conventional cylindrical buoys in absorbing the movements caused by the action of currents and waves. Conical floats can be shaped and welded from material cut out of 200-l oil barrels. The apex should be slightly weighted and have an iron ring with a swivel for fixing the chain that connects to the raft (Fig. 8).

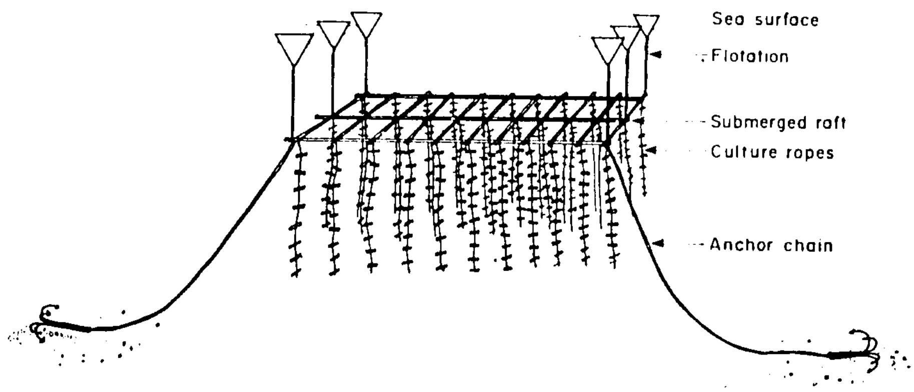


Fig. 8. Scheme of a submersible raft for mussel culture (drawn after Nayar et al. 1980).

The use of submerged rafts has, of course, various shortcomings. In most cases spat collecting efficiency is very limited in the open sea. Rafts, therefore, have to be stationed near-shore and temporarily changed to floating rafts by adding conventional buoys. During this time spat settlement can occur naturally or by seeding the ropes manually (Rajan 1980), after which the rafts are towed to deeper waters. No information is given by Rajan (1980) on the effect that marine borers will have on the durability of a submerged raft, though this problem definitely needs special attention.

Rafts can be anchored either singly or in a row. In the first case they are usually allowed to swing with the tide. When arranged linearly in rows parallel to the flow of flood and ebb tides, the first and the last raft are anchored to keep the row in position and minimize the problem of rope entanglement with neighboring rows (Cheong and Lee 1984). If, however, the whole setup consists of just one single row of rafts, arranging these rafts perpendicular to the prevailing currents would improve the productivity of the ropes (Andreu 1968). Depending on the currents, this can require, though, a much heavier anchorage. Rafts are connected to the anchors either by polyethylene ropes of 40 mm diameter (Cheong and Lee 1984) or by forged link chains (9-12 mm diameter) coated with anti-corrosive paint (Kuriakose and Appukuttan 1980). The length of the anchor rope or chain should be four to six times that of the water depth at Low Water Spring Tide (Kuriakose and Appukuttan 1980; Cheong and Lee 1984). Cheong and Lee (1984) mention a practice found in *Perna viridis* culture in Singapore, where the anchor is connected to a floating drum, to which the raft is tied by another rope or a wire cable (2.5 mm in diameter).

In view of the differences between farming sites no precise specifications can be given for mooring systems that would satisfy all needs. As Johns and Hickman (1985) emphasize, "the prospective farmer must ensure that the mooring system is appropriate to the type of sea bed and the degree of exposure ..." taking into account ..."the most adverse weather conditions that can occur in the area."

Marine anchors of grapnel or admiralty type (Kuriakose and Appukuttan 1980) or concrete blocks are used for anchorage. In the latter case, the total weight of the anchors should be at least twice the weight of raft and mussels combined. The weight of the mussels in water is approximately 20% (Cheong and Lee 1984) to 25% (Johns and Hickman 1985) of their weight when harvested, while the weight of the raft has to be estimated from the type and quantity of the wood used (Cheong and Lee 1984). Fig. 9 shows the construction details of a wedge-shaped mooring block that can be specially adapted for use over hard sea bed by the addition of steel spikes. These spikes will counteract the displacement of the block caused by violent movements of the raft during adverse conditions.

Longline systems: basic design and materials

Longline systems were originally developed for the Japanese oyster culture (Imai 1971). Their suitability for mussel culture was recognized and exploited commercially in New Zealand from the early 1970s (Hickman 1987). Adaptations of the system and the equipment to the less favorable conditions prevailing in exposed areas were intensively studied during 1977-1982 (Johns and Hickman 1985), in an investigation which arose from the need to look into the possibilities of extending the booming culture of *Perna canaliculus* to less sheltered waters.

In longline systems, culture ropes are suspended from buoyed headlines that can be of any manageable length. The important difference compared to raft culture is the absence of a rigid structure on the water surface. The low profile, streamlined longline system presents minimal resistance to weather and sea. The much smoother movement of the longlines in adverse condition causes less wear on anchor lines, shackles and thimbles (Johns and Hickman 1985). Further advantages of longline systems over rafts are (Johns and Hickman 1985):

- construction, set-up, and transport are much easier to accomplish;
- more economic use of flotation capacity as all buoys provided are available to support the

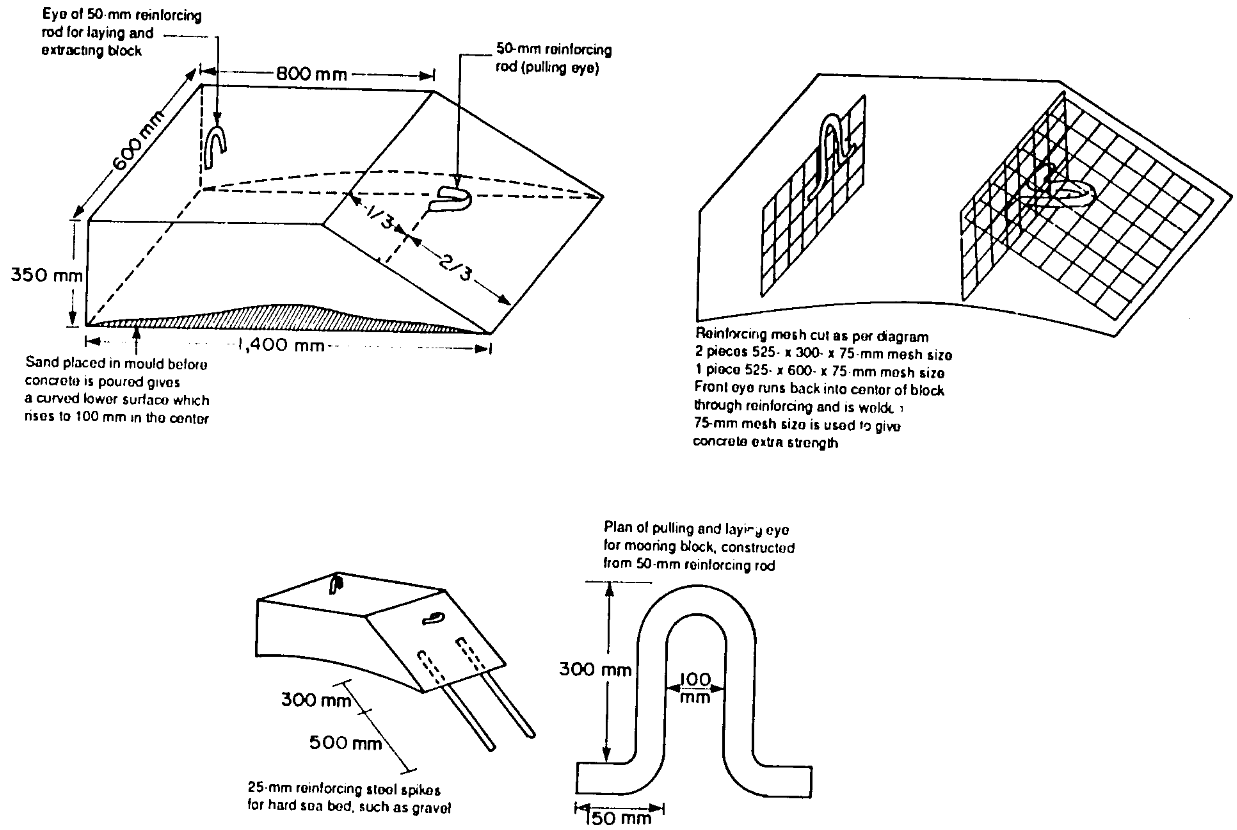


Fig. 9. Construction details for a 500-kg mooring block: reproduced Johns and Hickman (1985) with kind permission from the New Zealand Fisheries Research Division.

mussel crop (in contrast to rafts, where a considerable portion of the total buoyancy is needed to keep the raft afloat;

- convenient adjustment of the required flotation throughout the growing period in accordance with crop weight.

After experimenting with various sizes of headlines and floats, Johns and Hickman (1985) found a 60-m unit with uniform 55-kg displacement buoys to perform satisfactorily under load in various weather and sea conditions. They recommend this size as the most appropriate mussel farming structure for exposed conditions in terms of costs, carrying capacity and ease of operation.

A 60-m longline unit consists of 65 m polypropylene rope (24 mm diameter) with galvanized thimbles spliced into each end. 50 inflatable plastic buoys (55 kg displacement) are connected to the rope at 1.2-m intervals (Fig. 10). Culture ropes are suspended at 0.75-m spacing, totaling 80 ropes per longline unit.

Longlines should be positioned parallel to the prevailing currents and anchored at both sides. Depending on the nature of the sea bed, mooring consists of a concrete block for mud or sand, or a single fluke, pick-type anchor for gravel or sand), to which a chain (3-5 m long) is attached. The chain is connected to the headline by twin polypropylene ropes (forward mooring) and a single rope (aft mooring) of 24 mm diameter (Fig. 10). Johns and Hickman (1985) suggest a 20:1 ratio between expected crop weight and anchor weight.

Culture ropes can be of any type previously discussed. Their length has to be appropriate to the particulars of a given farm site. At the onset of the culture period, weights must be attached

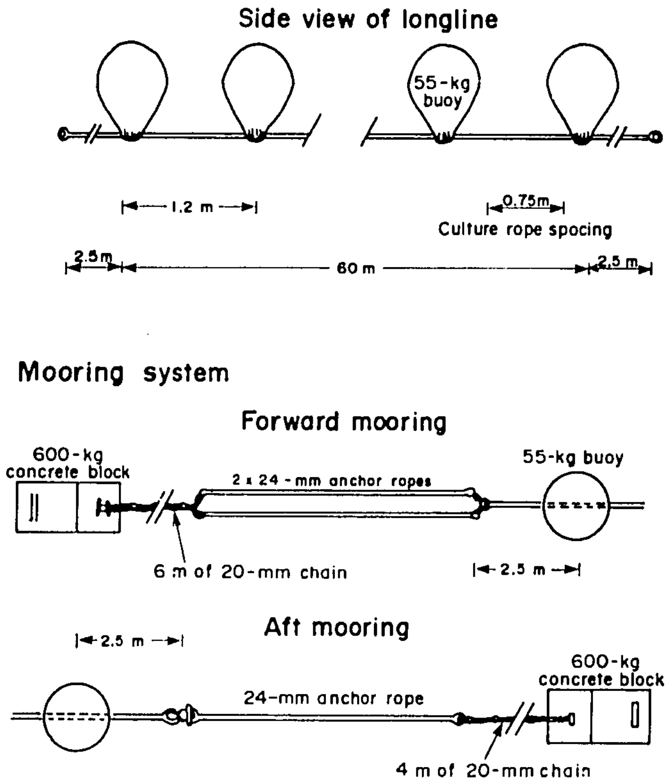


Fig. 10. Construction details for a standard 60-m longline system: reproduced Johns and Hickman (1985) with kind permission from the New Zealand Fisheries Research Division.

to the lower end of all culture ropes to keep them suspended vertically in the water column. If available, concrete-filled cardboard containers (as e.g., those in which dairy products are sold) can conveniently be utilized. Johns and Hickman (1985), however, caution against the use of galvanized wire for attachment of the weights to the culture ropes. Once the galvanizing is cracked, the wire has only a short life span. Rope offcuts, in contrast, are much more durable.

Spacing between single longline units should be maintained at 15-20 m to allow for lateral movements of the lines and ample room for service and harvest vessels. Harvesting could be done best from a catamaran-style pontoon with a simple derrick for lifting the heavy culture ropes (Johns and Hickman 1985).

Hatchery Techniques

The development of shellfish hatcheries is seen as a possible option to ensure regular seed supply through artificial seed production (Alagarswami 1980). Although a number of commercial oyster, clam, and abalone hatcheries exist, little attention has been paid to the development of mussel hatchery technology except in China (Nie 1982), Tahiti (AQUACOP 1982) and Thailand (Sahavacharin et al. 1988). This general disinterest results primarily from most mussel producing countries not being faced by any crisis of seed shortage (Silas 1980) and from the generally gloomy aspect of the economic viability of mussel hatcheries (Yap et al. 1979).

Except for a few cases of experimental rearing of *Perna perna* in Brazil (Romero 1980), most studies on artificial breeding have been concentrating on *Perna viridis*. *P. viridis* is known to be easily induced to spawn. The method most commonly applied is thermal shock, either through progressively heating the water up to 35°C (Rao et al. 1976; AQUACOP and de Gaillande 1979; Coeroli et al. 1984) or through repetitive temperature changes (Sivalingam 1977; Sahavacharin et al. 1984). Other methods successfully tried include changing of water (Tan 1975a) or the adding of hydrogen peroxide to the culture water at a concentration of 100-150 ppm. When left in the solution for 8 hours and then placed in a raceway with clean seawater, *P. viridis* with ripe gonads spawned after 1 to 4 hours (Sahavacharin et al. 1984, 1988).

Siddall (1978) used response surface analysis to investigate the changing environmental requirements associated with the various developmental stages of the larvae of *P. viridis* and *P. perna*. He concluded that for both species salinity affected growth and survival to a lesser extent than did temperature. Romero and Moreira (1981) achieved similar results when they tested the survival of embryos and veligers of *P. perna* in different temperature and salinity combinations. They noted that embryos were much less resistant to temperature and salinity variations than were the veligers. Seventy per cent survival of embryos was recorded from only a small range of combinations (20-25°C, 25-35 ppt), while 70% survival of veligers was observed in combinations of temperature and salinity ranging from 10-30°C and 25-35 ppt, respectively.

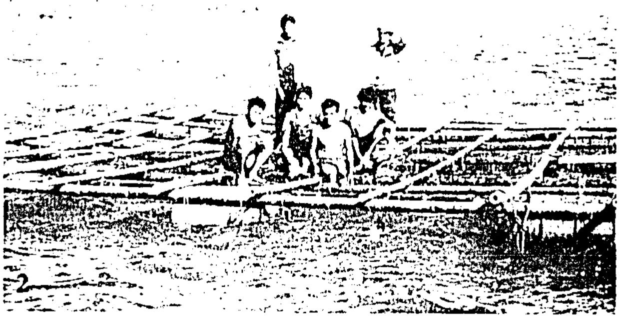
Though Siddall (1978) could trace different salinity optima for the first 24 days of the larval stages, no trend became apparent in the changes of these optima with time. Also, optima were different depending on whether growth or survival or both combined were to be maximized. Similar inconclusive results were obtained regarding specific temperature optima. In both *P. viridis* and *P. perna,* however, highest survival rates occurred at significantly cooler temperatures than did highest growth rates. Below 18°C, larvae stopped feeding.

Rao et al. (1976) fed the larvae of *P. viridis* with different species of algae and found a mixture of *Synechocystis* sp. and *Tetraselmis gracilis* to produce best growth. Other species of algae commonly used in the diet of *P. viridis* larvae are *Isochrysis galbana* and *Tetraselmis* sp. (Sahavacharin et al. 1984).

In an experimental hatchery in Tahiti, AQUACOP and de Gaillande (1979) were quite successful in rearing larvae of *P. viridis* through metamorphosis to the point of transfer for grow-out. Initially two algal species, *Isochrysis* sp. and *Monochrysis lutheri* were used in equal proportions of 25,000 cells each per ml to feed the mussel larvae. On settlement this quantity was reduced to 12,500 cells/ml and *Skeletonema costatum* was added at a rate of 50,000 cells/ml. The whole culture was also successfully carried out using only the two species *Isochrysis* sp. and *Chaetoceros gracilis*.

After about 15 days from fertilization, black polythene nets (AQUACOP and de Gaillande 1979), pieces of bamboo (Sahavacharin et al. 1984) or any other suitable medium are hung in the culture vats to provide a substratum for the larvae to settle. AQUACOP and de Gaillande (1979), starting with an initial density of 2,000-5,000 D-larvae per liter, achieved a settlement rate of 30-60%. With a survival of 90% during the ensuing stage AQUACOP and de Gaillande (1979) were able to produce in 1978 six million spat of *P. viridis* within one year, which were transferred to lagoons for the growing-on stage.

Aspects of Mussel Culture



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Photos by
J.M. Vakily

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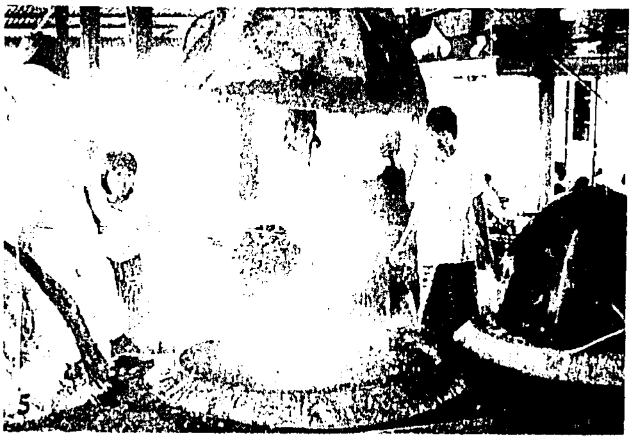


1. Construction of an experimental raft for mussel culture by the Brackishwater Fisheries Department, Thailand.

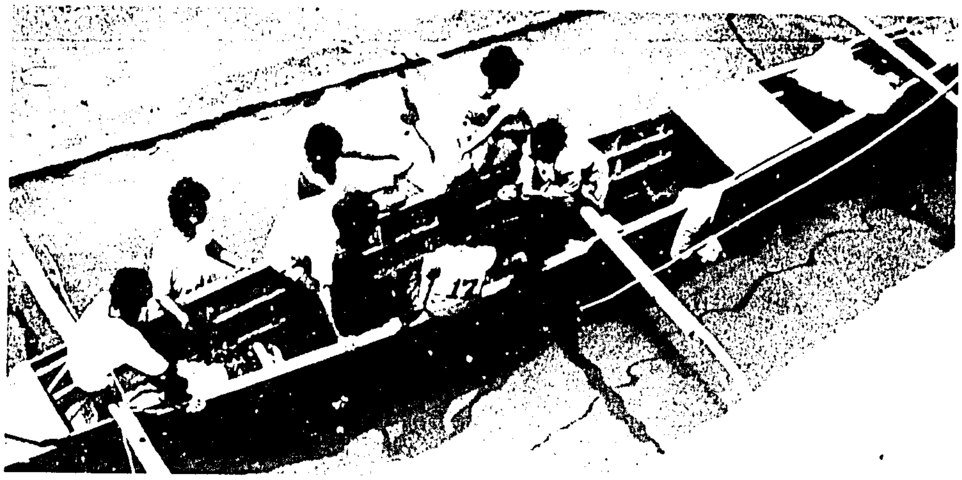
2. Experimental raft for mussel culture of the Thai Brackishwater Fisheries Department, Chumporn, Thailand.

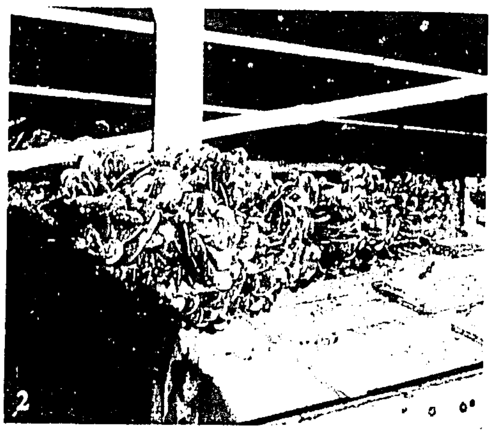
3. Harvesting of *Perna viridis* from bamboo poles, Chumporn, Thailand: removal of mussels with an iron rod.

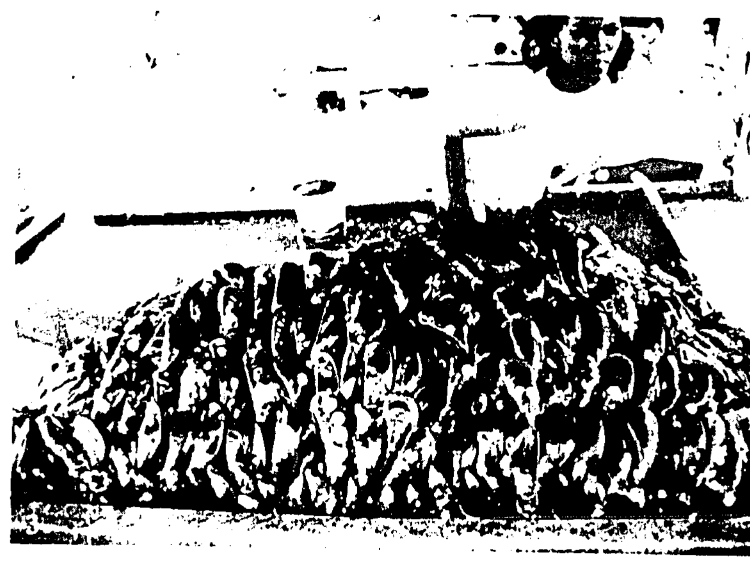
4. Processing of *Perna viridis*, Phetchaburi, Thailand: sorting of live mussels.

5. Processing of *Perna viridis*, Chonburi, Thailand: steam-boiling of mussels.

6. Processing of *Perna viridis*, Chonburi, Thailand: packing on ice of boiled mussels.







1. Landing of mussels at a mini landing port in Parañaque, Metro Manila, Philippines. Photo by R.B. Estarez.
2. *Mytilus smaragdinus* (local name: tahong) in Jaibong, northern Samar, Philippines.
3. Mussels sold to motorists in Parañaque, Metro Manila, Philippines. Photo by R.B. Estarez.
4. Harvesting mussels in Singapore.

Postharvest Handling

Mussels are a highly perishable product that require intensive care if the quality is to be maintained for some time after harvesting. Principally, mussels can be supplied to the consumer in two forms: live or processed. Whether keeping the mussels alive or having them processed, all post harvest handling should aim at reducing contamination with and growth rate of spoilage organisms. This is primarily achieved by controlling factors like temperature, pH, and amount of air present (Warwick 1984; Doe 1986).

In many countries throughout Asia mussels are sold primarily fresh in-shell. Malaysia, for example, does not report any processing at all (Oon et al. 1982), while in the Philippines at least a small amount is processed (Young and Serna 1982). In India (Silas et al. 1982) and Singapore (Cheong 1982) possibilities of processing *P. viridis* have been investigated experimentally. In contrast, Thailand has a very extensive processing industry at the village level (Saraya 1982; Vakily 1986), and even maintains a small export production to neighboring countries in Southeast Asia (Choo 1983; Wattanutchariya et al. 1985).

In New Zealand there exists a highly developed processing industry for *P. canaliculus* (Warwick 1984). Advanced technology allows New Zealand to supply the U.S.A. market with chilled live mussels. Besides being marketed along the traditional lines, *P. canaliculus* is also the base of a para-pharmaceutical product called "Seatone". Its claim to alleviate the symptoms of arthritis has lead to debate among medics and scientists in New Zealand and elsewhere over the scientific validity of the purported anti-inflammatory activity of the product (Miller and Ormrod 1980; Couch et al. 1982; Weston 1983; Weston and Patterson 1983).

Except for the New Zealand mussel industry, the degree of mechanization in postharvest handling is generally low. The very labor-intensive processing of *P. viridis* in Thailand is undertaken by small-scale processors who use their own family or hired personnel for manually declustering, "debearding" (removing the byssal threads) and cleaning the mussels (Vakily 1986). In order to handle large quantities of mussels in short time various types of machines have been developed in Singapore that can break up the mussel clusters into individuals, clean and grade them, remove byssal threads, and separate the meat of cooked mussels from the shell. These machines will handle between 0.6 to 1 tonne of individual mussels per hour (Cheong and Lee 1984).

Live Mussels

The shelf-life of live mussels and the rate of quality loss largely depend on the temperature at which they are stored or transported. Fig. 11 shows the length of time live mussels can be stored and still retain the quality standard of recently harvested live mussels. The optimum storage temperature ranges between 2° and 4°C. At 0°C, the mussels die and their shelf-life is reduced to one day, while at temperatures above 5°C the shelf-life also rapidly decreases.

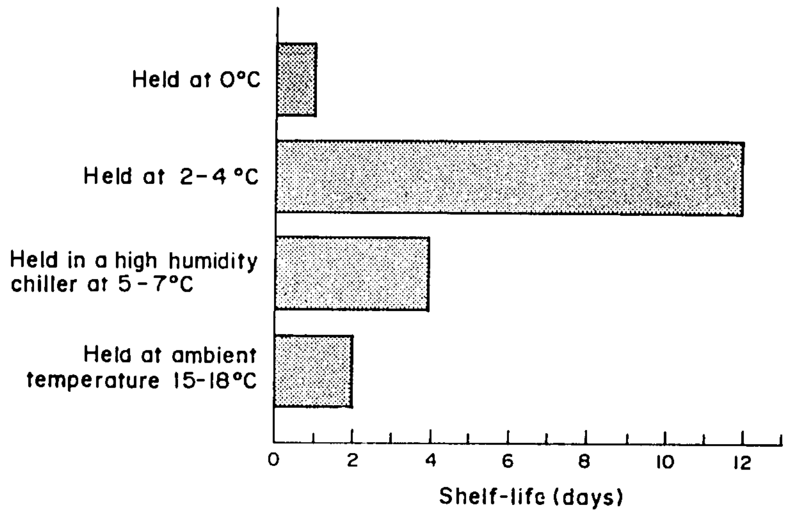


Fig. 11. Average shelf-life of live mussels held at different storage temperatures (after Boyd and Wilson 1982, modified).

Warwick (1984) recommended the following technique to efficiently chill live mussels:

- mussels are packed into insulated containers, covered with a layer of sack-cloth or any other piece of perforated material;
- sacking is covered with a layer of ice at a ratio of 1 part ice to 3 parts mussels;
- melt water must run over the mussels and then be drained away or allowed to collect in the bottom of the container;
- mussels should never remain immersed in melt water for any length of time;
- saltwater ice should not be used (except as a pre-chilling technique), because its temperature is about -3°C, which will cause the mussels to die.

In the Philippines, Yap and Orano (1980) tried a similar technique but kept the ice inside a metal container to prevent it from dripping on the mussels. This resulted in a storage temperature of 6° to 9°C and an average shelf-life of four days. Even though the maximum shelf-life was not realized, the method compared favorably in both survival rate of the mussels and flesh quality with more traditional forms of packaging (e.g., in sacks without cooling) where 50% mortality was reached after 36 hours and total loss occurred after three days.

Preventing the melt water from dripping on the mussels might indeed be most appropriate in areas where the cleanliness of the water used to produce ice cannot be guaranteed. This would eliminate an additional source of bacterial contamination.

A rather different approach to supply the market with live mussels was observed by Yap and Orano (1980) in the Philippines, where *P. viridis* is kept in holding facilities (net cages, concrete tanks) before being further transported to the market. They noted that even though holding facilities might increase the survival rate, the overall economic value of the animals decreases due to spawning. Mussels are known to be easily induced to spawn by removing them from the water for some time and subsequently re-immersing them. Spent mussels have only low nutritional and, hence, economic value.

Processed Mussels

Processing of mussels could have a crucial role in promoting mussel culture. Major markets are usually quite distant from the mussel producing areas. Processing allows the shelf-life of the product to be increased long enough for the mussels to reach the market in an acceptable form. Processing also greatly reduces the cost of transportation, because both the weight and volume of the product to be transported are substantially smaller once the mussels are separated from the shell.

There are principally two ways of removing the mussel from the shell, depending on what further processing is intended (Vakily 1986):

- manual shucking, i.e. forcing the shells open by means of a knife and severing the adductor muscle;
- Steaming, i.e., using heat treatment to open the shells before the mussel meat is shucked.

Table 9 gives an overview of the various processed forms of mussels typically available in Thailand and their respective shelf-life.

Table 9. Mussel products and average shelf-life.

Method of opening shells	Manual			Steaming		
Product form	fresh shucked	sun dried	pickled	steamed	sun dried	frozen
Form of packing	plastic bag, ice	plastic bag	tin container	plastic bag, ice	plastic bag	cardboard
Average shelf-life	1 day	3-4 days	20 days	4 days	3-4 days	3-10 months
(Source)	1)	2)	2)	3)	2)	4)

Source: 1) Vakily (1986); 2) Wattanutchariya et al. (1985); 3) Tokrisna et al. (1985); 4) Boyd and Wilson (1978).

FRESH SHUCKED

After shucking mussels, the meat is packed in plastic bags and ice is added. In Thailand, with its high ambient temperature, the ice has to be renewed at least once before the product reaches the retail market (Vakily 1986). The possibility of bacterial contamination is relatively high, since no special heat treatment is used. The addition of ice - besides being a source of contamination itself - usually does not effectively reduce bacterial growth or residual enzymic activity because the ice melts rather rapidly.

SUN DRIED

Fish processing by drying the product in the sun is commonly practiced in most traditional fisheries in tropical countries. The technique is simple and does not require expensive equipment.

Basically, preservation is achieved by reducing the amount of free or loosely bound water in the foodstuff that is susceptible to microorganism growth and enzymatic or chemical reactions. A measure of this unbound water is the "water activity". (For an introduction to the concept of water activity see Troller and Christian (1978) and Lupin (1986).)

Water activity is closely related to the product's moisture and salt content. For a given moisture content, the water activity decreases with increasing salt content (Doe 1986).

Translated into practical application, this means that placing the product in a brine solution for a short period prior to the drying process will positively assist in the removal of the water from the flesh.

The simplest method of drying mussels involves shucking the meat, spreading it evenly over a flat surface such as netting or bamboo racks and leaving it exposed to the sun for a few hours (Vakily 1986). When using bamboo racks, the meat is turned after some time by placing a second rack on top of the mussels to hold them in place and then turning both racks together in a swift movement. The use of netting material makes this "turning" superfluous, as the meshes allow the whole surface of the mussel meat to have contact with the air.

In Thailand, this method has been replaced in recent years by a slightly more sophisticated procedure (Vakily 1986). The mussels are thoroughly shucked in order to not destroy the mantle texture. The meat is then left for some time in a weak brine before it is placed on cloth or netting material with the two sides of the mantle carefully flattened and spread out, taking the shape of a "butterfly".

Though more labor intensive, this method has some clear advantages:

- use of brine prior to drying decreases the water activity and hence reduces the possible growth of spoiling organisms;
- spreading and flattening increases the surface area, resulting in a better evaporation rate (Doe 1986);
- careful handling gives the product an appealing look, making it more attractive to potential consumers.

The usual drying time for mussels in Thailand is about 5 to 6 hours during which the moisture content of the meat is reduced to 40-50% (Vakily 1986). The average shelf-life of this product is 3-4 days (Wattanutchariya et al. 1985). Chongpeepien et al. (1984) showed that the moisture content could be as low as 10-15%, if the drying period were extended to 9 to 10 hours. Very dry products could realize a shelf-life of up to two months (Wattanutchariya et al. 1985).

PICKLED

Pickling is another way of preserving freshly shucked mussels. In its most basic form, mussel meat and salt are mixed at a ratio of 7:1 and then left in large jars for about a week. After this period they are repacked in tin containers lined with plastic bags (Wattanutchariya et al. 1985). Instead of using merely salt, a more refined product can be obtained by mixing the mussel meat with a spicy sauce like the Thai fish sauce ("nam plaa"), which by itself has a high salt content (Wattanutchariya et al. 1985). Such products would have an average shelf-life of 20 days without refrigeration.

MARINATED

Marinated mussels are mussels preserved in acetic acid, with salt added to render the proteins insoluble and, thus, prevent excessive loss of proteins from the mussels (Warwick 1984). This method is mainly found in the processing of *P. canaliculus* in New Zealand, but could without doubt be applied to any other species of *Perna*. Warwick (1984) recommends that the ratio of mussels to marinade should be 1.5 : 1 by weight; the acid content of the final pack after processing should be 2.0% and the pH must be 4.2 or below to stop food poisoning bacteria from growing. He indicates that the product has a shelf-life of only a few days when kept at ambient temperature above 10°C, but storing it at 1-4°C can extend the shelf-life to about two months. Six months shelf-life without the need for refrigeration could be achieved if the marinated mussels were pasteurized at 85°C.

When using heat processing to open mussels, steaming time is critical. Warwick (1984) notes that "it must be long enough to open the mussels for shucking and destroy the spoilage organisms, but not so long that large weight losses occur or the mussel meat toughens." Boyd and Wilson (1978) gave an optimum steaming time of 5 minutes at atmospheric pressure for mussels of 45-55 g live weight.

In Thailand, boiled mussels are a popular product that even has some potential for export. Wattanutchariya et al. (1985) report exports of dried boiled mussel meat to Hong Kong and Singapore and frozen boiled mussels to Australia totaling on average 90 tonnes per year. Mussels are steamed, shucked and then cooked again in a brine solution for a few minutes. After this, they are spread over a netting material for cooling and elimination of excessive water. Then they are packed in plastic sacks and stored in wooden crates with a layer of ice on top to keep the product chilled during transportation (Wattanutchariya et al. 1985; Vakily 1986).

If chilled at 1-4°C, boiled mussels have a high quality shelf-life of 2-3 days (Warwick 1984). Wilson and Brooks (1984) found that a modified atmosphere packaging using at least 96% CO_2 would give a high quality shelf-life of 10 days if stored at 0°C.

FROZEN

The production of frozen mussel meat is found solely in export-oriented processing industries. It has been reported from only a few countries, namely Thailand (Wattanutchariya et al. 1985), New Zealand (Warwick 1984) and India (Silas et al. 1982).

In Thailand, meats are frozen at -40°C for 10 hours and than stored at -18°C prior to export (Wattanutchariya et al. 1985). Boyd and Wilson (1978) recommend frozen storage at, -29°C, which would guarantee a shelf-life of 10 months, compared to only 3 months shelf-life when stored at -20°C (given the mussels had been steamed for 5 minutes before freezing and all processing steps had been carried out with minimum delay!).

In New Zealand, mussels frozen on the half shelf were developed specifically for export to Japan (Hickman, pers. comm.). Half-shell mussels are considered to be more of a premium product than frozen blocks, individually quick frozen mussels, or shatter packs (Warwick 1984).

SMOKE-CURED

So far, only little research has been done on the possibilities of smoke curing mussels. In India, Muraleedharan et al. (1979) developed a technique of smoking mussels with a resulting shelf-life of more than 6 months. More recently, Mendoza (1986) concluded from some preliminary trials that traditional Philippine methods of fish smoking could successfully be applied to *P. viridis*. A certain exception, once again, is New Zealand, where smoked mussels are becoming increasingly popular, holding a share of 8% in the domestic market (Hickman, pers. comm.).

Public Health Aspects

Bivalves such as *Perna* are mostly cultured in coastal and estuarine areas and may thus be exposed to industrial waste and sewerage discharges. Studies on European mussels have shown their general tolerance to a wide range of environmental contaminants and also their ability to accumulate pollutants from the environment without these pollutants limiting their distribution (see Roberts (1976) for a comprehensive review). To not only ensure the wholesomeness of the product but also assist in the choice of sites for farming the mussels, there is a clear need to monitor heavy metals and other possible pollutants in prospective or existing culture areas (Tan and Lim 1984). Depuration techniques are extensively studied in connection with European mussel industries but so far have received little attention in tropical regions (De Guzman and Mabesa 1985; Rosell 1985).

Bacterial Contamination

The presence of bacterial and viral pathogens are usually the consequence of sewage pollution (Lewis et al. 1986). Lewis et al. (1982) describe a technique to detect and identify human enteroviruses from contaminated mussels using pH-mediated elution and acid precipitation. The level of pollution is often closely related to the discharge of freshwater from land. This makes it in some cases mandatory to develop guidelines to restrict harvesting of mussels following periods of heavy rainfall (Brock et al. 1985). Contamination with bacterial and viral pathogens presents a major risk to the consumer, especially when the mussels are eaten raw or only lightly cooked (Roberts 1976; Pillai 1980). Viral infection from eating oysters that lead to infective hepatitis has been well documented (Mason and McLean 1962). Lack of awareness of the possible linkage between human fatalities and the consumption of mussels might be the primary reason that so far no reports exist on bacterial disease transmitted through consumption of any of the *Perna* species.

Depuration of mussels is recommended when they are to be eaten raw or semi-cooked. Studies in Singapore showed promising results when highly polluted mussels, stocked at a density of 100 kg/m^3 water in a recirculating seawater system, were depurated to acceptable limits (< 20 MPN Escherichia coli/g flesh) within 48 hours (Cheong and Monzil 1982). The water was sterilized by means of ultraviolet radiation. Water flow was maintained at 6 m^3/hour, with a complete replacement of the water after 24 hours. De Guzman and Mabesa (1985) evaluated the organoleptic properties of *P. viridis* depurated in stagnant water and sucrose solution (200 ppm) and found color, texture, flavor and general acceptability not affected by the depuration. They noted, however, a significant change in fat and protein content after 24 hours period of depuration.

Paralytic Shellfish Poisoning

Many countries with good prospects of culturing *Perna* have become increasingly aware (see various regional reports in White et al. 1984) of the grave public health and economic problems associated with the sporadic outbreak of paralytic shellfish poisoning (PSP). Bivalves, including *Perna* can carry substances poisonous to humans as a result of bio-accumulated toxins produced by a small number of species of dinoflagellates, notably those belonging to the genus *Gonyaulax* (= *Protogonyaulax*), *Gymnodinium* and *Pyrodinium* (Roberts 1976; Ferraz-Reyes et al. 1985). The toxins isolated from infected shellfish were in general derivates of saxitoxin, neosaxitoxin or gonyautoxin (Gacutan et al. 1984). They belong to the class of neurotoxins which cause symptoms such as weakness of the limbs, fatigue, and numbness and tingling in the fingers, toes, lips and tongue of humans (Jaafar and Subramaniam 1984). The toxins are heat-stable (Arafiles et al. 1984), but detoxification down to acceptable levels within 6 to 7 days can be achieved by treatment with ozone or PVP-iodide-iodine complex (Gacutan et al. 1984).

White et al. (1984) suggest that standardized toxicity testing be applied such as the standard mouse bioassay technique (Horwitz 1980) advocated by the AOAC. The toxicity threshold set by the United States Food and Drug Administration for closure of shellfish beds is fixed at 80 μg toxin/100 g mussel flesh (Gacutan et al. 1984). In dependence of the method applied, this represents approximately 400 mouse units (MU) per 100 g mussel flesh (Arafiles et al. 1984).

Throughout the Indo-Pacific region, *Pyrodinium bahamense* var. *compressum* (Maclean 1984) is considered the major causative organism of PSP. Tamiyavanich et al. (1985) suggested from their investigations that *Protogonyaulax tamarensis* triggered the occurrence of a few cases of PSP in Thailand in 1983.

The blooms of dinoflagellates that can pose an increased risk of PSP are usually called "red-tide". This phenomenon seems to be, therefore, of primary importance in any monitoring program. Maclean (1984) gives an account of (and a bibliography on) red-tide occurrences in the Indo-Pacific region. Jaafar and Subramaniam (1984) suggest aerial surveys, flown at an altitude of 300 m, to be most useful in detecting and monitoring red-tides. Wong Tung Sang and Ting Thian Ming (1984) caution, however, that PSP can occur, as in Malaysia, without any visible planktonic bloom. This might happen either because the concentration of dinoflagellates can reach toxic levels before their presence is manifest in red-tides (Arafiles et al. 1984) or because of the long retention period of the toxins in the shellfish, which can last for several months (White et al. 1984). The possible absence of clearly distinguishable indicators make standard monitoring programs indispensable. Plankton and sediment samples should be collected regularly together with oceanographic data (White et al. 1984). Their evaluation should enable the timely closing of mussel farming areas and the launching of public awareness programs.

Trace Elements

A substantial number of investigations has been carried out to determine concentrations of trace metals in *Perna*. This was born out of concern over the far reaching implications for human health of the mass-culture and marketing of marine organisms that could contain potentially dangerous levels of heavy metals.

So far no generally accepted standards exist for upper limits of heavy metal concentrations in bivalves. The reason for this has to be seen in the fact that only the final concentration of contaminants in humans is of real concern. Recommendations on maximum tolerable levels of contaminants in humans are published by the World Health Organization (OMS 1978). Relating this to recommended upper concentration limits of heavy metals and other contaminants in bivalves on a global scale is impracticable. National differences in consumer preferences have to be considered when determining the respective thresholds of tolerable contamination. Regulations, therefore, vary from country to country as has been shown in a compilation of relevant data by Nauen (1983).

In Thailand, trace metal concentrations in *P. viridis* and other economically important shellfish species have been investigated by Huschenbeth and Harms (1975), Menasveta and Cheevaparanapiwat (1981), Hungspreugs and Yuangthong (1984) and Phillips and Muttarasin (1985). With the exception of the data presented by Menasveta and Cheevaparanapiwat (1981) the results suggest that the contamination of *P. viridis* with trace metals is at acceptable levels in Thailand. The extremely high levels of lead reported by Menasveta and Cheevaparanapiwat (1981) are rejected both by Hungspreugs and Yuangthong (1984) and Phillips and Muttarasin (1985), methodological problems being cited as the probable reason for the observed disagreement. Phillips and Muttarasin (1985) concede that "the analysis of marine organisms for lead has been fraught with difficulties throughout the last decade".

Sivalingam and Bhaskaran (1980) investigated environmental pollution at various coastal stations along the Island of Penang, Malaysia, in 1978 and determined trace metal contents in cultured *P. viridis*. Except for nickel (Ni) at 46 ppm, total trace metal content was still within acceptable limits.

Hungspreugs and Yuangthong (1984) found a marked increase in the levels of chromium (Cr) and copper (Cu) in mussels during the rainy season and related this to the reduced salinity of the water. A similar pattern of seasonal variation in the levels of trace metals in *P. viridis* was observed in India (Lakshmanan and Nambisan 1983). The authors cite low pH values during the rainy season as a possible reason for the increased dissolution of precipitated forms of trace metals. This coupled with industrial effluents carried by the freshwater discharge and the increased rate of filtration in mussels would necessarily result in higher concentrations of trace metals in *P. viridis*. Soria (1988), investigating the contents of trace metals in *P. viridis* in the Manila Bay, Philippines, also noted an increased heavy metal level in the mussels during the rainy season. She concluded, however, that lower concentrations (in relation to dry flesh weight) during summer were probably a mere "dilution effect", caused by the mussels being in better condition.

Pollution Monitoring

Bivalve molluscs are commonly used as sentinel organisms to monitor aquatic pollution by conservative contaminants which they accumulate above ambient levels (Watling 1983; Tan and Lim 1984; Phillips 1985). Whether any of the *Perna* species can act as bio-indicators largely depends on their capacity to reflect efficiently and accurately ambient concentrations of the pollutants. Cossa (1988) investigated data on cadmium content in *Mytilus* worldwide which also included some information on *P. viridis*. He found a highly significant relationship between cadmium concentrations in mussel soft tissue (Cd_{mussel}, in µg/g dry weight) and seawater (Cd_{water}, in ng/liter) of the form:

$$Cd_{mussel} = 0.39 + 0.074 \cdot Cd_{water}$$

Cossa (1988) used this relationship to suggest that in mussel breeding areas a standard of 150 ng/liter should be proposed as the upper limit for cadmium content of the seawater.

Tan and Lim (1984) have shown that the uptake of lead in *P. viridis* is almost linear over a period of seven days. In addition to the tracing of lead concentrations, Phillips (1985) considered *P. viridis* was also very suitable for the monitoring of copper, organochlorine pesticides and PCBs. He doubted, however, whether the same held true for cadmium, mercury and zinc. In experiments with *P. viridis*, D'Silva and Kureishy (1978) found a linear uptake of copper and zinc. They calculated the rate of uptake to be 0.14 and 0.22 µg/g/week in 0.005 and 0.01 ppm copper concentrations, respectively. In 0.1 and 0.2 ppm zinc the estimated rate of uptake was 1.16 and 8.01 µg/g/week, respectively.

Rosell (1985) showed a continuous uptake of mercury in *P. viridis* exposed to a concentration of 100 ppb over a period of 45 days. He noticed that depuration was a very slow process. Even after 151 days of continuous self-cleansing, 15.3% of the total mercury body burden remained unpurged. Sivalingam and Bhaskaran (1980) concluded from their studies that *P. viridis* could be used as a bio-indicator for cadmium, cobalt, chromium, copper, nickel, and lead, but was unsuitable for iron, manganese, and zinc.

De Rezende and de Lacerda (1986) investigated the influence of sex, size and substrate on the bio-accumulation of heavy metals in *P. perna* along the coast of Rio de Janeiro, Brazil. Beside substrate-specific differences in the uptake of Fe and Ni, they also found concentrations of Ni to be positively, and Fe and Cu to be negatively correlated with the size of *P. perna*. De Rezende and de Lacerda (1986) could not trace any sex-related differences in heavy metal uptake, but Asso (1982) mentions a higher degree of accumulation of Zn and Mn in males of *P. perna* collected off the Algerian coast.

Investigations into the bio-accumulation of radionuclides along the Rio de Janeiro coast (Brazil) in *P. perna* revealed significant levels of ^{210}Po (Gouvea et al. 1987). This endorsed an earlier assumption that *P. perna* might be a valuable bio-indicator for radioactive pollution of the marine environment (Gouvea et al. 1985). Nagarajah et al. (1985) studied the reaction of *P. viridis* to different water soluble fractions of diesel fuel. They noted that byssal thread production and, hence, attachment, was significantly depressed in all but very low concentrations of the toxicant. A similar effect on byssus production was observed under ammonia stress (Menon et al. 1983).

Ni and Huang (1985) investigated the load of fecal coliforms in the waters around Hong Kong. Though tremendous differences in bacterial contamination between sites existed, they found a close relationship between the number of fecal coliforms in the water and in bivalves, one of which was *P. viridis*.

Economics of Mussel Culture

Large-scale production of mussels is confined to the exploitation of *P. viridis* in a few countries in Asia and the highly industrialized farming of *P. canaliculus* in New Zealand (Table 10). To date, no significant utilization of *P. perna* has been reported. Both in Thailand and the Philippines a substantial amount of mussels is harvested annually. In terms of economic value, however, the production represents only a small share of the value of the total fisheries production (Table 11).

Table 10. Annual production of mussels of the genus *Perna*, summarized for the major producer countries.

Species	Country	Production method	Annual production (t)	Authority
P. viridis	Thailand	stakes	25,000	FAO (1989)[1]
	Philippines	stakes	13,258	FAO (1989)[1]
	Malaysia	raft	709	FAO 1989[1]
	India	fishery	3,000	Alagarswami et al. (1980)
	Singapore	raft	250	Cheong and Loy (1982)
P. canaliculus	New Zealand	longline	17,000	FAO (1989)[1]
P. perna	Venezuela	raft	460	FAO (1989)[1]

[1]Production data refer to the year 1987.

Table 11. Economic importance of the production of the green mussel *Perna viridis* in Thailand and the Philippines (source: SEAFDEC 1986)

	Thailand		Philippines	
	Quantity ($x10^6$ t)	Value ($x10^6$ US$)	Quantity ($x10^6$ t)	Value ($x10^6$ US$)
Fishery Sector				
Total production	2.1.	774	2.1	1,644
Mussel Culture				
Total production	0.76	4.4	0.22	10.3
Share of total fishery production	3.6 %	0.6 %	1.0 %	0.6 %

Few studies have been carried out on the economic viability of mussel culture in the tropics and subtropics though it is recognized as offering opportunities for employment and income to a considerable part of the populace in coastal areas. Economic and financial analysis, especially in the assessment of new culture techniques, is often confined to data generated by experimental or demonstration projects. Given the vagaries of extrapolating such findings to large-scale operation, many of the results presented have to be considered preliminary until more reliable estimates of basic commercial production figures are available. This, however, does not invalidate the general tendency of most reports that depict mussel farming as an economically viable alternative among the various aquaculture systems, if appropriate technology is applied. Mussel culture should be given due consideration in the general planning for the management of coastal resources in most tropical and subtropical countries.

The economics of stake culture of *Perna viridis* in Thailand are characterized by a marketing system that channels the mussels from the farmer to the final consumer through a widespread net of intermediate processors and collectors. The system has been extensively described by Tokrisna et al. (1985) and Wattanutchariya et al. (1985). Kao-ian (1988) computed an average profit of 120% on total investment cost for stake culture of green mussel in Thailand. His analysis showed that large regional differences exist with the respective profits ranging from 31% to 266%.

A detailed analysis of standardized profit margins for the various forms of processed mussels was presented by Vakily et al. (1988a). This attempt to relate seasonal variations in profit to biological factors such as the condition index of the mussels yielded inconclusive results. The authors concluded that the price structure at lower levels of the marketing channel was predominantly influenced by economic factors and only to a small extent by biological aspects, an assumption also supported by McCoy et al. (1988).

These findings, and the often very small (Vakily et al. 1988a) or even negative (McCoy et al. 1988) profit margins for mussel farmers and village-based processors might find their explanation in a statement made by Sribhibhadh (1973), that "the economic dominance of the middlemen subjects fish farmers and shellfish growers to unfair price manipulations and, consequently, low return for the products."

Mussel farming is, nevertheless, attractive in Thailand, despite the unfavorable price environment. This is, among other factors, a consequence of the usually low economic status of the farmers, to whom even the smallest profit can still be an incentive, if the alternative is no income at all because of lack of alternative use of their labor in economically depressed coastal areas (McCoy 1985; McCoy et al. 1988).

Detailed studies on the economics of *P. viridis* cultured in the major mussel farming areas in the Philippines were presented by Orduña and Librero (1976), Guerrero et al. (1978) and Glude et al. (1982). As in Thailand, low return for the product was cited as a major constraint on the further development of the mussel industry. Other factors included irregular supply and demand. Market channels in the Philippines are comparatively simple since most mussels reach the consumer fresh in-shell (Glude et al. 1982).

The productivity of stake culture in terms of estimated annual yield per stake ranges from 9-13 kg (Guerrero et al. 1983) to 40 kg (Macintosh 1982). Glude et al. (1982) recommend a minimum economic size of 0.1 ha for a mussel farm employing the stake culture method. They admit, however, that depending on the economic status of the farmer, even farm sizes down to 0.06 ha still can be considered economically viable. Their report on the profitability of different culture systems projected for mussel farming at Samar in the Philippines, indicated an almost 50% increase in relative earnings for longline and rope-web systems compared to the traditional stake method (Glude et al. 1982).

Omar (1985) looked at existing coastal aquaculture practices in Malaysia and used economic criteria such as internal rate of return (IRR) to rank the various culture systems. Though mussels cultured on rafts came last in the list (together with shrimp culture in ponds), its IRR of 49% compared very favorably with any agriculture-sector investment, or with the IRR of 18.2% computed for the trawler fishery.

An investigation into the profitability of raft culture in Singapore (Cheong and Loy 1982) dealt with the economic aspects of high wages in the mussel farming industry. Though not yet a factor of too much concern in any other of the mussel producing countries in Asia, this aspect and its consequences for farm management should not be ignored.

In Singapore, staff emolument is the single most expensive item under "variable costs". Sensitivity tests revealed its relative impact on production cost to be greater than the cost of the raft. Cheong and Loy (1982) concluded that mussel farming in Singapore was economically viable only if the labor cost can be minimized and the yield increased. Reduction in labor costs could be achieved by:

- making the spat transfer operation superfluous through the use of polycoco ropes, which serve both as spat collector and grow-out medium;
- introducing a certain degree of mechanization in harvesting and postharvest handling, as, for example, described by Cheong and Lee (1984).

To compensate for the high capital outlay on rafts high yields are necessary. Cheong and Loy (1982) recommend a minimum farm size of 0.5-0.75 ha, if 20% utilization of the water space is assumed for suspending culture ropes, and two harvests per year can be achieved. Polycoco ropes have also proven most valuable in terms of production. After a six-month culture period, the average yield per 4-m rope was 56.37 ± 13.88 kg shell-on mussel. This compared well to the 45.97 ± 6.04 kg average yield that was obtained from 4-m polyethylene ropes.

Hickman (1987) gave an account of the economics of the New Zealand mussel farming industry, citing the availability of markets for the end product to be the major constraint on the further growth of this industry. Average production of P. canaliculus on longlines is high at 18 t/ha/year. Productivity and yield have a crucial impact on the profitability of a farm. A farm in a high tonnage, high yield area can realize a 20% return on total investment, while farms operating under less favorable conditions would show a return of less than 10% or losses even if the highest possible selling prices could be realized (Hickman 1987).

Research Needs

Applied research is still needed on *Perna*. Topics requiring further attention include its biology and ecology, culture technology, pollution and diseases, postharvest handling, and the economics of mussel culture.

Biology and Ecology

With available inshore waters becoming scarce for mussel culture, more information is needed on the growth potential of *Perna* in different ecosystems such as the open sea. For comparative purposes and to allow more reliable estimates of possible production, the carrying capacity of given ecosystems should be assessed and classified.

The relative ease with which mussels can be transplanted has raised questions on the ecological consequences of such actions, especially when used to introduce *Perna* as an exotic species to a new area. Beside the potential danger of also importing diseases so far unknown in the area, the remarkable adaptability of *Perna* to different environments could easily lead to undesirable changes in the ecological equilibrium.

Culture Technology

Most tropical mussel production still uses the bamboo and stake method. The large number of mussel culture experiments involving rafts, however, strongly indicates that mussel culture in the future will rely on some sort of rope culture system. Research should concentrate on the development of low-cost, simple farming methods that are appropriate to the educational and economic background of the target population. Studies are needed on the feasibility of extending mussel farming into more exposed waters in the open sea, with emphasis on the use of partly submerged systems.

Hatchery technology may not be an economically viable alternative in the near future, so methods of obtaining seed from the wild will have to be improved. This includes development of spatfall forecasting techniques through plankton sampling or monitoring of the gonad condition of mussels. Another means of increasing seed supply for farming is by transfer of spat over long distances. This technique, however, still needs improvement at least in those areas where deficiencies in the road network and other structural constraints often cause long delays in transportation. Studies could be undertaken to determine optimum conditions during transport to minimize overall mortality.

Pollution and Diseases

Much research is still required before regular monitoring programs for industrial pollution and the occurrence of toxic dinoflagellates can be set up. This research should also help to assess the reliability of *Perna* as a bio-indicator organism for heavy metal pollution.

So far, few studies have been carried out on the development of cost-effective depuration techniques for mussels in the tropics. Chlorination, ozonation, and ultraviolet light treatment are viable alternatives, but more information is needed on the long-term effects of such systems.

Postharvest Handling

The development of an intensive processing industry is a necessary prerequisite for the large-scale production of mussels. Consumer preferences for different product forms have to be investigated, and simple techniques should be developed for processing at the village level without compromising sanitation standards.

Economics

There is a strong need for detailed economic studies on the various farming systems in areas of existing or potential culture. Alternative production techniques should be assessed in terms of capital requirement, labor demand and engineering design, and in comparison with other possible forms of resource use. Though labor intensive techniques probably have better chance of being economically viable in most tropical countries, the feasibility of capital intensive, export oriented mussel culture should not be disregarded.

Studies should be conducted to determine what level of mussel production can be absorbed by local markets. Projection should also be made of the potential growth in both local and export markets for mussel products, so that coastal planning and mussel production can be synchronized with the development of markets for the resulting products.

Prospects and Constraints

Many of the countries in the tropics and subtropics are being challenged to raise the production of cheap animal protein to meet the needs of an ever increasing population. The spectacular decline in catch landed by some of the marine fisheries, as for example in the Gulf of Thailand, has forced governments to look at alternatives to capture fisheries. Aquaculture in coastal areas (or mariculture, as it is often called) seems to be a viable option in many respects: not only does it provide food of high nutritional value, but it also supports a most welcome diversification in the artisanal fisheries sector. Being usually labor intensive, it also creates opportunity for employment in areas that otherwise are often characterized by high unemployment especially among unskilled labor.

Mussels of the genus *Perna* are in many respects highly suitable candidates for culture in coastal areas. Being plankton feeders, they occupy a place low in the food chain, making their exploitation a very economic utilization of the primary production available in coastal waters. Mussels have a high protein content, averaging up to 67 g/100 g dry weight (Cheong 1982). This value compares favorably with other traditional food items such as beef, pork, or chicken, and underlines the importance of mussels as a source of inexpensive animal protein especially for that part of the population with low income.

So far, only Thailand, the Philippines and, to a lesser extent, New Zealand have ventured into the large-scale exploitation of *Perna*. Many other countries especially in Southeast Asia have shown interest in establishing and promoting mussel culture in their coastal waters. Annual yields have been projected ranging from 20-68 t/ha for stake culture to an estimated 300 t/ha for raft culture systems (Glude et al. 1982). These figures clearly show the enormous pote ial that lies in the artificial culture of mussels.

From a biological point of view, mussel culture apparently does not face serious problems. The elevated water temperature in the tropical zone supports a rapid growth of *Perna* which allows the mussels to be harvested at a marketable size of 50-70 mm after 6 to 7 months. This contrasts very positively with the 15 to 24 months it takes for *Mytilus* to grow to marketable size in temperate waters (Sivalingam 1977).

Regular seed supply is an important factor in the management of any bivalve culture. It is a general observation that in areas where *Perna* is established, the natural abundance of mussel larvae is usually sufficient in quantity to be not a limiting factor in culture operation, provided the farmers use appropriate spat collecting techniques. Establishment of *P. viridis* in areas where it is not endemic was successfully demonstrated in experiments carried out in Thailand (Brohmanonda et al. 1988), being proof of the feasibility and potential use of this method. On the other hand, the transfer of *P. viridis* from the Philippines to Tahiti has shown the limitations of this technique as the population is solely maintained by hatchery-reared spat. The ability of *Perna* to survive dry periods for some time and to adapt qu to new environmental conditions can also be used to overcome shortages in local seed supply by transferring spat from neighboring culture areas with more intensive spat fall. Mussel culture can successfully be implemented on very different technological levels, ranging from the simple cultivation of mussels on bamboo poles to more elaborate raft and longline systems. This permits introduction of mussel culture in communities with little or no previous experience in coastal aquaculture to be undertaken on a technological level appropriate to the skills and traditions of the target population. This in turn substantially increases the chances that mussel culture will be accepted as a full-time or additional occupation by a broad number of people with different vocational backgrounds.

The market for fresh mussels is usually limited in tropical countries, primarily because high ambient temperature represents a major obstacle to keeping the mussels in good condition over an extended period of time. Large-scale production of mussels, therefore, has to be combined with the development of processing techniques that - when kept simple - provide additional opportunity for employment. The very extensive processing of *P. viridis* in Thailand is an important economic aspect of this industry in many of the coastal villages. It allows especially women and elder persons to contribute to the family income, who otherwise would stand little chance of finding employment.

The success of the experimental mussel culture reported from a number of tropical countries justifies the assumption that biological problems do not pose a significant barrier to the dissemination of mussel culture. There are, however a number of socioeconomic factors that need careful evaluation before the transition from experimental to industrial-scale production of mussels can be considered. In most cases, these constraints are interrelated, and, therefore, require an integrated approach to overcome the difficulties. Typically, such constraints are:

- Coastal aquaculture, in contrast to aquaculture in inland waters, is practically unknown in most countries in the tropics. This holds especially true for the African continent. As a result, there is general hesitation on investment in this new venture often combined with inadequate training in the basic skills required in coastal aquaculture operations.
- Consumer acceptance for mussel products is generally low. It it is not uncommon to find areas with natural stocks of *Perna*, where these mussels are not considered fit for human consumption at all. A reason for this negative bias towards mussels is the often very low quality standard of the marketed products (be it fresh or processed) and the sporadic appearing of news on the outbreak of mussel-transmitted diseases. The low value of mussels compared to other seafood products also contributes to their negative image as the "poor man's oyster".
- Marketing of mussels in tropical countries is beset with a seemingly unsolvable contradiction: to keep the price of the end product low and thus affordable to the poor, the mussel farmer's profit margin must be minimal. This is an effective deterrent to many quality and production improving measures and a hindrance to the opening of new markets with a wider range of potential consumers.

Economic constraints, mainly in the form of unfavorable cost versus return relationships in the domestic market, are the most important factors limiting production of mussels and stalling technological improvements in culture methods. This applies both to the highly developed and industrialized mussel industry, as in New Zealand (Wellstead 1985), and to the traditional mussel farming systems found in various countries throughout Asia. In Thailand, for example, the market-dependent price structure is such that mussel culture is hardly remunerative to the farmers. Depending largely on the "middlemen" system, the farmer has little influence on the marketing system. The fact that mussel culture is nevertheless an attractive business in Thailand has most probably to be viewed in the light of the depressed economic situation of mussel farmers and their (almost non-existing) choice of alternative options. Provisions should, therefore, be made for setting up a marketing system that favors mussel farmers by securing a sizable share of the profit margin to be redistributed to the farmers. Otherwise, mussel culture technology (if not export-oriented) bears the risk of stagnation because of the lack of financial incentives for additional capital investment to improve culture methods.

Unsatisfactory consumer acceptance is usually a direct result of sanitation problems often encountered in mussel culture. The ability of mussels to accumulate heavy metals and other industrial pollutants has been extensively documented. Of even more severe consequence is the increasing number of reports of casualties caused by paralytic shellfish poisoning from toxic dinoflagellate blooms. Beside the tragic consequences for those directly affected, the spreading of news on mussel-related diseases usually leads to a complete, temporary collapse of the mussel market. A devasting blow is dealt to the economic situation of all farmers including those that might have cultured mussels in different areas and whose crop could be considered safe for human consumption.

Development of mussel culture, therefore, should be promoted in the context of a broad coastal management scheme which clearly separates areas assigned for industrial development from those areas reserved primarily for coastal aquaculture activities. In addition, programs should be established in the culture areas to monitor pollution levels and blooms of toxic dinoflagellates ("red tide"). Enforced temporary suspension of mussel harvesting could have a much less severe overall impact on the mussel farming industry than a complete loss of the crop due to rejection of the mussels by the consumer.

Contamination of mussels with fecal coliforms usually originates from the lack of sewage systems in coastal villages and the tendency to set up mussel farms in inshore waters. Since this form of pollution can be difficult to control locally, consumers should be educated through brochures on how best to prepare mussels for safe consumption. Personnel involved in postharvest operation (i.e., processing, packing, transport) should be trained in appropriate sanitation methods. The use of depuration techniques might have to be made mandatory in some areas. Ultraviolet radiation has been considered very suitable because it is easy to handle, has no residual effect and is comparatively inexpensive (Davy and Graham 1982).

Quality-control measures, of course, will increase the cost of production. They should, however, eventually help to remove the market bias against mussels as human food. This should lead to improved sales that most likely would offset the cost incurred in taking such measures.

Policy Implications

In the light of the socioeconomic constraints that tend to obstruct the large-scale implementation of mussel culture, governments must seek ways to improve the institutional framework under which mussel culture is to be developed. There is an immediate need of perspective planning and formulation of development priorities in coastal management (Silas 1980). This should take into consideration all potential forms of utilization of coastal resources, including navigational requirements. Farming of mussels requires a reliable system of leasing public water areas to individuals with protection against encroachment. Possible conflicts between traditional capture fisheries and culture activities should be anticipated and dealt with accordingly to ensure optimum conditions for the development of both fisheries sectors.

Governments should initiate programs that attract interest and investment of individuals and the industry. Especially in countries where the marine fisheries sector is under increasing economic pressure, incentives should be given to entice fishermen into mussel culture either as a full-time or part-time occupation with additional income potential. This would definitely require some sort of financial assistance from public institutions and should include - at least during an initial phase - an element of risk coverage. The industrial sector should be invited to assist in developing a domestic market for processed mussels and also to look into the potential of exporting mussels within the region.

One option so far widely overlooked concerns the utilization of mussels for other than human consumption. This includes the feeding of (mainly undersized) mussels to ducks, which McCoy et al. (1988) showed to be theoretically an economically viable use of this product. Using mussels for fish and shrimp feeds - either directly or as an ingredient - are other possibilities. In Singapore, mussels are mechanically crashed and fed to fish raised in cage culture (Prein, pers. comm.).

Propagation of mussel culture for other than human consumption has, however, two major drawbacks: by converting mussel meat into some other form of consumable product (i.e., fish, duck, etc.) almost 90% of the original energy contents of the product "mussel" is lost, a waste that is hardly justifiable in face of the urgent demand for cheap protein in many tropical countries. Secondly, while mussels sold as mussels are a commodity readily available to the low-income populace, mussels used as feeds will transform this cheap source of protein into a high-price commodity that is beyond the means of many of those that need it most. This option, therefore, should be considered only in cases where a surplus production of mussels exist, or where sociocultural aspects oppose the direct use of mussels for human consumption.

Introduction either of mussel culture technology in areas without existing traditions, or of technological improvements in already established mussel farming systems, has to be accompanied by extension work that provides hands-on training, such as the "lab-to-land" program initiated in India (Silas 1980).

Finally, all these measures are of little value, if the expected mussel production is not matched by a corresponding demand from the consumer. Authorities concerned have to initiate well-organized nutrition programs to increase consumer awareness and teach correct handling of the mussels. Regulations have to be set up and enforced that ensure a continuous high quality standard of the mussel products. This will in the long term benefit both the consumer and the mussel farmer. The consumer obtains a safe product of high nutritional value at an affordable price, and the farmer will be assured of a constant and calculable demand for his mussels.

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