Chapter 2
Activity Concentration and Radiation Dose due to $^{40}$K to marine biota

2.1 Introduction

As regards the radiation dose received by marine biota, $^{40}$K seems to be the most important natural radionuclide, since approximately 90% of the radioactivity of seawater is due to $^{40}$K (UNSCEAR, 1993; Jimonet and Metivier, 2007). Potassium is one of the structural elements of biota and in nature it has three isotopes namely, $^{39}$K, $^{40}$K and $^{41}$K. $^{40}$K has an abundance of 0.0118% relative to stable K, and a very long half-life of 1280 million years (Eisenbud and Gessel, 1997). Potassium is inevitable for carrying out different physiological functions in organisms right from nerve and muscle responsiveness, heart rhythm and metabolism of nitrogenous compounds to maintain the intercellular fluid pressure. Particularly in animals, the osmotic system is controlled by potassium. $^{40}$K finds its way into marine organisms along with stable potassium. Similarly to stable K, the accumulation and retention of $^{40}$K in organisms is homoeostatically controlled, irrespective of the fluctuation of this element in the environment. Hence, $^{40}$K delivers a stable radiation dose (UNSCEAR, 1982; Eisenbud and Gessel, 1997). However, as far as the radiation dose is concerned, $^{40}$K scores over the contributions of $^{210}$Pb, and the anthropogenic radionuclide, $^{137}$Cs. This is because the concentration of $^{40}$K seems higher than that of $^{210}$Pb and $^{137}$Cs, according to Malta and Carvalho (2011). Although $^{137}$Cs acts as an analogue of potassium, the rate of accumulation of this radionuclide by biota is very low because its concentration in seawater is inversely proportional to that of $^{40}$K (Whicker and Schultz, 1982). According to Aarkrog et al. (1997), among natural radionuclides, $^{40}$K is considered to
be the highest dose contributor besides \(^{210}\text{Po}\). Radiological assessment of this radionuclide in marine organisms hence merits attention. Although considerable studies have been carried out pertaining to the level of \(^{40}\text{K}\) in marine organisms in the Gulf of Mannar region (Khan et al., 2007; Khan, 2009), studies are scanty on non-human biota of the Kudankulam coast. Hence this study aimed to analyse the \(^{40}\text{K}\) activity concentration and radiation dose to various marine biota.
2.2 Material and methods

2.2.1 Study area

To analyze the baseline level of $^{40}$K in Kudankulam coastal waters and marine biota such as macroalgae, crustaceans, molluscs, echinoderms and fishes, samples were collected from seven stations along the coastal stretch covered within 30 km radius of the Kudankulam Nuclear Power Project (KKNPP). The sampling stations are situated on either side of KKNPP. Stations such as Kanyakumari, Chinnamuttom, Rasthacaud and Panchal, are situated on the western side and Kuthankuzhi, Idinthakarai and Uvari are on the eastern side of KKNPP (Fig. 1.1).

2.2.2 Collection of seawater and marine biota

Six stations around KKNPP from which the coastline watersamples were collected, are Kanyakumari, Rasthacaud, Panchal, Kuthankuzhi, Idinthakarai and Uvari (Table 2a). About 5 litres of seawater sample was collected from each location. Biota samples were collected from Kanyakumari, Chinnamuttom, Rasthacaud, Panchal, Kuthankuzhi, Idinthakarai and Uvari (Table 2a-2f). During the period of study, 2011-2013, samples were collected at an interval of 4 months. About 2 kg of biota sample was collected in polythene bags from the stations, based on availability. Details of the sampling and processing procedure are given in Sections 1.4.2, 1.4.3 and 1.4.5.1.

2.2.3 Analysis of $^{40}$K in seawater and marine biota

The preconcentrated seawater samples were filled in polypropylene containers and the preconcentrated biota samples were filled in transparent vials. The samples
were counted for $^{40}$K in a HPGe gamma counter. The detailed analytical procedure is given in Section 1.4.5.

2.2.4 Statistical analysis

The activity concentration of $^{40}$K in all the samples analysed in the present study were checked for normality. The below detectable limit (BDL) values were treated with fuzzy arithmetic analysis to calculate the percentile range. The details of the statistical analyses are given in Section 1.8.

2.2.5 Radiation dose estimation

The total radiation dose comprises the external and internal radiation dose. The external absorbed dose rate calculated for marine organisms using the following formula:

$$D_{\text{ext}}^j = \sum_i \text{DCC}_{\text{ext},i}^j \times C_{\text{water},i}$$

where $C_{\text{water},i}$ is the median concentration of the radionuclide $i$ in water (Bq l$^{-1}$, dissolved phase); DCC$^j_{\text{ext},i}$ is the dose conversion coefficient (Ulanovsky and Pröhl, 2008) for external exposure [a ratio of the dose rate to the organism $j$ to the average concentration of the radionuclide $i$ in the environment (water) (µGy h$^{-1}$ per Bq l$^{-1}$)].

The internal dose rate for biota can be derived from the activity concentration in the selected reference organism using the following equation:

$$D_{\text{int}}^j = \sum_i C_i^j \times \text{DCC}_{\text{int},i}^j$$

where $C_i^j$ is the activity concentration of the radionuclide $i$ in the biota $j$ (Bq kg$^{-1}$ f.w.) and DCC$^j_{\text{int},i}$ is the radionuclide-specific dose conversion coefficient for internal
exposure [a ratio of the dose rate to the organism to the average concentration of the radionuclide $i$ in the organism $j$ $(\mu$Gy h$^{-1}$ per Bq kg$^{-1}$f.w.)].

2.3. Results and Discussion

2.3.1. Seawater

2.3.1.1 Activity concentration

Seawater samples were collected from six locations around the KKNPP (Fig. 1). The activity concentrations are presented in Table 2a and Figure 2a. The mean activity concentration of $^{40}\text{K}$ was in the range of 4.4–7.9 Bq l$^{-1}$. The water samples of Kanyakumari showed the minimum activity and Uvari the maximum, 4.4 and 7.9 Bq l$^{-1}$, respectively. The observed results are within the range of Kudankulam inshore and offshore waters (3.8–8.4 Bq l$^{-1}$) reported by Khan (2009). But in general, the activity values obtained in the present study are comparable with that of the seawater samples of other coastal regions worldwide. The activity of $^{40}\text{K}$ in Kuwait coastal waters was found to range from 8.9 to 9.3 mBq l$^{-1}$ (Uddin et al., 2015); in coastal waters of Mumbai from 4 to 7 Bq l$^{-1}$ (Singhal et al., 2009); and in seawater samples collected from the southern coast of Bangladesh from 6.9 to 11.0 Bq l$^{-1}$ (Alam et al., 1999). The activity values observed in the present study are lower than that recorded in seawater samples of Karachi coast, Pakistan (14.43 Bq l$^{-1}$; Saleem et al., 2015); seawater samples of Straits of Malacca (14.5 to 20.1 Bq l$^{-1}$; Khandaker et al., 2015); coastal waters of northern Oman (132.6 to 148.87 Bq l$^{-1}$; Zare et al., 2015); coastal waters of Bay of Bengal (26.5 to 49.1 Bq l$^{-1}$; Bhuiyan et al., 2014); and seawater samples of Adriatic Sea [6063 to 10,519 Bq m$^{-3}$ (0.606 to 1.05 Bq l$^{-1}$); Petrinec et al., 2012]. The average activity of $^{40}\text{K}$ in the world’s oceans is 12.5 mBq l$^{-1}$ (Varksog, 2003), which is higher than the range reported in this study.
The activity concentrations of $^{40}$K in macroalgal species such as *Ulva fasciata* (chlorophyte), *Sargassum wightii* (phaeophyte), *Amphiroa anceps* (rhodophyte) and a seagrass, *Syringodium isoetifolium* were analysed (Table 2b; Fig. 2b), and the values fell in the range of 4.25–373.8 Bq kg$^{-1}$ f.w. The chlorophyte registered a lower $^{40}$K activity ranging from 4.25 to 8.13 Bq kg$^{-1}$ f.w. and the rhodophyte a higher (11 to 373.8 Bq kg$^{-1}$ f.w.). The sea grass displayed the activity value varying from 18.15 to 214 Bq kg$^{-1}$ f.w. The activity of $^{40}$K in the marine flora in this study was in the following order: rhodophyte>sea grass>phaeophyte>chlorophyte.

The activity values of $^{40}$K in the marine flora obtained in present study are higher than those (4–270 Bq kg$^{-1}$ d.w.) reported in samples collected from Kudankulam waters by Khan (2009). The activity values in the present study are concordant with values reported worldwide. The activity concentration of this radionuclide was in the range of 20.5 to 583 Bq kg$^{-1}$ f.w. in macroalgal species of Korean Peninsula (Lee and Lee, 2016) and it found to be higher in activity values than those of the present study. Certain activity values reported in the literature are lower than values observed in the present study. The macroalgal species of Black Sea displayed $^{40}$K activity ranging from 34 to 125 Bq kg$^{-1}$ f.w. (Nonova and Tosheva, 2014); those of the Black Sea, 7.2 to 200 Bq kg$^{-1}$ (Strezov and Nikolova, 2014); marine flora of south and north Pacific beaches of Fukushima Nuclear Power Plant, 34 to 109 Bq kg$^{-1}$ f.w. (Baumann *et al*., 2013); those of Moroccan coastal waters, 27 to 186 Bq kg$^{-1}$ f.w. (Benkdad *et al*., 2011); seaweeds of the Bulgarian Black Sea, 11 to 149 Bq kg$^{-1}$ f.w. (Strezov and Nonova, 2009); the rhodophytic species of
Bulgarian Black Sea, 7.2 to 165 Bq kg\(^{-1}\) f.w. (Nonova and Strezov, 2005); those of the Black Sea coast, 24 to 200 Bq kg\(^{-1}\) f.w. (Strezov and Nonova, 2005); macroalgae of the northern Pacific coast of Japan, 142 to 285 Bq kg\(^{-1}\) f.w. (Ishikawa et al., 2004); those of eastern Mediterranean waters, 5.6 to 200 Bq kg\(^{-1}\) f.w. (Al-Masri et al., 2003); those of eastern Black Sea, <13.6 to 102 Bq kg\(^{-1}\) f.w. (Topcuoğlu et al., 2003); and macroalgal species of the coasts of Oman and United Arab Emirates, 8 to 435 Bq kg\(^{-1}\) f.w. (Goddard and Jupp, 2001). 50 to 170 Bq kg\(^{-1}\) f.w. for those of Milos, Aegean Sea (Florou and Kritidis, 1991).

2.3.3. Crustaceans

2.3.3.1 Activity concentration

Crustacean species such as the Indian white prawn, *Fenneropenaeus indicus*, the mole crab, *Albunea* sp., the shore crab, *Ocypode ceratophthalmus*, the free-swimming crab, *Portunus sanguinolentus* and the rock lobster, *Panulirus homarus* were selected in this study. The activity concentration values of \(^{40}\text{K}\) are presented in Table 2c and Figure 2c. In these organisms, it ranged between 2.97 and 108.4 Bq kg\(^{-1}\) f.w. The mole crab registered the lowest and the rock lobster displayed the highest activity. They accumulated \(^{40}\text{K}\) in the order: rock lobster>white shrimp>shore crab>free-swimming crab>mole crab.

The activity of \(^{40}\text{K}\) in crustaceans (edible portion) reported in Kudankulam waters (7.5–138.5 Bq kg\(^{-1}\) f.w.) by Khan (2009) was found to be slightly higher than that of the present study. The values obtained in the present study are concordant with those reported in the literature. Of the studies conducted in various crustaceans, Khandaker et al. (2015) reported a mean value of 34 Bq kg\(^{-1}\); Amin et al. (2013)
reported values ranging between ND and 230 Bq kg\(^{-1}\) in South China Sea waters; Khandaker et al. (2013) between 216 and 316 Bq kg\(^{-1}\) in the west coast of peninsular Malaysia; Desideri et al. (2011) recorded the values between 95.8 and 137 Bq kg\(^{-1}\) f.w. in central Adriatic Sea; Hasan et al. (2006) between 4.92 and 14.07 Bq kg\(^{-1}\) f.w. in Bay of Bengal.

### 2.3.4 Molluscs

#### 2.3.4.1 Activity concentration

The molluscan species like the top shell, *Trochus radiatus*, the brown mussel, *Perna indica* and the cuttle fish, *Sepia pharaonis* were analysed for \(^{40}\)K. The activity values are presented in Table 2d and Figure 2d. The activity concentration of \(^{40}\)K in molluscan species varied between 9.93 and 123.4 Bq kg\(^{-1}\) f.w. Among them, the lowest was noted in the brown mussel, and the highest value in the cuttle fish. The activity concentration of \(^{40}\)K displayed by the molluscan species was in the order: cuttle fish>top shell>brown mussel.

The \(^{40}\)K activity results observed in molluscan species were compared with the literature available worldwide. Khan (2009) reported \(^{40}\)K activity for molluscs (edible portion) in Kudankulam waters (15.6-110.8 Bq kg\(^{-1}\) f.w.) and the values were concordant with those of the present study. The average activity level ranged between 41 and 48 Bq kg\(^{-1}\) for molluscs of coastal waters of peninsular Malaysia (Khandaker et al., 2015); 340.3 to 445.7 Bq kg\(^{-1}\) d.w. in *Mytilus galloprovincialis* of Marmara Sea (Kiliç et al., 2014); 300 to 353 Bq kg\(^{-1}\) d.w. in mussel samples of the Japanese shoreline (Baumann et al., 2013); 90 to 350 Bq kg\(^{-1}\) in molluscs of South China Sea waters (Amin et al., 2013); 118 to 281 Bq kg\(^{-1}\) in molluscs of west coast of Peninsular
Malaysia (Khandaker et al., 2013); 77 to 124.5 Bq kg\(^{-1}\) f.w. in molluscs of Central Adriatic Sea (Desideri et al., 2011); 274 to 426 Bq kg\(^{-1}\) d.w. in mussel samples of Central Adriatic Sea (Meli et al., 2008); 441 Bq kg\(^{-1}\) d.w. in molluscs of northern Pacific coast of Japan (Ishikawa et al., 2004); 23.1 to 80 Bq kg\(^{-1}\) in molluscs of southern coast of Bangladesh (Alam et al., 1999); and 37 to 122 Bq kg\(^{-1}\) f.w. for \(^{40}\)K in mussel samples of Korean coast (Oh, 1994).

2.3.5. Echinoderm

2.3.5.1 Activity concentration

The sea urchin, Strongylocentrotus sp. was analysed for \(^{40}\)K activity concentration and the results are presented in Table 2e and Figure 2e. The activity concentration of \(^{40}\)K ranged from 9.44 to 74.3 Bq kg\(^{-1}\) f.w., with a median value of 34.57 Bq kg\(^{-1}\) f.w. There is no literature available for discussion.

2.3.6. Fin fishes

2.3.6.1 Activity Concentration

Fish species like the lesser sardine, Sardinella gibbosa, the silver belly, Leiognathus fasciatus, the wolf-herring, Chirocentrus dorab, the croaker, Otolithes sp., the lizard fish, Saurida tumbil, the sole fish, Cynoglossus macrostomus and the sting ray, Dasyatis zugei were analysed for \(^{40}\)K. The activity concentrations are given in Table 2f and Figure 2f. The radiometry of different fish species for \(^{40}\)K ranged between 36.47 and 127.2 Bq kg\(^{-1}\) f.w. The lowest activity was observed in the silver belly and the highest in the wolf herring. The activity concentrations of \(^{40}\)K observed in fin fishes of the present study are comparable with findings of similar studies carried out elsewhere. The \(^{40}\)K activity in the fish species of Saudi Arabia was in the range of 14.02 to 352.32 Bq kg\(^{-1}\) d.w. (Hamidalddin and AlZahrani, 2016); in
Rastrelliger kanagurta samples collected from the waters of the straits of Malacca the range was 268.7 to 387.6 Bq kg\(^{-1}\) d.w. (Khandaker et al., 2015); 230 to 447 Bq kg\(^{-1}\) d.w. for fish species of Kuwaiti waters (Uddin et al., 2015); average activity concentration of 84.7 Bq kg\(^{-1}\) f.w. in Pacific blue fin tuna (Fisher et al., 2013); 67 to 132 Bq kg\(^{-1}\) f.w. for fishes of coastal waters of Kuwait (Al-Ghadban et al., 2014); 124.9 to 174.4 Bq kg\(^{-1}\) f.w. in fish species of Central Adriatic Sea (Desideri et al., 2011); 32 to 152 Bq kg\(^{-1}\) f.w. for fishes of North Atlantic Ocean (Carvalho et al., 2011); 48.2 to 68.6 Bq kg\(^{-1}\) in fish species of Aleutian Islands (Hong et al., 2011); 150 to 200 Bq kg\(^{-1}\) f.w. for fishes of coastal waters of Mumbai (Singhal et al., 2009). An activity range 38 to 48 Bq kg\(^{-1}\) calculated for fishes of coastal waters of peninsular Malaysia (Khandaker et al., 2015) and 18.1 to 86.4 Bq kg\(^{-1}\) f.w. observed for fishes of Bay of Bengal (Ghose et al., 1999) – the above-mentioned values have been found to be lower than that of the present study. An activity range of ND to 230 Bq kg\(^{-1}\) for fishes of South China Sea waters (Amin et al., 2013); 38 to 570 Bq kg\(^{-1}\) for fishes of Oman waters (Goddard et al., 2003); 491.1 to 685.91 Bq kg\(^{-1}\) for fish species of Manjung coastal area (Abdullah et al., 2015); 269 to 711 Bq kg\(^{-1}\) d.w. for Pacific blue fin tuna (Madigan et al., 2013) have been reported – these values are higher than those of the present study.

2.4 Concentration factor

Concentration factor values for \(^{40}\)K in marine biota are presented in Table 2g and Figures 2g-2j. Macroalgae and seagrass displayed a concentration factor ranging from 1.07 to 31.33 and the seagrass registered a value of 19.07. The values varied between 2.98 and 15.18 in molluscan species and for crustaceans it ranged from 1.05
to 14.36. The sea urchin species exhibited a CF value of 8.16 and those of the fish species it ranged between 11.04 and 18.06.

The extent of variation in concentrating a particular radionuclide (\(^{40}\text{K}\)) by a variety of marine biota was evaluated in the present study. Among macroalgae and seagrass, the lowest CF value (1.07) was noticed in the chlorophyte and the highest (31.33) in the rhodophyte. Considering molluscan species, the bivalve, brown mussel registered the minimum CF value (2.98) and the cephalopod, cuttlefish the maximum (15.18); and in crustaceans, the lowest CF value was recorded in the mole crab (1.05) and the highest value (14.36) in the rock lobster. The echinoderm recorded a CF value of 8.16. In the case of fishes, the silver belly displayed the lowest CF value (11.04) and the wolf-herring showed the highest (18.06). As far as the CF values for \(^{40}\text{K}\) registered in the marine biota are concerned, no clear variation could be observed. Because stable potassium is an element essential for maintaining the physiological functions of biota, its accumulation and level in any organism is controlled homeostatically. Subsequently, \(^{40}\text{K}\) too follows the same metabolic pathway and its level in biota is maintained constant. Khan (2009) reported the CF values in the edible portion of biota of Kudankulam waters and for crustaceans it ranged from 1.79 to 32.98; molluscs 3.71 to 26.38 and fishes 8.79 to 54.5. These CF values were found to be higher than those of the present study.

2.5 Radiation dose
2.5.1 Macroalgae

Radiation dose to different marine macroalgae was estimated and the values are presented in Table 2b; Fig. 2k. As regards the radiation dose received by
macroalgae from $^{40}\text{K}$, it ranged from $3.21\times10^{-3}$ to $6.24\times10^{-2}$ µGy hour$^{-1}$. The highest radiation dose value ($6.24\times10^{-2}$ µGy hour$^{-1}$) was registered to the rhodophyte and the lowest value ($3.21\times10^{-3}$ µGy hour$^{-1}$) to the chlorophyte. Brown et al. (2004) observed a radiation dose of $1.6\times10^{-2}$ µGy hour$^{-1}$ for macroalgae, which is higher than values reported in the present study.

2.5.2 Crustaceans

The radiation dose values due to $^{40}\text{K}$ to the crustacean species are presented in Table 2c; Fig. 2l. The radiation dose to crustaceans due to $^{40}\text{K}$ ranged from $2.62\times10^{-3}$ to $2.86\times10^{-2}$ µGy hour$^{-1}$. The mole crab registered the lowest radiation dose and the rock lobster the highest. Radiation dose due to $^{40}\text{K}$ reported for crustaceans ($3.8\times10^{-2}$ µGy hour$^{-1}$) by Brown et al. (2004) was found to be higher than that of the present study.

2.5.3 Molluscs

The radiation dose imparted to the molluscs due to $^{40}\text{K}$ was estimated (Table 2d; Fig. 2m). The radiation dose absorbed by the molluscan species ranged from $6.15\times10^{-3}$ to $2.84\times10^{-2}$ µGy hour$^{-1}$. The minimum radiation dose ($6.15\times10^{-3}$ µGy hour$^{-1}$) was noted in the brown mussel and the maximum ($2.84\times10^{-2}$ µGy hour$^{-1}$) in the cuttle fish. When compared with the dose value ($3.8\times10^{-2}$ µGy hour$^{-1}$) reported by Brown et al. (2004), the dose obtained in the present study was lower.

2.5.4 Echinoderm

The radiation dose due to $^{40}\text{K}$ was estimated for the echinoderm (Table 2e) and the value was found to be $1.65\times10^{-2}$ µGy hour$^{-1}$. 
2.5.5 Fin fishes

The radiation dose due to \( ^{40}\text{K} \) to different marine fish species was estimated (Table 2f; Fig. 2n). The values varied between \( 2.22 \times 10^{-2} \) and \( 3.6 \times 10^{-2} \) \( \mu \)Gy hour\(^{-1} \). The lowest radiation dose due to \( ^{40}\text{K} \) was observed in the silver belly \( (2.22 \times 10^{-2} \mu \text{Gy hour}^{-1}) \) and the highest in the wolf herring \( (3.6 \times 10^{-2} \mu \text{Gy hour}^{-1}) \). Comparing the radiation dose to fishes reported by Brown et al. (2004) \( (3.8 \times 10^{-2} \mu \text{Gy hour}^{-1}) \) the values recorded in the present study were lower.

2.6 Radiation dose proportion – internal and external

2.6.1 Percentage contribution of internal and external dose to macroalgae and sea grass

The percentage contribution of internal and external dose to the macroalgae and seagrass due to \( ^{40}\text{K} \) is given in Table 2h and Figure 2p. The internal dose due to \( ^{40}\text{K} \) to the marine flora ranged between \( 2.1 \times 10^{-3} \) and \( 6.13 \times 10^{-2} \mu \text{Gy hour}^{-1} \) and the external dose (\( 1.11 \times 10^{-3} \mu \text{Gy hour}^{-1} \)). The major proportion (65-98%) of the total dose due to internally deposited \( ^{40}\text{K} \) was varied from 65 to 98% for macroalgae and seagrass.

2.6.2 Percentage contribution of internal and external dose to crustaceans

Crustaceans assessed for the percentage internal and external dose contribution \( (^{40}\text{K}) \) and the values are presented in Table 2i and Figure 2q. The crustaceans received the highest percentage contribution dose from the internally accumulated \( ^{40}\text{K} \) (>78%) and it ranged from \( 2.05 \times 10^{-3} \) to \( 2.81 \times 10^{-2} \mu \text{Gy hour}^{-1} \).
2.6.3 Percentage contribution of internal and external dose to molluscs

The percentage of internal and external radiation dose contribution to the molluscan species was analysed and given in Table 2j and Figure 2r. The contribution of internal dose due to $^{40}$K was more than 88% of the total dose imparted to the molluscan species and it was varied from $5.43 \times 10^{-3}$ to $2.77 \times 10^{-2}$ µGy hour$^{-1}$.

2.6.4 Percentage contribution of internal and external dose to echinoderm

The sea urchin was assessed for the percentage of internal and external dose imparted by $^{40}$K and the values are given in Table 2k. The contribution of internal dose in percentage was the highest (>96%). The internal dose due to $^{40}$K was $1.59 \times 10^{-2}$.

2.6.5 Percentage contribution of internal and external dose to fin fishes

The internal and external dose contribution percentages due to $^{40}$K were calculated in fin fishes and are given in Table 2l and Figure 2s. Of the total dose imparted to the fin fishes, the internal dose contributed to the maximum (>97%) and the external dose contribution was negligible. The internal dose was ranging from $2.16 \times 10^{-3}$ to $3.53 \times 10^{-3}$ µGy hour$^{-1}$. 