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Research Article

Uptake of uranium by *Anadara granosa* (Linnaeus, 1758) under laboratory conditions

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The uptake, loss, and retention of uranium by the marine bivalve *Anadara granosa* (Linnaeus, 1758) at ambient concentrations of 2 ppm and 5 ppm in seawater were investigated under controlled laboratory conditions. At both concentration levels, the animals reached apparent equilibrium with the active medium within 5 – 6 days and released uranium at a rapid rate when transferred to a non-active medium. However, the uranium content of 5 ppm turned out to be toxic to the animals, resulting in physiological stress and mortality. The acute concentration factors of < 1 for uranium in edible portion appear to be much lower than the chronic concentration factors of 7 – 8 ppm obtained for the field population of the bivalve in the natural habitat. The present study emphasises the importance of both concentration factors while estimating the maximum permissible concentrations of uranium in seafood for human consumption. Updated insights from recent bioaccumulation studies and marine radioecology are incorporated to contextualise the findings of this classical study within current scientific understanding.

[**Keywords**: *Anadara granosa*, Bioaccumulation, Concentration factors, Marine bivalves, Radioecology, Uranium]

Introduction

The distribution and accumulation of radionuclides in marine organisms have long been of considerable interest due to environmental, ecological, and public health implications. Coastal regions of India, in particular, have been sites of extensive industrialisation, nuclear research, and natural geological inputs that influence the background levels of uranium and other radionuclides. Early data on the ability of marine organisms harvested along the Indian coastline to concentrate natural and anthropogenic radionuclides were limited, despite their economic and nutritional importance. To address this gap, extensive radioecological research was initiated in the 1960s at the Bhabha Atomic Research Centre (BARC) in Bombay, India, to study the ability of commercially important fish, shellfish, seaweeds, etc. to accumulate radioactivity from the marine environment[1-6]. These studies sought to identify radionuclide accumulation patterns and derive the Maximum Permissible Concentrations (MPCs) of these radionuclides allowed for human consumption[7]. BARC also conducted laboratory investigations to supplement the field studies[8-10]. The present paper documents one such laboratory study on the uptake, loss, and retention of the naturally radioactive element uranium by the marine bivalve, *Anadara granosa* (Linnaeus, 1758).

Natural radionuclides like ^{238}U and ^{232}Th and their decay products, as well as singly occurring ^{40}K and ^{87}Rb, constitute most of the radioactivity in the oceans. Based on a uranium content of ~0.003 ppm in seawater, the global oceans hold about 4.5 billion tons of uranium, which translates to 1.15×10^{20} Bq. In addition, marine sediments containing ~2 – 3 ppm uranium contribute 200 – 300 billion tons of uranium equivalent to 5.03×10^{21} Bq – 7.54×10^{21} Bq to the marine environment. Both pelagic and benthic organisms are continuously exposed to this radiation, which causes physiological and biochemical stress. It is therefore important to assess the role of uranium in marine organisms in both natural and laboratory environments.

The ark shell mollusc *Anadara granosa*, popularly known as "blood clam" because of the presence of haemoglobin in its body fluid, is widely distributed throughout the Indo-Pacific region, stretching from the east coast of South Africa to Southeast Asia, Australia, Polynesia, and Northern Japan[11]. These bivalves live primarily in the intertidal zones, burrowed in the sand or mud. They are economically important as a source of seafood rich in protein and are consumed raw or cooked in considerable amounts by coastal populations. *Anadara granosa* is an excellent bio-indicator of marine pollution, especially

for radionuclides, heavy metals, and other hazardous materials. The relative ease of collection of this bivalve from the intertidal zone makes it an ideal candidate for environmental monitoring programs at coastal locations where they grow. *Anadara granosa* is a versatile and convenient "model organism" for physiological and biochemical research in marine invertebrates due to its unique haemoglobin-based blood system, resilience, and abundance, as reported by Patel & Patel[11]. It is highly responsive to environmental variables, making it particularly suitable for experimental ecology, stress physiology, and toxicology studies. Patel & Patel[11] conclude that blood clams like *A. granosa* could bridge the knowledge gap between vertebrate and invertebrate physiology because of their atypical oxygen-transport system. *Anadara granosa* has been successfully used in radioecological investigations (field and laboratory) as documented earlier[8-10,12,13]. Furthermore, recent literature reinforces the value of bivalves like *A. granosa* as sentinels of coastal contamination, particularly for uranium, thorium, and trace metals[13-16].

Materials and Methods

Anadara granosa (3 – 5 cm length) specimens were collected at the low-water mark from the Sewri mudflats off Bombay coastal waters and acclimatised in well-aerated seawater for 3 – 4 days after cleaning them with a nylon brush. During this process, most of the trapped mud and the mud that adhered to the shells were eliminated and bleeding individuals were weeded out. The remaining healthy animals were tagged by inscribing numbers on their shells with waterproof India ink, and these were referred to as "experimentals".

Twelve experimentals were introduced into a polyethylene aquarium (30 cm × 23 cm × 15 cm) containing 2 litres of filtered seawater spiked with 4 mg of uranium in the form of acetate. This concentration level (2 ppm U) is about 670 times higher than the natural abundance of 0.003 ppm uranium in seawater. The pH of the medium was 7, and the salinity was 35 PSU. Six aquaria with the same uranium concentration were maintained along with one batch in non-active seawater as "controls". The experimentals were not fed during the study period to avoid confounding uptake pathways, but the medium was changed daily to maintain consistent activity, pH, and salinity. These experiments were carried out at a room temperature of 28 °C.

A representative sample of experimentals from each aquarium was withdrawn at fixed time intervals. The medium was drained off, and the six experimentals were washed with seawater and kept on filter paper for 1 – 2 h prior to dissection. This helped remove the trapped medium, which would otherwise have accentuated the total activity of the experimentals. They were then forced open with a scalpel, and blood was withdrawn from both right and left extrapallial sinuses, pooled, and centrifuged to separate corpuscles from plasma. The soft parts, including muscle, foot, gills, viscera, etc., from the six experimentals were combined and digested with a combustion mixture of nitric, sulfuric, and perchloric acids (180+160+60 ml); shell walls were ground, and 200 mg of powder was used for chemical analysis. In all these fractions, uranium was determined by UV-based fluorimetry. While fluorimetry was the standard uranium measurement method in the 1960s-1980s, modern approaches now routinely employ Inductively Coupled Plasma-Mass Spectrometry (ICP-MS), alpha spectrometry, Neutron Activation Analysis (NAA), laser fluorimetry, Thermal-Ionisation Mass Spectrometry (TIMS), X-Ray Fluorescence (XRF), etc., with significantly improved detection limits. Nevertheless, historical fluorimetric data, when properly calibrated, remain reproducible and scientifically valuable. This manuscript retains the original analytical framework for historical integrity. A brief description of the analytical procedure used is given below.

To the digested tissue extracts, or 200 mg of shell powder contained in 5 ml of nitric acid (1 N), 10 g of aluminium nitrate was added as a salting-out reagent. The solution was transferred to a separatory funnel, made up to 10 ml and extracted with an equal volume of ethyl acetate. The organic layer was evaporated to dryness at low heat. 10 ml of concentrated nitric acid was added to the residue, evaporated down to a few ml, and made up to the original volume of the ethyl acetate extract with deionised water. 0.2 ml aliquots of this solution were transferred to 3 platinum planchets (0.5 ml capacity) and the solutions evaporated to dryness under an infrared lamp. 0.05 μg uranium standard was added to one of the planchets. The same amount of uranium was taken in triplicate separately as stand-alone standards. 0.5 g of flux (made by mixing potassium carbonate, sodium carbonate, and sodium fluoride in the proportion 45:45:10) was added to each planchet, and the flux

was fused by briefly flaming for 2 min over a burner. The planchets were cooled in a desiccator, and the fluorescence of the samples, reagent blank, and standards was measured in a Jarrell Ash type of fluorimeter. The uranium content of the samples was calculated, applying self-quenching and reagent blank contributions if necessary.

The experimentals were maintained at a uranium concentration of 2 mg/L or 2 ppm for about a week, during which an apparent equilibrium was reached between the animals and the medium. They were then transferred to a non-active medium to monitor loss and retention of uranium. This was also continued for about a week. Another series of experiments with a medium concentration of 5 mg/L or 5 ppm uranium (1670 times the natural abundance of 0.003 ppm U in seawater) was conducted, which could be continued only up to 96 h as the animals became lethargic and started bleeding because of physiological stress and chemical toxicity.

To obtain the concentration and distribution of uranium in various tissues of the bivalve in its normal habitat, a few animals were collected afresh, the various tissues were dissected out, and the uranium was determined in them.

Results and Discussion

The tissue-wise distribution of uranium in the field population of *A. granosa* is given in Table 1. The data indicate that the soft parts of *A. granosa* concentrate about 11 times the Uranium present in seawater (0.003 ppm U). The highest concentration of 6.02×10^{-8} g U/g wet weight or 0.060 ppm U is observed in viscera. This is not surprising, since viscera includes the kidney and hepatopancreas, which are considered to be high in uranium content. Uranium accumulation in bivalves is clearly tissue-specific, with the digestive gland (viscera/hepatopancreas) consistently exhibiting the highest concentrations, as also reported by several other investigators[17-22]. Gills represent the second major site of uptake; while muscle, mantle, and shell contain only minor amounts. Despite differences among species and environments, the pattern is universal: viscera > gills >> other soft tissues, establishing the digestive gland as the critical organ for uranium bioaccumulation in bivalves. Multiple field and laboratory studies[17-23] also report that soft tissues (viscera / digestive gland / hepatopancreas) and gills usually contain higher uranium concentrations than adductor muscle or shell (though the exact order varies with species, exposure route, and environment). One of the more recent studies by Stefanelli *et al*.[20] emphasises the tissue-specific accumulation of uranium in the mussel *Mytilus galloprovincialis* following the order: hepatopancreas ≫ gill > body ≥ mantle > foot, with viscera (hepatopancreas) being the dominant sink. The lowest value of 0.43×10^{-8} g U/g wet weight or 0.004 ppm exhibited by plasma (Table 1) is the same order of magnitude as that of seawater. The plasma, or body fluid, of marine invertebrates is known to be isotonic with the external medium, *i.e*., seawater. The Chronic Concentration Factor (CCF) of 11 obtained in the present work is very similar to 8 and 12 for the same species collected from Sewri & Trombay[12] and included in Table 2. Uranium in the edible portion of the ark shell mollusc is comparable to the same order of magnitude (9 – 18) exhibited by other marine organisms such as fishes, crabs, lobster, bivalves, and seaweeds, as reported by others[14,17,23,24] and are

Table 1 — Tissue-wise distribution of uranium in *Anadara granosa* (Field population)

Tissue	U ppm (wet weight)	U ppm (weighted average)
Adductor muscles	0.021±0.002	-
Foot	0.021±0.002	
Mantle folds	0.025±0.003	
Gills	0.029±0.003	
Viscera	0.060±0.006	
Soft parts	-	0.033
Corpuscles	0.027±0.003	-
Plasma	0.004±0.001	
	-	-
Whole blood	-	0.007
Total soft parts + blood	-	0.021
Seawater	0.003	-

Table 2 — Uranium content of soft tissues in marine bivalves from different geographical locations

Species	Location	U (ppm) dry weight basis	U (ppm) wet weight basis	CCF	Reference
Anadara granosa	Sewri, Bombay		0.033	11	Present work
Anadara granosa	Trombay, Bombay	0.146	0.037	12	Bangera & Patel[12]
Anadara granosa	Sewri, Bombay	0.089	0.022	7	Bangera & Patel[12]
Crassostrea cucullata	Colaba, Bombay	0.547	0.128	43	Unni[4]
Crassostrea cucullata	Colaba, Bombay	0.292	0.064	21	Unni[4]
Crassostrea gryphoides	Mahim, Bombay	0.506	0.125	42	Unni[4]
Crassostrea gryphoides	Mahim, Bombay	0.707	0.130	43	Unni[4]
Katelysia marmorata	Bombay Harbor		0.139	46	Unni[4]
Mytilus edulis	Kovalam, Kerala	0.172	0.030	10	Unni[4]
Mytilus edulis	Manavalakurichi, Kerala	0.452	0.071	24	Unni[4]
Mytilus edulis	Trivandrum, Kerala	0.341	0.051	17	Unni[4]
Mytilus edulis	California, USA	0.250	0.038	13	Hamilton[23]
Mytilus edulis	Gdansk Bay, Baltic Sea	0.210	0.028	40	Szefer & Wenne[17]
Mya arenaria	Gdansk Bay, Baltic Sea	0.150	0.025	33	Szefer & Wenne[17]
Cardium glaucum	Gdansk Bay, Baltic Sea	0.270	0.048	33	Szefer & Wenne[17]
Macoma balthica	Gdansk Bay, Baltic Sea	0.350	0.080	130	Szefer & Wenne[17]

presented in Table 2. It is significant that such a high order of CF obtained on chronic exposure is not achieved under acute laboratory conditions, even after exposure to about a thousand times higher concentrations of uranium in the medium as described below.

The experimentals reached apparent equilibrium with the active medium containing 2 ppm U within 5-6 days, after which they behaved erratically. In the short span of time as that in the present investigation, the experimentals did not concentrate uranium as expected in the enriched medium. Even when the animals were maintained at a higher concentration of 5 ppm U in the second series of experiments, they took up uranium only to the same extent as that observed in the first set of experiments. However, in the second series, equilibrium was reached within 2 – 3 days. On further exposure, the animals became moribund and started bleeding. The rate of uptake also became erratic with a pronounced reduction in blood volume. Tables 3 and 4 and Figure 1 depict the uptake, loss, and retention of uranium by *A. granosa* at two different concentration levels. In general, the soft parts and blood show a Concentration Factor (CF) of less than 1 and shells a CF of about 3 with respect to the active medium. Even though the shells absorbed the highest levels of uranium from the medium, the rate of loss of uranium from the shells was more pronounced than that of the other fractions. At equilibrium, *A. granosa* concentrated about 50 times, and the whole blood 150 times the uranium content at 0-hours. When the experimentals were transferred to a non-active medium, they gave up uranium, and the process continued for nearly 3 days. Both shell and blood lost activity more rapidly than the soft parts. However, a portion of the uranium was retained in the body. This retention was about 25 times higher for the soft parts and whole blood compared to the 0-hour values. The net accumulation of uranium after 7 days was 40 %, 20 %, and 12 %, respectively, in soft parts, blood, and shell.

Statistical and kinetic analysis

Uranium uptake and loss/depuration kinetics in *A. granosa* were analysed using a first-order one-compartment model commonly applied in marine radioecology. Uptake could be described by the equation $C_t = C_{eq}(1-e^{-kt})$ and loss/depuration kinetics by $C_t = C_0 e^{-kt}$; where, C_t is the uranium concentration in a given tissue at time t (hours), C_{eq} - the apparent equilibrium concentration approached during continuous exposure, C_0 - the concentration at the start of depuration phase, and k - the first-order uptake or elimination rate constant. In both cases, larger values of k indicate a faster approach to equilibrium or faster loss, respectively. Biological half-times could be computed as $T_{1/2} = ln2/k$. These models were fitted to the mean time-series values reported in Tables 3 and 4 using nonlinear least-squares regression. The kinetic rate table for uranium uptake and depuration by *A. granosa* (medium concentrations = 2 and 5 ppm) is also shown in Table 5. These estimates provide the characteristic rates and equilibrium levels governing uranium biokinetics in *A. granosa*. The uranium uptake data for *A. granosa* followed classical first-

Table 3 — Uptake/depuration of uranium by *Anadara granosa* (Medium concentration = 2 ppm U)

Hours	Uranium (ppm)				
	Soft parts	Plasma	Corpuscles	Whole blood	Shell
0	0.032±0.003	0.004±0.001	0.027±0.003	0.007±0.001	0.108±0.011
24	0.660±0.066	0.320±0.032	1.060±0.106	0.400±0.040	2.050±0.205
48	1.060±0.106	0.580±0.058	0.980±0.098	0.630±0.063	2.700±0.270
72	1.130±0.113	0.890±0.089	2.210±0.221	1.040±0.104	3.400±0.340
96	1.420±0.142	0.900±0.090	2.750±0.275	1.080±0.108	4.290±0.429
144	1.990±0.199	-	-	1.000±0.100	7.890±0.789
168	1.670±0.167	1.020±0.102	1.100±0.110	1.040±0.104	5.580±0.558
Transferred to non-active medium					
24	1.950±0.195	-	-	0.700±0.070	2.980±0.298
72	0.830±0.083	-	-	0.320±0.032	1.460±0.146
96	0.760±0.076	-	-	0.190±0.019	0.850±0.085
168	0.830±0.083	-	-	0.190±0.019	0.730±0.073

Table 4 — Uptake of uranium by *Anadara granosa* (Medium concentration = 5 ppm U)

Hours	Uranium (ppm)				
	Soft parts	Plasma	Corpuscles	Whole blood	Shell
24	0.91±0.09	1.07±0.11	1.31±0.13	1.11±0.11	2.00±0.20
48	1.76±0.18	1.73±0.17	2.07±0.21	1.79±0.18	2.60±0.26
72	1.41±0.14	0.68±0.07	3.70±0.37	1.18±0.12	3.64±0.36
96	2.21±0.22	1.81±0.18	3.82±0.38	2.22±0.22	5.90±0.59
120	Animals moribund and bleeding				4.90±0.49

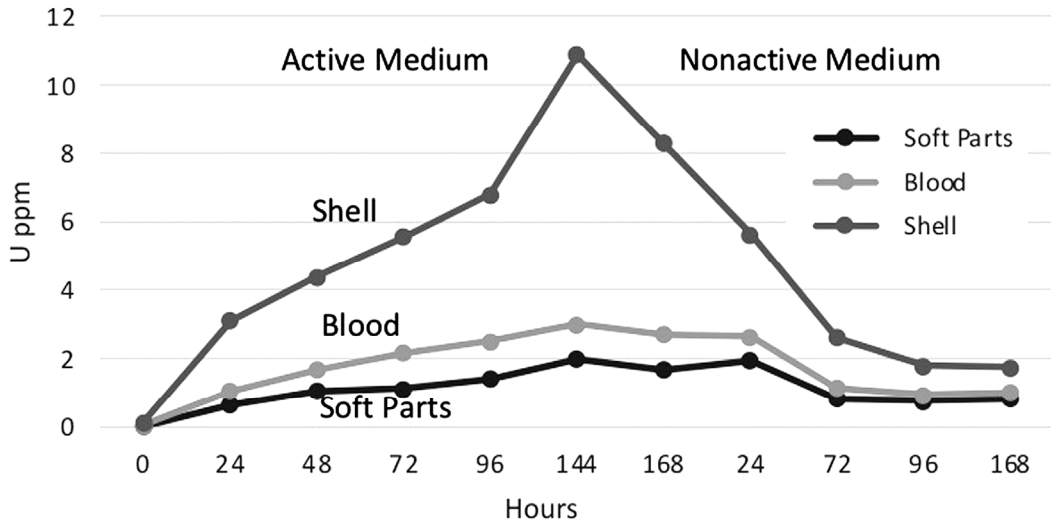

Fig. 1 — Uptake and release of uranium by *Anadara granosa* from seawater containing 2 ppm U

order kinetics, which is typical of metal and radionuclide bioaccumulation in bivalves. Nonlinear regression applied to the mean time-series values (Tables 3 and 4) demonstrated that a single-compartment exponential model adequately described both uptake and depuration phases, consistent with established radioecological behaviour in lamellibranch molluscs.

The kinetic behaviour of uranium uptake and depuration in *A. granosa* shows marked differences between environmentally realistic exposures (2 ppm) and physiologically stressful concentrations (5 ppm). At 2 ppm, first-order one-compartment models provided excellent fits for all tissues, demonstrating smooth, asymptotic accumulation

Table 5 — Kinetic rate table for uranium uptake and depuration by *Anadara granosa* (Medium concentrations = 2 and 5 ppm)

Experiment	C_{eq} or C_0 (ppm)	k (h^{-1})	Biological half-time (h)
2 ppm soft parts uptake	1.994	0.01428	48.55 h
2 ppm whole blood uptake	1.109	0.02264	30.62 h
2 ppm shell uptake	9.46	0.007279	95.23 h
2 ppm soft parts depuration	2.26	0.009664	71.72 h
2 ppm whole blood depuration	0.965	0.01438	48.20 h
2 ppm shell depuration	4.101	0.01403	49.42 h
5 ppm soft parts uptake	2.271	0.02253	30.76 h
5 ppm whole blood uptake	1.929	0.0347	19.98 h
5 ppm shell uptake*	12,769.15	0.00000454	152,721 h (~17.4 years)

*Shell uptake does not follow first order kinetics as explained in the text

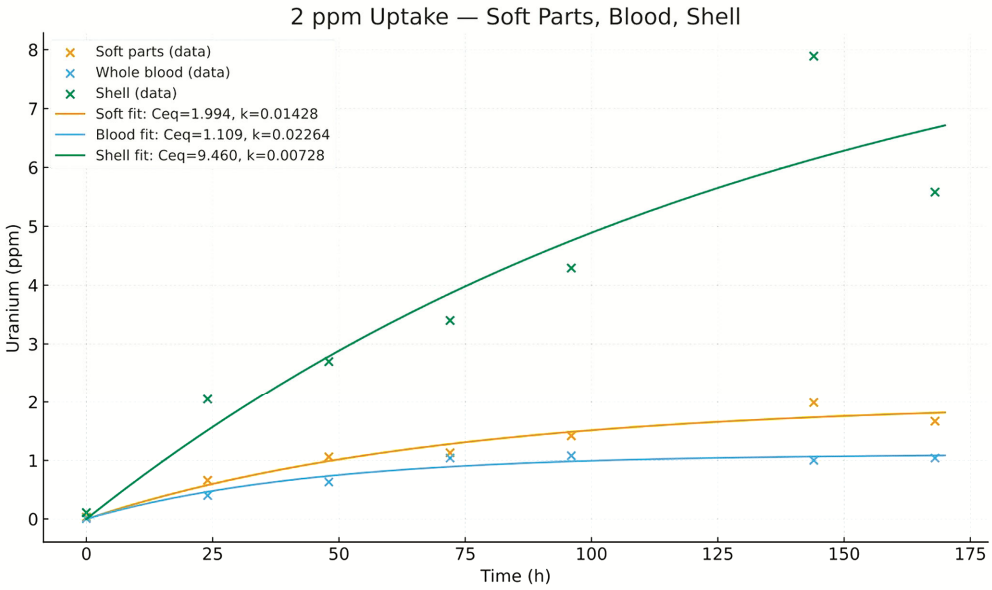

Fig. 2 — Regression curves generated for the uptake of uranium by *Anadara granosa* at 2 ppm medium concentration

toward equilibrium (Fig. 2). Soft parts and whole blood exhibited relatively short uptake half-times (~31 – 49 h), reflecting rapid distribution into metabolically active compartments. Shell uptake proceeded more slowly, with a half-time near ~95 h, consistent with diffusion and surface-complexation processes typical of calcareous matrices. Depuration at 2 ppm also followed first-order loss (Fig. 3), with soft tissues and blood showing half-times between ~48 – 72 h, indicating moderate reversibility and the presence of both labile and intracellularly bound pools. These results provide mechanistic evidence for the retention component observed in classical chronic field concentration factors.

In contrast, the 5-ppm exposure clearly departs from ideal first-order kinetics. Although soft parts and blood still yielded mathematically stable first-order fits (Fig. 4) with short half-times (20 – 31 h), the shell data displayed a strongly non-asymptotic pattern, rising nearly linearly across the exposure window without approaching saturation. When fitted with a first-order model, this produced unrealistically large equilibrium concentrations and vanishingly small rate constants, behaviour that is physiologically impossible and statistically diagnostic of departure from the model. A linear model provided a much more realistic description of shell uptake, consistent with impairment of regulatory and filtration processes at high uranium concentrations. This kinetic disruption at 5 ppm strongly suggests the onset of physiological stress, including reduced blood volume, impaired shell-surface chemistry, or inhibition of ion-transport pathways that normally control uranium

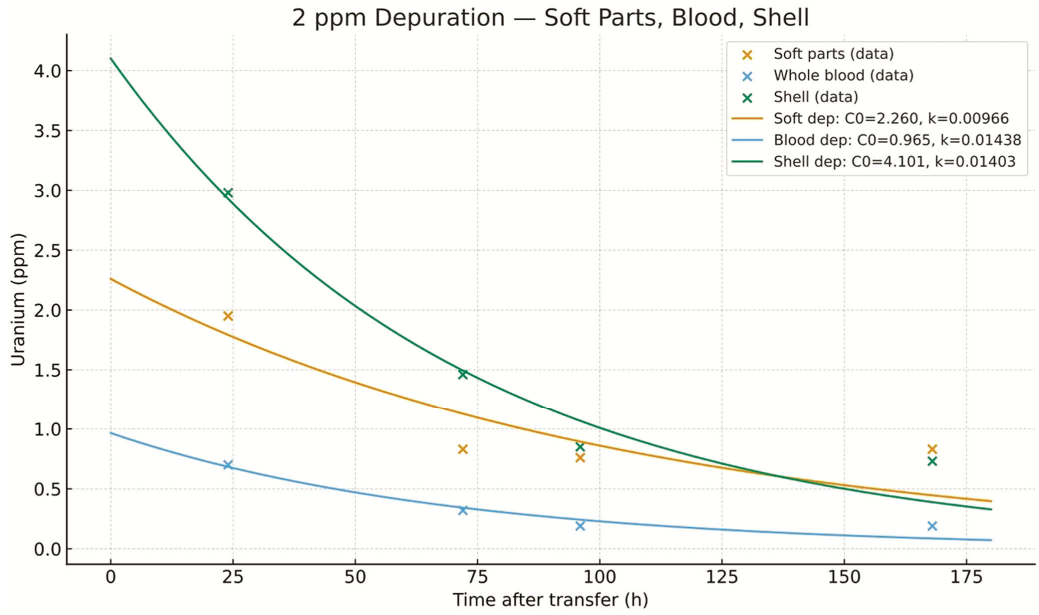

Fig. 3 — Regression curves generated for the depuration of uranium by *Anadara granosa* at 2 ppm medium concentration

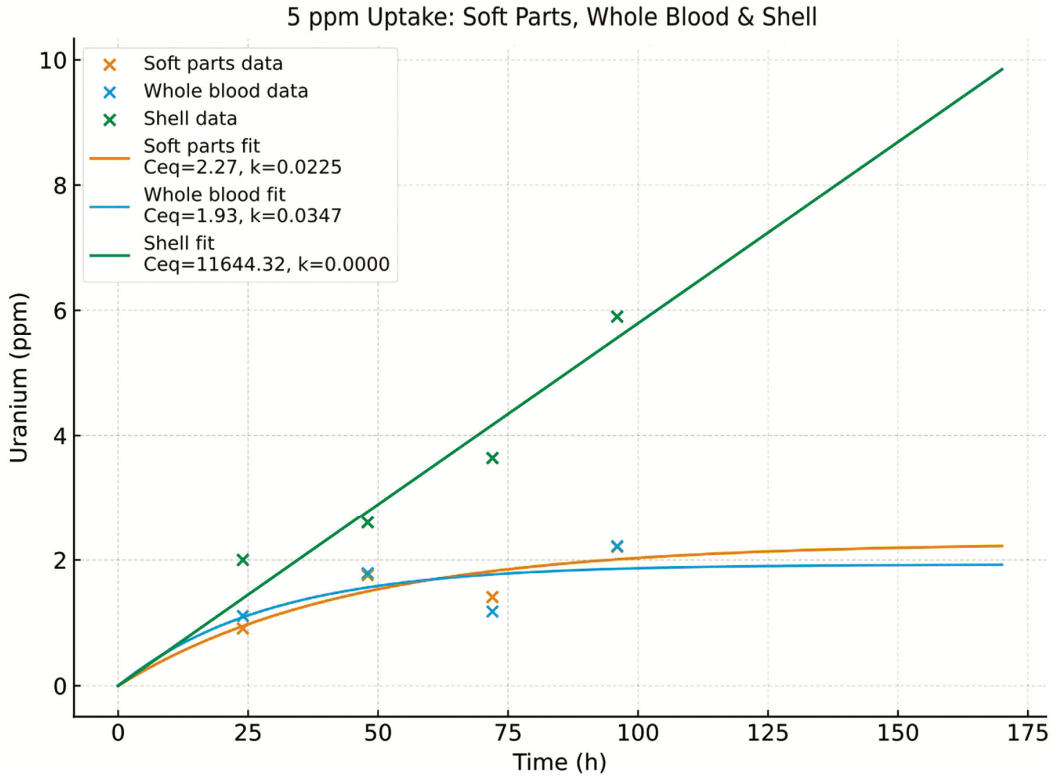

Fig. 4 — Regression curves generated for uranium uptake by *Anadara granosa* at 5 ppm medium concentration (See text for explanation of the linear fit instead of first-order kinetic fit for shell)

sorption and internalisation. This is a hallmark of metabolic suppression, commonly observed in bivalves exposed to high contaminant loads, and confirms our finding that acute laboratory concentration factors substantially underestimate natural chronic accumulation potential.

Overall, the statistical and kinetic results reinforce a fundamental distinction between acute laboratory

accumulation and chronic environmental bioaccumulation. At low exposure, uranium uptake follows predictable saturating kinetics, allowing well-defined rate constants and half-times. At elevated concentrations, however, the kinetics become non-ideal, tissue-specific, and strongly influenced by physiological stress, making first-order parameters unreliable. These findings support conclusion drawn from the present study that high-dose exposure experiments should not be used to infer natural chronic concentration factors in bivalves.

Laboratory studies on the uptake of artificial radionuclides ^{54}Mn and ^{65}Zn by *A. granosa* exhibit close resemblance to the response of the bivalve to uranium[8-10,13]. In these instances, the CFs never exceeded 20 and 106 for ^{54}Mn and ^{65}Zn, respectively. This is in sharp contrast to much higher CFs of 1000 for stable manganese and 800 for stable zinc in field populations of *A. granosa*. In general, marine bivalves are known to accumulate radioisotopes of several elements, including Mn, Zn, Co, Cs, etc., to a very high degree in their bodies in the natural habitat. The present study provided unmistakable evidence that any addition of uranium above 2 ppm is more or less lethal to *A. granosa* on prolonged exposure. It would appear, therefore, that the Maximum Permissible Concentration (MPC) of 9 μg U/ml or 9 ppm suggested by Aten *et al.*[25] needs to be reduced in the case of filter-feeding benthic animals like *A. granosa*. They arrived at this value by considering the MPC for natural uranium of 2×10^{-4} μc/ml in drinking water for occupational exposure, as per ICRP (International Commission on Radiological Protection) recommendations of 1960[(ref. 26)] and a CF of 20 for uranium in some food fishes. Subsequently, the ICRP in 1964[(ref. 27)] scaled down the $(MPC)_w$ value of uranium to 6×10^{-6} μc/ml. The health-based benchmark, defined as the Minimum Contaminant Level (MCL) for uranium in drinking water, is later established at 0.03 ppm by the WHO (World Health Organization)[28], the Council of the European Union[29], the US EPA (United States Environmental Protection Agency)[30], and the ICRP[(ref. 31)]. In contrast, there is no direct MCL available for seawater or marine organisms for human consumption. Using bioaccumulation factors of about 10 for fish muscle and as a protection for seafood consumers, IAEA (International Atomic Energy Agency)[32] suggests a conservative target concentration in the range of 0.001 – 0.010 ppm uranium in seawater. Incidentally, this coincides with the global average of 0.003 ppm uranium in seawater reported by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)[33]. Furthermore, based on IAEA data of 0.01 ppm uranium in seawater and a CF of 10, fish muscle could reasonably contain 0.1 ppm uranium. If a person eats 50 kg of fish annually, it translates to ~5 mg of uranium intake per year, which is well below the WHO's TDI (Tolerable Daily Intake) based on the annual intake limit of ~15 mg/yr for a 70 kg adult.

Significance of concentration factors

When animals are exposed under laboratory conditions to higher concentrations of radioactivity for short periods, the CFs obtained may be termed "acute concentration factors". This reflects rapid absorption kinetics, early biological redistribution, and immediate physiological responses, as in stress-related accumulation. Acute concentration factors clarify exposure events such as contamination pulses, spills, or laboratory tracer studies. In contrast, the "chronic concentration factors" attained in the natural environment, where populations have persisted from generation to generation and thereby have the time to acclimatise and ultimately reach higher steady-state equilibrium conditions with the natural habitat. This is characterised by a slow approach to equilibrium, the influence of metabolic turnover and elimination, and tissue-specific accumulation patterns (*e.g.*, gills *vs.* viscera *vs.* mantle). Chronic concentration factors form the basis for bioindicator applications and long-term ecological risk analyses. Molluscs such as *A. granosa* exhibit two kinetically distinct phases of uptake behaviour: a fast (acute) one involving metabolically active organs (gills, mantle, hepatopancreas) and a slow (chronic) one involving storage organs (kidney, viscera). Acute and chronic concentrations represent fundamentally different ecological states and should not be used interchangeably as equivalents in environmental assessments. From a radioecological standpoint, chronic concentrations are better indicators of long-term environmental contamination, trophic transfer potential, and the biological half-lives of radionuclides. In light of the current data on uranium, as well as those for other artificial radionuclides and the significant differences between the two CFs, it becomes obvious that both must be considered in evaluating the MPCs for seawater and marine

organisms. Recent marine radioecology consensus acknowledges that laboratory-based CFs often underestimate real ecosystem values because they do not capture multigenerational adaptation, natural feeding pathways, or sediment interactions. This study anticipated that understanding decades earlier.

Concentration Factors (CFs) indicate the levels to which the natural as well as artificial radioactive elements are accumulated in biomaterial with respect to the corresponding levels in the aquatic medium. They are used to compute MPCs for elements in aquatic foods consumed by the human population. Typical formula employed in one such calculation is as follows:

$$MPC \times D = PSC \times f \times F$$

Where, *MPC* = Maximum permissible radioactivity in drinking water, μc/ml; *D* = volume of water drunk per week, taken as 15,000 ml; *PSC* = permissible seawater concentration, μc/ml; *f* = concentration factor for organisms; and *F* = weekly consumption of fish, taken to be 1.5 kg, assuming a density of 1.0 to be equivalent to 1500 ml.

Conclusion

Laboratory studies on the uptake, loss, and retention of uranium by the marine bivalve *A. granosa* conclusively demonstrate that the animals cannot tolerate any levels of uranium greater than 2 ppm in the active medium. Furthermore, the "acute concentration factors" in the edible portion of *A. granosa* turned out to be much lower than the "chronic concentration factors" obtained for the field population. *Anadara granosa* exhibits similar uptake patterns when exposed to other radionuclides such as ^{54}Mn, ^{65}Zn, ^{58}Co, ^{60}Co, and ^{137}Cs[refs. 8-10,13]. The study supports the continued use of *A. granosa* as a sensitive bioindicator of radionuclide contamination in coastal ecosystems and underscores the critical distinction between acute and chronic CFs while developing regulatory guidelines. There is no direct, standalone Maximum Contaminant Level (MCL) for uranium in seawater or marine fish for human consumption. The protective limit is derived indirectly through a pathway analysis based on the MCL of 0.030 ppm for drinking water standard established by several international and national agencies. A conservative target concentration for uranium in seawater to protect seafood consumers would be in the range of 0.001 – 0.010 ppm, depending on local consumption rates.

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Conflict of Interest

The authors declare no competing or conflict of interest.

Ethical Statement

This is to certify that the reported work in the paper entitled "Uptake of uranium by *Anadara granosa* under laboratory conditions" submitted for publication is an original one and has not been submitted for publication elsewhere. We further certify that proper citations to the previously reported work have been given and no data/table/figure has been quoted verbatim from other publications without giving due acknowledgement and without the permission of the author(s). The consent of all the authors of this paper has been obtained for submitting the paper to the "*Indian Journal of Geo-Marine Sciences*".

Author Contributions

Conceptualisation: CKU. Data curation, manuscript writing & editing: CKU & MPU.

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