Wave power potential at a few shallow-water locations around Indian coast

V. Sanil Kumar[1,]*, K. K. Dubhashi[1], T. M. Balakrishnan Nair[2] and Jai Singh[1]

[1]CSIR-National Institute of Oceanography (Council of Scientific and Industrial Research), Dona Paula, Goa 403 004, India
[2]Indian National Centre for Ocean Information System (Ministry of Earth Sciences), P. B. No. 21, IDA-Jeedimetla, Hyderabad 500 072, India

Variations in nearshore wave power at four shallow-water locations along the east and west coast of India are examined based on the measured wave data for one-year period. The study shows that along the west coast of India, 83–85% of the annual wave power is during the summer monsoon period (June–September), whereas at Visakhapatnam (on the east coast), 55% of the annual wave power is during the summer monsoon period. Along Puducherry coast in the east, wave power is relatively less with maximum value of 31.8 kW m^{-1}. The average wave power during the summer monsoon is high (15.5–19.3 kW m^{-1}) along the west coast of India. The study shows that the annual average wave power (1.8–7.6 kW m^{-1}) along the locations studied is much lower than that available for temperate zones.

Keywords: Arabian Sea, Bay of Bengal, energy period, wave energy, wave height.

FOSSIL fuels mainly are used to meet the energy demand globally. Due to the increasing demand there has been a significant increase in oil prices in the recent past and this has resulted in looking for renewable energies. Among the renewable energy sources, ocean waves contain the highest energy density and have the potential to become a commercially viable energy source[1]. Studies on India's wave power resource and wave energy conversion devices were done at the Indian Institute of Technology Madras, Chennai[2]. As of today, the only surviving near-shore oscillating water column-based wave energy plant is that at Vizhinjam, India[3]. Based on the analysis of wave data from buoys, satellites, numerical wave hindcasts, or a combination of these sources, several authors have reported the wave energy resource assessments for particular regions or countries: United Kingdom[4], Ireland[5], Portugal[6,7], Canada[8], California[9], the North Sea[10] and Malaysia[11]. From the wave climate predictions generated by wind-wave model WAVEWATCH-III spanning the 10-year-period from 1997 to 2006, Cornett[12] provided a global wave energy resource assessment. So far the wave power estimate based on the measured data covering one year for the Indian coast has not been attempted. Also, since many agencies are now looking to invest in wave energy projects around the Indian coast, we have studied the variations in wave power over an annual cycle based on the measured wave data at four shallow-water (10–15 m water depth) locations (Figure 1) covering the east and west coast of India.

Wave data used in this study are those measured using moored Datawell directional waverider buoy[13] at the four locations (Table 1). At all the locations, data are recorded for 30 min duration at 1.28 Hz interval. The waverider buoy is equipped with a heave pitch roll sensor, a three-axis fluxgate compass, x and y accelerometers and a dedicated microprocessor. The microprocessor takes information from the sensors in the waverider buoy and converts them to three acceleration values (vertical, north, west). The data are then digitally integrated to displacements, filtered, and Fourier-transformed with a Nyquist frequency of 0.64 Hz. Wave spectrum is obtained through Fast Fourier Transform (FFT). FFT of eight series, each consisting of 256 measured vertical elevations of the buoy data, is added to obtain the spectra. Significant wave height (Hs) is obtained based on the spectral parameter. The period corresponding to the maximum spectral energy is referred as spectral peak period (T_p) and is estimated from the wave spectrum. Mean wave direction (Dp) is estimated based on circular moments[14]. The wave period parameter used in the wave power analysis is called the energy period (T_e) and is defined as $T_e = m_{-1}/m_0$, where m_{-1} is the reciprocal of the first spectral moment (the mean frequency) and m_0 is the zeroth moment. Wave parameters are converted to wave power (P) using the expression given below[15].

$$P = \rho g \int_0^{2\pi} \int_0^{\infty} C_g(f,d) S(f,\theta) \, \mathrm{d}f \, \mathrm{d}\theta, \quad (1)$$

where ρ is the water density, g the acceleration due to gravity, C_g the group velocity, $S(f, \theta)$ the directional wave spectrum, f the frequency, d the water depth and θ is the wave direction.

For deep water, the above expression can be simplified to

$$P = kT_e Hs^2. \quad (2)$$

where coefficient k is 500 W s^{-1} m^3 for more realistic ocean waves[16].

Annual average significant wave height is around 1 m, except at Puducherry where the average Hs is 0.7 m (Table 2). The annual average energy period varied from 6.3 to 8.6 sec and the energy period of the swells (T_p > 10 sec) ranged from 4 to 14 sec. Hs values measured in 2011 at Honnavar are consistent with the average wave parameters for the same location[17] in 2009 and

*For correspondence. (e-mail: sanil@nio.org)

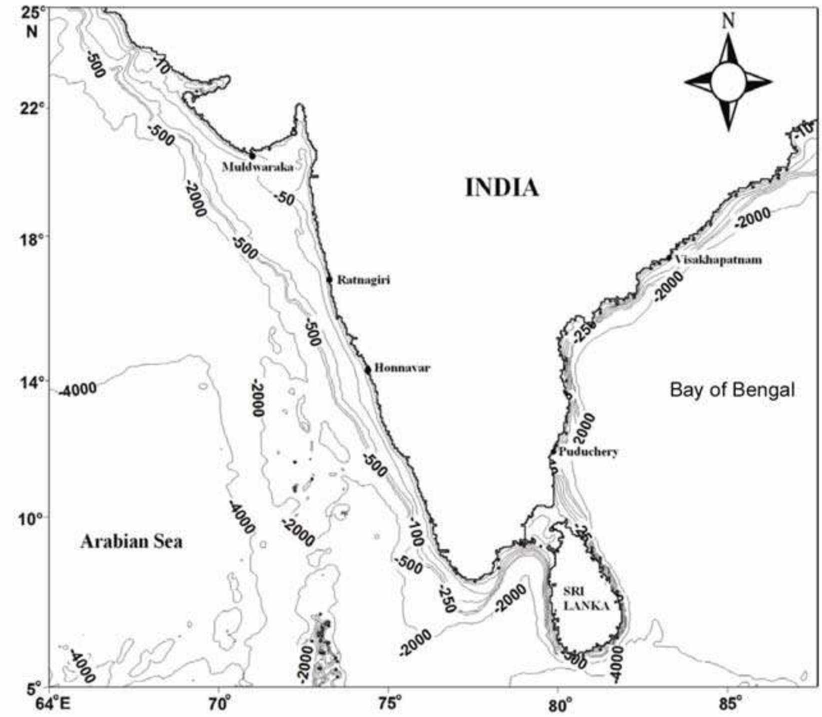

Figure 1. Locations considered in the study. Ratnagiri and Honnavar along the west coast of India and Visakhapatnam and Puducherry along the east coast of India.

Table 1. Measurement locations and water depth

Location	Latitude; longitude	Water depth (m)	Measurement period
Ratnagiri, west coast	16.9801°N; 73.2584°E	13	1 January 2011 to 31 December 2011
Honnavar, west coast	14.3042°N; 74.3907°E	10	1 January 2011 to 31 December 2011
Puducherry, east coast	11.9249°N; 79.8507°E	12	1 January 2010 to 31 December 2010
Visakhapatnam, east coast	17.6321°N; 83.2649°E	15	1 January 2010 to 31 December 2010

2010. Generally, the energy period (T_e) is estimated[16] as $T_e = 0.9 \times T_p$, when the spectral shape is unknown. The data used in the present study indicate that this expression is not valid for waves having spectral peak period more than 8 sec (Figure 2).

Daily and seasonal variability of the wave power is an important factor in selection of the location for a wave power plant. Along the west coast of India, most of the annual wave energy (83% at Honnavar and 85% at Ratnagiri) is during the summer (southwest) monsoon period (June–September), and the average wave power during this period is 15.5 kW m^{-1} at Honnavar and 19.4 kW m^{-1} at Ratnagiri (Figure 3). The monthly mean wave power is high (~23 kW m^{-1}) during June and July along the west coast of India. Daily variation in wave power ranged from 0.2 to 40 kW m^{-1} and the average daily wave power varied from 0.4 to 56 kW m^{-1}. This large variation is due to the influence of summer monsoon which creates large differences in daily wave height (daily average *Hs* varying from 0.3 to 3.5 m). Johnson *et al.*[18] found that the wave height increases from south to north along the west coast of India with the average significant wave height at the northern location being 20% more than that at the southern location due to the increased swell height. The wave power varied from 6.7 to 114 kW m^{-1} with an average value of 28 kW m^{-1} off Muldwarka in the northern Arabian Sea at 10 m water depth during June–August. Along the west coast of India, the waves having peak wave period between 8.3 and 13.3 sec accounted for more than 83% of the total wave power. Along the east coast of India, at Visakhapatnam, 55% of the annual wave power is during the summer monsoon period and at Puducherry it is only 28%. At Puducherry 50% of the annual wave power is during the northeast monsoon period (October–January), since the wave activity is relatively high during this period. The east coast of India is frequently affected by cyclones and the wave power is relatively high during these brief cyclone periods. Wave power was more than 10 kW m^{-1} during cyclone *Jal* (18–22 May 2010) and during cyclone *Laila* (6–8 November 2010).

Table 2. Range and average value of wave height (*Hs*), wave period (T_e) and wave power at different locations

Location	*Hs* (m)	T_e (s)	Wave power (kW m^{-1})
Ratnagiri	0.2–4.2 (1.1)	3.8–15.0 (7.3)	0.2–84.3 (7.6)
Honnavar	0.3–3.8 (1.0)	4.2–15.8 (8.6)	0.3–61.2 (6.3)
Puducherry	0.2–2.7 (0.7)	3.4-11.8 (6.3)	0.1–31.8 (1.8)
Visakhapatnam	0.1–3.0 (1.0)	3.6–16.1 (8.6)	0.2–41.4 (5.2)

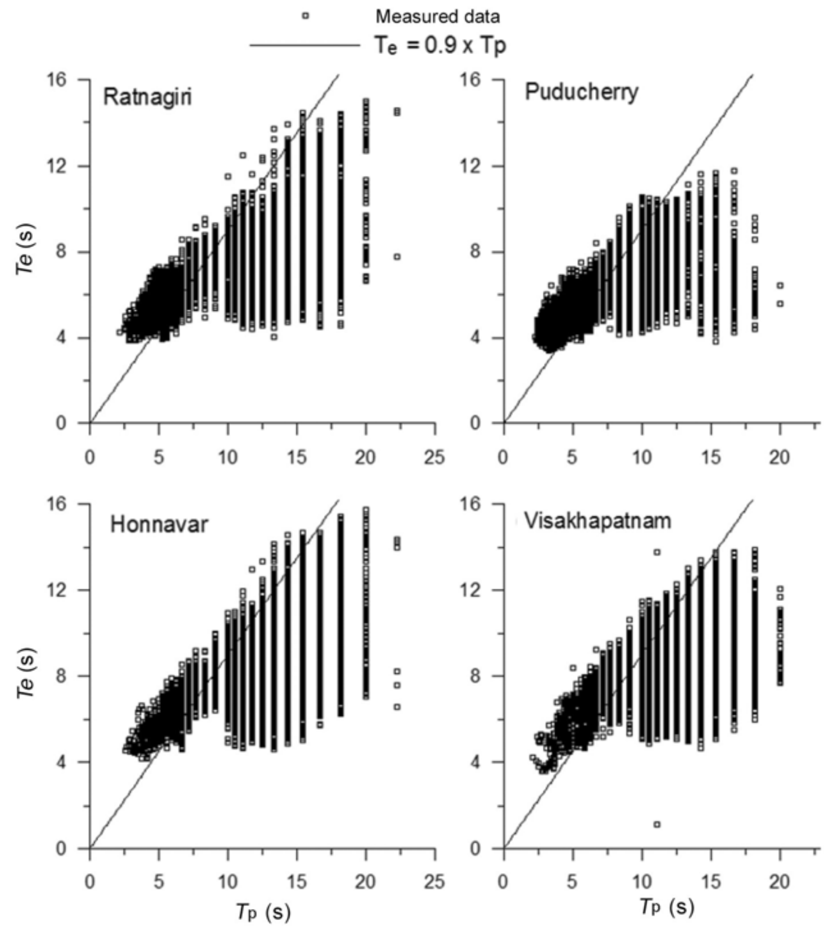

Figure 2. Scatter plot of energy wave period (T_e) with peak wave period (T_p) at four locations.

Along the west coast of India, wave power exceeds 30 kW m^{-1} during 4.5% of the time at Ratnagiri and 2.8% at Honnavar. Along the east coast of India (at Visakhapatnam), only during 0.1% of the time, the wave power exceeded 30 kW m^{-1}. Along Puducherry coast wave power is relatively less with maximum value of 31.8 kW m^{-1}, since the wave conditions are different due to the shadow of the Sri Lankan land mass. At Puducherry, the wave power exceeds 20 kW m^{-1} during 0.13% of time. The wave power available along the Indian coast is much lower (annual mean wave power ranges from 1.8 to 7.6 kW m^{-1}) than that available for temperate zones. The average wave power potential for the southwest coast of India near Thiruvananthapuram[2] is 13 kW m^{-1}. The wave power plant at this location delivers 75 kW during April–November and 25 kW from December to March[19]. During June–September, it has peaks of 150 kW. The average power production during monsoon months was 120 kW. Highest wave climates, with annual average power between 20 and 70 kW m^{-1} or higher, are found in the temperate zones (30° to 60°N and S lat.) where strong storms occur[20]. Since the seasonal variations are in general considerably larger in the northern than in the southern hemisphere, the southern coasts of South America, Africa and Australia are attractive for wave energy exploitation[20]. The maximum annual mean wave power in the southern hemisphere is ~125 kW m^{-1}, found southwest of Australia near 48°S, 94°E. In the northern

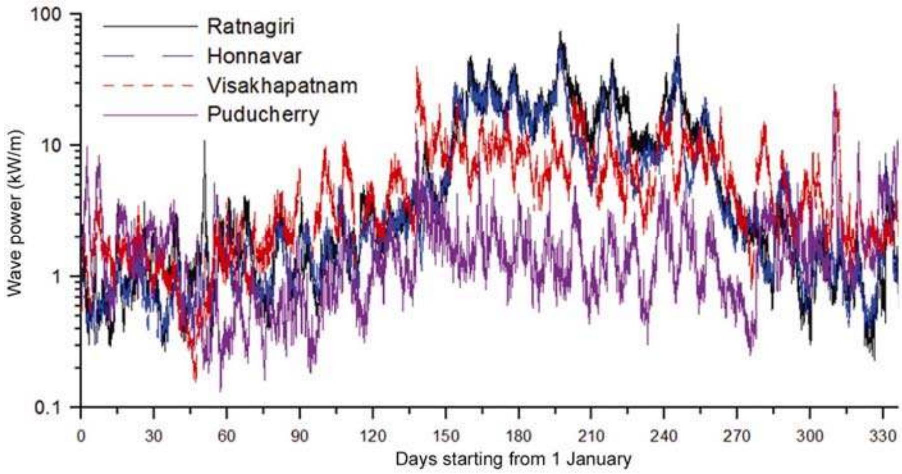

Figure 3. Variation in wave power over a period of one year at four locations.

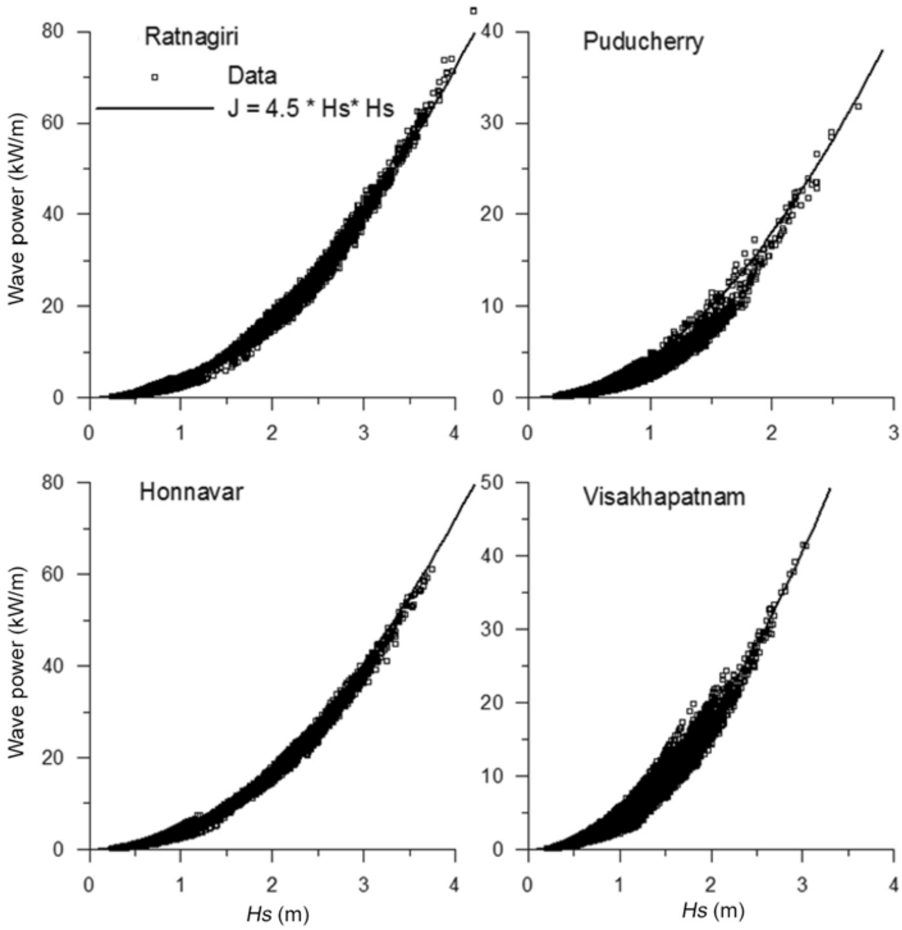

Figure 4. Variation of wave power with significant wave height at four locations based on one-year data.

hemisphere, the annual mean wave power south of Iceland exceeds 80 kW m^{-1} around 56°N, 19°W, while the maximum in the North Pacific[12] is ~75 kW m^{-1}, near 41°N, 174°W.

The wave power estimated based on the simplified expression for deep water (eq. 2) is 0.8–1.4 times the value obtained based on the expression for shallow water (eq. 1). Even though the wave power varies with wave height and group velocity/period, the variation is more related to *Hs* than the other parameters (Figure 4). For the study area, the wave power can be estimated based on the expression: $P = 4.5 \times Hs^2$. The average energy period

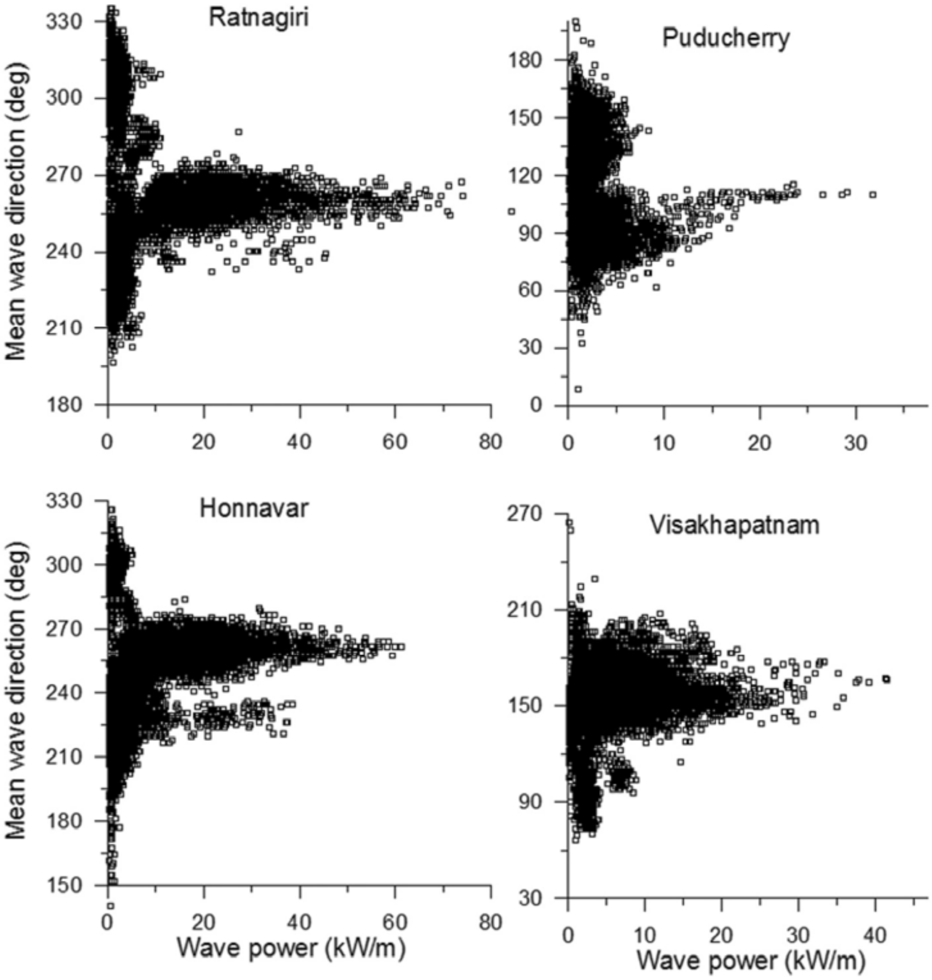

Figure 5. Variation of wave power with mean wave direction at four locations based on one-year data.

of high waves is 9 sec at Honnavar and Visakhapatnam, and is 8.5 sec at Ratnagiri. Hence, the product of k and T_e is around 4.5. Even though the west coast is exposed to seasonally reversing monsoon winds, due to the westerly winds close to the coast during the southwest monsoon period, the waves are approaching almost perpendicular to the coast at Honnavar and Ratnagiri. Scatter plot of wave power per unit width against mean wave direction (Figure 5) indicates that high wave power (> 10 kW m^{-1}) along the west coast of India is from the southwesterly waves (250–270°) and occurred during the SW monsoon period. During other periods, the wave power is less than 10 kW m^{-1}. At Visakhapatnam, the coastal inclination is 45° to the east from the true north. High wave power (> 10 kW m^{-1}) along Visakhapatnam is from the southeasterly waves (140–180°) and mostly occurred during the SW monsoon period.

Along the Indian coast there is a large seasonal variation in wave power. For the west coast of India, most of the annual wave energy (83% at Honnavar and 85% at Ratnagiri) is during the summer monsoon period and high average wave power (15.5 kW m^{-1} at Honnavar and 19.4 kW m^{-1} at Ratnagiri) is found during the summer monsoon period. Wave power available along the locations studied is much lower (annual mean wave power ranges from 1.8 to 7.6 kW m^{-1}) than that available (20–70 kW m^{-1}) for temperate zones. Along the Puducherry coast, wave power is relatively less and is always less than 31 kW m^{-1}. The average wave power is high (≈ 28 kW m^{-1}) off Muldwarka in the northern Arabian Sea at 10 m water depth during June–August.

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Immunomodulatory constituents from *Annona squamosa* twigs provoke differential immune response in BALB/c mice

Vishal Kumar Soni[1], Manisha Pathak[1], Dinesh Kumar Yadav[2], Rakesh Maurya[2], Mahendra Sahai[3], Swatantra Kumar Jain[4] and Shailja Misra-Bhattacharya[1,*]

[1]Division of Parasitology, and
[2]Medicinal and Process Chemistry Division, Central Drug Research Institute, 10/1, Sector 10, Janakipuram Extension, Lucknow 226 001, India
[3]Institute of Medical Sciences, Banaras Hindu University, Varanasi 221 005, India
[4]Department of Biotechnology, Faculty of Science, Jamia Hamdard University, Hamdard Nagar, New Delhi 110 062, India

***Annona squamosa* (AS) has traditionally been used as ethnomedicine and various parts of the plant have been used to combat several disorders including dysentery, cancer and hyperthyroidism. Since the twig of this plant is reported to contain a large number of alkaloids, we chose to study its medicinal properties on the immune response of BALB/c mice. The present study, thus, aims at evaluation of immunomodulatory activity in the crude ethanolic extract and its four fractions, viz. hexane (F1), chloroform (F2), *n*-butanol (F3) and aqueous (F4) prepared from the twigs of AS to locate the active constituents in the fractions. The extract and fractions were fed orally at 3, 10 and 30 mg/kg for 14 consecutive days and mice were euthanized to assess various immune parameters. The ethanolic extract and its three fractions F2, F3 and F4 were found active since they increased splenic T and B cellular proliferation with a significant accentuation in peritoneal macrophage function, differentially increased the CD4+, CD8+ T lymphocytes and CD19+ B lymphocytes. The extract and its active fractions also demonstrated significant Th1 or Th2 mixed cytokine response at almost all doses tried in a dose-dependent manner. Its hexane fraction, however, could only induce reactive oxygen species production in peritoneal macrophages and could not induce lymphocytes; thus, it remained inactive. Thus, the activity could be localized distributed in its three fractions (chloroform, *n*-butanol and aqueous). Further purification and evaluation of the active molecule/s is underway in our laboratory.**

Keywords: *Annona squamosa*, flow cytometry, immunomodulatory activity, lymphocytes, reactive oxygen species.

INDIA is a rich biodiversity hotspot. It bears several plant species claimed to have traditional medicinal impor-

*For correspondence. (e-mail: shailja_cdri@rediffmail.com)