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Detection and monitoring of *Trichodesmium* blooms in the coastal waters off Saurashtra coast, India using IRS-P4 OCM data

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***Trichodesmium* blooms have been observed in the coastal waters off Saurashtra coast, Gujarat, India using Indian Remote Sensing satellite IRS-P4 Ocean Colour Monitor (OCM) data. Bloom-forming features were identified using false colour composites of channels 8, 6 and 5 (865, 670, 555 nm). Several bloom features of *Trichodesmium* like spiral eddies, stripes, slicks and parallel bands were detected in satellite images during 29 April to 7 May 2002. A strong backscattering signal was observed in the near-infrared band of OCM data, indicating the surface manifestation of *Trichodesmium* bloom. The chlorophyll images have been analysed during the bloom period; overestimation of pigments has been observed and the bloom patches appear darker. Subramaniam's protocol for *Trichodesmium* bloom study has been evaluated utilizing IRS-P4 OCM data for the waters off Saurashtra coast, and appeared to be relevant in detection by ocean colour remote sensing. The *in situ* information confirmed the presence of the bloom as coastal waters turned dark brown in colour with an appearance of sawdust spray.**

TRICHODESMIUM, a marine nitrogen-fixing cyanobacterium, forms extensive surface blooms that discolour vast regions of tropical and subtropical seas. *Trichodesmium* normally occurs in macroscopic bundles or colonies and is responsible for most of the N_2 fixation in oceanic and coastal waters[1]. It has been reported to bloom every year from February to May in near-shore waters off Goa as well as other locations along the west coast of India, where it mainly remains confined to the surface[2,3]. The mapping of *Trichodesmium* bloom has been carried out in the Coral Sea using CZCS data[4]. Infrared channels appear to show the potential for identifying *Trichodesmium* blooms. Surface cyanobacterial blooms have been observed with a distinct signal at 865 nm using SeaWiFS satellite data[5]. The presence of these blooms is reported to play an important role in the enrichment of water by releasing nitrogen and phosphorus. Nutrient enrichment assumes importance, since other processes of nutrient enrichment are minimal[6].

Trichodesmium can grow fast or bloom and accumulate as dense, visible patches near the surface of the water[7]. These algal blooms have been reported to promote the growth of diatoms and dinoflagellates on which the herbivores feed, followed by carnivores[8]. *Trichodesmium* has some unique characteristics that may help or hinder its detection by satellite data. In addition to its bloom-forming capacity, it has gas vacuoles that make it buoyant and keep it near the surface (within the upper 20 m), where colonies can be more readily detected[9]. *Trichodesmium* blooms are now of great scientific interest to the satellite remote sensing community. The phytoplankton in this bloom fixes nitrogen gas under fully aerobic conditions while photosynthetically evolving oxygen. It is now known to occur throughout the oligotrophic and subtropical oceans. The N_2 fixation property of *Trichodesmium* is likely to be a major input to the marine and global nitrogen cycle. Since fixed nitrogen commonly limits phytoplankton production in the ocean, oceanic nitrogen fixation has direct links to the ocean carbon cycle[10]. Stratification of the water column is a necessary condition for the formation of *Trichodesmium* blooms, as this allows cells to float on the surface with the help of their gas vacuoles. Stability of the surface waters is necessary for protection of the nitrogenase[11]. Although *Trichodesmium* is seen easily in the tropical seas, it has been difficult to detect it remotely by satellite. A robust detection protocol has been used[9]. But this is hampered by the fact that the spectral signature of *Trichodesmium* is strikingly identical to that of sediment plumes. High-resolution optical spectra at sea using hyper-spectral radiometers would resolve this problem[10].

However, the colour of the bloom varies and has been described as red, brown, green, yellow and silvery grey, depending on the age of the bloom[2] and the concentration of *Trichodesmium*[12]. In the present study we report the satellite detection and monitoring of *Trichodesmium* bloom in the coastal waters of the Arabian Sea along the Saurashtra coast, Gujarat, India. High spatial resolution data of Ocean Colour Monitor (OCM) sensor has been used for this study and satellite observations are supported by *in situ* investigations.

The study area lies in the coastal waters of the Arabian Sea along the west coast of India. The area is bounded by longitude 68.5 to 71.5°E and latitude 20 to 23°N. The

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OCM on-board Indian Remote Sensing Satellite IRS-P4 is optimally designed for estimation of chlorophyll in coastal and oceanic waters[13,14], detection and monitoring of phytoplankton blooms[7], studying the suspended sediment dynamics[15] and characterization of the atmospheric aerosols[16]. The specifications of the OCM sensor are given in Table 1 and other technical details are available elsewhere[17]. Five days of OCM data corresponding to path 9 and row 13 overpass and covering parts of the coastal waters around Saurashtra coast in the Arabian Sea were used in the present study (Figure 1). The data acquisition period is the last week of April and the first week of May 2002 (29 April 2002; 1, 3, 5 and 7 May 2002).

One of the most widely used data format for information extraction is the False Colour Composite (FCC) image. Extraction of information from such images about ground reality is done by image interpretation. Also, different band combinations of satellite data for three primary colours result in different FCC images, which are suitable for different applications[18]. Every application of remote sensing deals with a specific subject or integrated process of different subjects. The display colour assignment for any band of multispectral image can be done in an entirely arbitrary manner. In this case, the colour of a target in the displayed image does not have any resemblance to its actual colour. The resulting product is known as a FCC image[18]. There are many possible schemes of producing FCC images.

IRS-P4 OCM-derived FCC has been generated using near-infrared, visible red and visible green wavelengths (bands 8, 6, 5, depicted in red, green and blue respectively). Clear water appears dark-bluish (higher green band reflectance), while turbid water appears cyan (higher red reflectance due to sediments) compared to clear water, and the bloom features appeared reddish-brown in colour. The land portion of the FCC images was masked to enhance features. Figure 2 shows enhanced FCC for 1 May 2002. A strong backscattered signal from the bloom was observed in the 865 nm band images. Figure 3 *a–d* shows the spatial distribution of the bloom on different days in April and May of 2002. The spectral properties of the *Trichodesmium* patches were studied using the spectral profiles of top of the atmosphere (TOA) radiance for four different types of waters, namely clear water, sediment-laden water, waters above *Trichodesmium* bloom patches and waters around the *Trichodesmium* patches. Figure 4 shows the spectral curves for each of these categories.

For generating chlorophyll images, atmospheric correction of the IRS-P4 OCM imagery has been followed. As in remote sensing of the ocean, the signal received at the satellite altitude is dominated by radiance contributions through atmospheric scattering processes and only 8–10%

Table 1. Technical characteristics of IRS-P4 OCM

Spectral range	404–882 nm
No. of channels	8
Wavelength (μm)	Channel 1: 404–423 (340.5)
	Channel 2: 431–451 (440.7)
	Channel 3: 475–495 (427.6)
	Channel 4: 501–520 (408.8)
	Channel 5: 547–565 (412.2)
	Channel 6: 660–677 (345.6)
	Channel 7: 749–787 (393.7)
	Channel 8: 847–882 (253.6)
Satellite altitude (km)	720
Spatial resolution (m)	360 × 236
Swath (km)	1420
Repeativity	2 days
Quantization	12 bits
Equatorial crossing time	12 noon
Along-track steering (to avoid sunglint)	20°

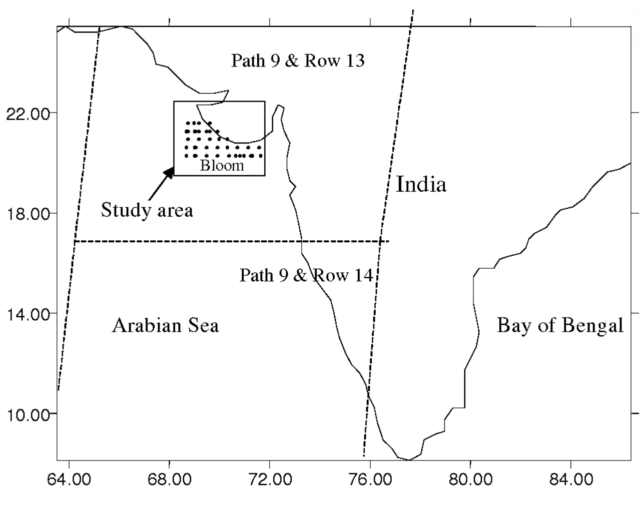

Figure 1. Map showing the study area around Saurashtra coast, Gujarat, India covered by the path 9 and row 13 overpass of IRS-P4 OCM satellite.

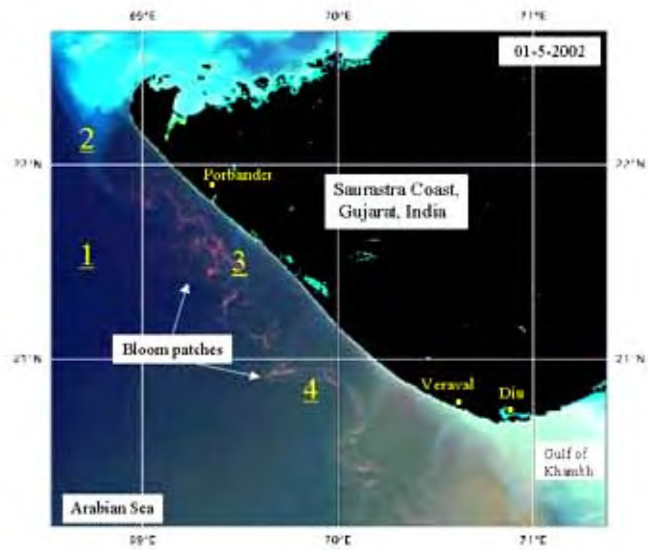

Figure 2. IRS-P4 OCM FCC image of channels (8, 6 and 5) showing *Trichodesmium* bloom.

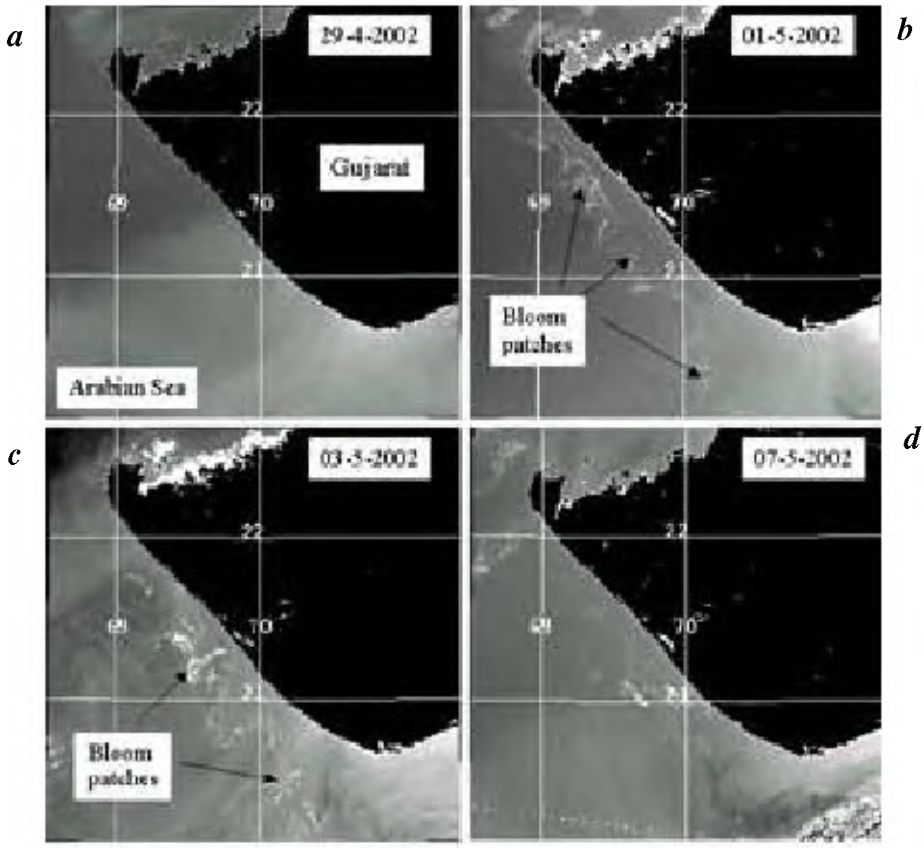

Figure 3. Top of the atmosphere radiance images of channel 8 (865 nm) of IRS-P4 OCM data showing algal bloom on (***a***) 29 April 2002, (***b***) 1 May 2002, (***c***) 3 May 2002 and (***d***) 7 May 2002.

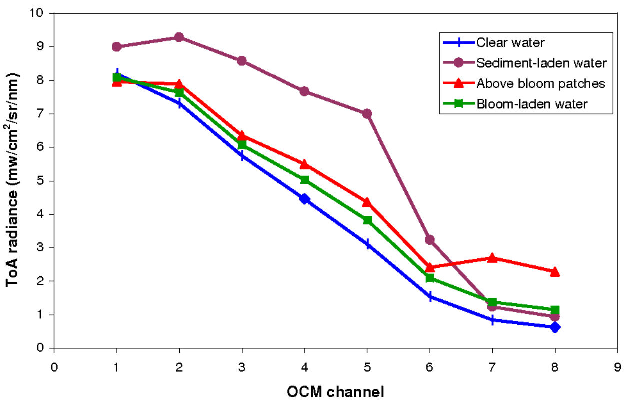

Figure 4. Spectral response in eight OCM bands for four different types of water, from TOA radiance image of 1 May 2002 (Figure 3 *b*).

of the signal corresponds to oceanic reflectance[19]. Therefore, it has been mandatory to correct the atmospheric effect to retrieve any quantitative parameter from space. An algorithm has been developed at the Space Applications Centre (ISRO), Ahmedabad, to correct OCM data for atmospheric contamination[20]. The OCM scenes were corrected for atmospheric effects of Rayleigh and aerosol scattering using an approach called long-wavelength atmospheric correction method. The approach uses the two near-infrared channels at 765 and 865 nm to correct for the contribution of molecular and aerosol scattering in visible wavelengths at 412, 443, 490, 510 and 555 nm. The chlorophyll algorithm is used for the water-leaving radiance images. A number of bio-optical algorithms for retrieval of chlorophyll have been developed to relate measurements of water-leaving radiance to the *in situ* concentrations of phytoplankton pigments. An empirical algorithm (also known as Ocean Chlorophyll 2 or OC2) is being operated for SeaWiFS ocean colour data[21]. This algorithm captures the inherent sigmoid relationship between the log-transformed band ratio ($R_{rs}490/R_{rs}555$) and chlorophyll concentration C, where R_{rs} is the remote sensing reflectance at 490 and 555 nm bands respectively. The algorithm was shown to retrieve low as well as high chlorophyll concentration. The algorithm operates with five coefficients and has the following mathematical form.

$$C = 10^{[0.319-2.336*X + 0.879*X2-0.135*X3]} - 0.071,$$

where C is the chlorophyll concentration in mg/m^3 and $X = \log_{10}[R_{rs}490/R_{rs}555]$.

While comparing all available algorithms for Indian waters, it was observed that this algorithm provided best

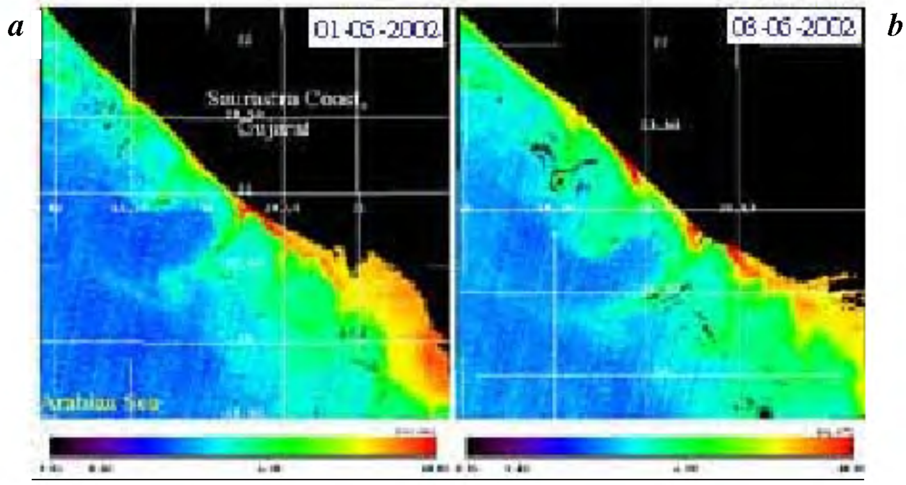

Figure 5 ***a*, *b*.** Chlorophyll images derived from IRS-P4 OCM data showing the *Trichodesmium* patches in dark bands, slicks and stripes off Saurashtra coast.

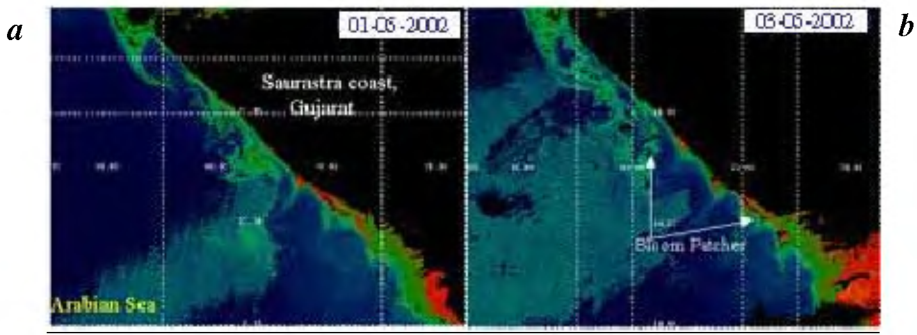

Figure 6 ***a*, *b*.** Images generated from IRS-P4 OCM data after applying the Subramaniam's protocol for detecting *Trichodesmium* bloom; darker patches show the persistence of bloom.

results for chlorophyll retrieval[22]. The algorithm has been presently used for generating the chlorophyll maps (Figure 5 *a* and *b*) using IRS-P4 OCM-derived water-leaving radiances.

Further, Subramaniam's protocol for *Trichodesmium* detection utilized for CZCS images[9], has been applied over the IRS-P4 OCM-derived radiance and chlorophyll images for two dates during our bloom detection and monitoring study off Saurashtra coast. The protocol is as follows:

$$\text{Protocol pixel value} = (m_2)^2(m_3)(L_{520})Chl,$$

where $m_2 = (L_{520} - L_{550})30$ and $m_3 = (L_{440} - L_{550})110$.

L_{440}, L_{520} and L_{550} are grey level values at 440, 520 and 550 nm respectively, and *Chl* is the derived chlorophyll grey-level value. The factors m_2 and m_3 which were used to identify absorption due to phycoerythrin at 550 nm, was used to identify blooms with higher reflectance. The term *Chl* identified the area with higher pigment concentration and served to prevent the protocol from reacting to turbid waters[9]. The OCM channels are almost identical to the CZCS channels and the channels 2 (443 nm), 4 (510 nm) and 5 (555 nm) of OCM have been used for the protocol-derived images (Figure 6 *a* and *b*).

Trichodesmium has high reflectance due to the presence of gas vacuoles, and blooms are confined to the surface part of the water column[12] and absorption is around 550 nm due to the presence of phycoerythrin[23]. Chlorophyll-*a*, which represents the main pigment, is accompanied by accessory pigments such as carotenoids and the phycobillins, phycocyanin and phycoerythrin, similar to algae belonging to Rhodophyceae[24], which imparts a brown colour to the cells and allows them to absorb light throughout the visible spectrum[25]. Channel-8 (865 nm, 40 nm bandwidth) images of OCM data were selected to detect the algal bloom as *Trichodesmium* produces high reflectance in the near infrared channels, where the ocean has maximum absorption. So, the near-infrared channels have the advantage over the visible channels in distinguishing *Trichodesmium* patches, even when chlorophyll concentrations are high.

The bloom patches were clearly observed in the channel-8 image of IRS-P4 OCM data (Figure 3 *a*–*d*). The bloom appears to have been initiated on 29 April 2002, with brighter pixels around the Saurashtra coast (Figure 3 *b*), indicating high reflectance in the near-infrared channel of the OCM data. The FCC image generated for 1 May 2002 shows dark brown and red coloured features and appears to be moving towards the Gulf of Khambat (Figure 2). Filamentous yellowish and reddish-brown algal blooms were observed during our cruise in April 2000 off the Gulf of Khambat (Figure 7). The filaments were identified to be of *Trichodesmium* species using compound microscope on-board *ORV Sagar Kanya* (SK-152 cruise). The bloom observed in the present study continued for about ten days and is seen decaying in the image of 7 May 2002 (Figure 3 *d*). The movement of bloom patches appeared to be heading southwards, towards the Gulf of Khambat from the central Saurashtra coast off Porbander, where it had been initiated. The bloom was found to be covering a distance of about 200 km in length parallel to the coastline and about 15–20 km in width at its peak on 1 and 3 May 2002. The bloom appeared to be intense with spiral, curly patches. But, the distinction about the bloom condition was quite clear in the TOA radiance images. *In situ* information has been gathered (US, CIFT) from the tidal features and from various fishermen operating from the Veraval harbour. *In situ* observations suggest prolongation of the bloom until the second week of May, although satellite images for that period were not analysed due to large cloud cover over the study area. The water was dark brown and appeared as if saw dust had been sprayed on the sea surface. A closer view of the bloom near the coast suggests that it started appearing at 40 m and was evenly distributed up to 150 m in distance, from Diu to Jakhau and beyond. Such a bloom is seen every year before the closing of the fishing season.

To study the spectral characteristics of waters in different cases, we have selected pixel locations from four different types of waters: (i) clear water, (ii) sediment-laden water, (iii) above bloom patches and (iv) bloom-laden water from IRS-P4 OCM data of the 1 May 2002 around the study area (location of these pixels in Figure 3 *b*). TOA radiance data retrieved from all eight channels of OCM sensor were plotted (Figure 4). The visible channels (1–6, 412–670 nm) show typical trends in the TOA spectra for all three water types ((i), (iii) and (iv)), except the type (ii) or sediment-laden water, which showed high values of TOA radiance at 555 nm. In the case of near-infrared channels (7–8, i.e. 765 and 865 nm), three cases ((i), (ii) and (iv)) show similar trend in TOA radiance values. But, type (iii) water showed exceptionally high TOA radiance values.

Figure 7. Filamentous *Trichodesmium* bloom stripes observed off the Gulf of Khambat during our IRS-P4 OCM validation ship cruise in April 2000, northeast Arabian Sea.

IRS-P4 OCM data have been analysed to generate chlorophyll images for the study area. High chlorophyll patches and plumes have been observed off Saurashtra coast. There is a clear difference observed between the *Trichodesmium* bloom patches (black coloured patches seen in the image) and surrounding chlorophyll patches (blue, green, yellow and red colour being represented in image respectively, depending on the concentration; Figure 2). The chlorophyll images monitored *Trichodesmium* bloom patches. The pigments could not be quantified accurately in the chlorophyll image as the pigments contained in *Trichodesmium* are phycocyanin and phycoerythrin, and the absorption peaks are around 495, 545 and 565 nm. This is different from the absorption peaks of common phytoplankton group diatom, which peaks at around 443 and 685 nm (fluorescence) due to the presence of chlorophyll. There is need for a more precise algorithm to detect *Trichodesmium* using satellites. We have applied Subramaniam's protocol using IRS-P4 OCM data and images extracted show the bloom patches in coastal water of Saurashtra (Figure 6). Features like spiral eddies, stripes, slicks and parallel bands observed in IRS-P4 OCM satellite images in the present study, are in good agreement with those from previous studies using other satellite datasets[4,5]. More *in situ* observations are needed to evaluate bloom dynamics, spreading and its impact on the ocean ecosystem.

In the present study we have observed *Trichodesmium* bloom patches and their movement in coastal water of the Arabian Sea using near infrared channel (865 nm) of IRS-P4 OCM satellite data. The colour of the water was dark brown and reddish, which has been observed from satellite-derived FCC image and *in situ* observations. The chlorophyll images were generated using OCM data and bloom patches appear dark. Subramaniam's protocol for *Trichodesmium* bloom study has been evaluated using OCM data and the results seem to be logical. The large bloom of *Trichodesmium* in the present study is of importance to the pelagic ecosystem in the Arabian Sea in terms of phytoplanktonic productivity and atmospheric nitrogen fixation. Satellite images are probably the ideal tool to observe and evaluate the distribution of phytoplankton blooms, especially *Trichodesmium* species.

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Biosorption of methyl violet, basic fuchsin and their mixture using dead fungal biomass

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The effect of different parameters on sorption of methyl violet, basic fuchsin and their mixture in an aqueous solution was studied. Dead biomass of *Aspergillus niger* was observed to be an efficient biosorbent. Maximum sorption was seen within 10 min. The sorption was independent of dye concentration and pH. The interaction of pH, dye concentration and biosorbent concentration showed variable results. The desorption profile showed that 0.1 M HCl was a better eluant than 50% ethanol.

CONTROL of pollution is one of the prime concerns of society today. With economic constraints on pollution control processes, affordable and effective methods have become a necessity. Untreated or partially treated wastewaters and industrial effluent discharges into natural ecosystems pose a serious problem to the ecosystem and the life forms. Among the many types of organics present, the most difficult to remove is colour. With increasing consciousness about pollution control, biosorption is

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