colonized the reproductive parts and caused sooty mould of flowers after 18 days of spraying (Figure 1*d* and *e*). Due to infection premature dropping of flower buds was also noticed. In the natural environment, pathogen colonized the reproductive parts and caused sooty mould of flowers after 18 days of spraying. During infection process *A. pullulans* produced blastospores, conidia and chlamydospores. The secondary spread of disease was through wind-borne conidia/blastospores.

Further, impact of *A. pullulans* infection on seed viability was studied by seed germination test. Infection resulted in production of sterile and malformed seeds (Table 4; Figure 1*f*–*h*). Thus *A. pullulans* as a floral pathogen inhibited floral development, embryo development, seed filling and rendered the seeds sterile. It was noticed that all its morphological stages were infective. As the pathogen produces chlamydospores, it may be an added advantage to carry over the pathogen to the next season and to formulate it at commercial scale. Spraying of *A. pullulans* has no deleterious effects on other plant species which share the common ecological niche, as was confirmed by host safety test. However, a detailed study on its ecology needs further attention. In view of copious seed production, wind dispersal nature and invasive capacity of eupatorium weed even in hilly areas and plains, exploitation of *A. pullulans* as a floral pathogen appears to be a hopeful potential mycoherbicide of eupatorium, as it causes sterile and malformed seeds, and thereby checks the weed seed production and its spread to virgin lands. Research is in progress to develop formulation of *A. pullulans* as a mycoherbicide for large-scale field application.

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Coal-fire detection and monitoring in Raniganj coalfield, India – A remote sensing approach

Raniganj coalfield, West Bengal is the largest coalfield in India, belonging to the Gondwana Super Group[1]. Asansol, situated about 210 km NW of Kolkata (Figure 1), is the main town in this coalfield. Mining in this region dates back to the British period. Initially coal mining was confined to open cast mines only, but gradually it was extended to the underground also. Coal-fire in Raniganj coalfield is either because of fire infection from adjacent fire-affected coal seams or anthropogenic activities or spontaneous combustion of coal. Oxidation of coal is an exothermic process and if the heat generated is allowed to accumulate, then the accumulated temperature ignites the coal. This natural process is called spontaneous combustion and is one of the major causes of coal fire in Raniganj coalfield. Thus India is losing good quality coal prior to its exploitation. Hence, there is need for detection and monitoring of coal fires in coalfields in order to control them effectively.

Remote sensing technique in thermal band offers a cost-effective and time-saving technology for mapping various geoenvironmental features like coal fires, forest fires, oil-well fires, volcanic eruptions, etc.[2]. These features are identified in band-6 (10.4–12.5 μm) as high-temperature anomalous areas[3] because hot bodies on the surface of the earth mostly emit radiation in this band Landsat-5 Thematic Mapper (TM) daytime digital data were used for this study. Night-time data were not considered for this study because ground control points, which are required for registration of the satellite image to the base map, are difficult to identify. The limitation of daytime data is that thermal anomalies represent partial underground coal fires with partial solar heating of non-burning coal seams and black shale with higher emissivity[4]. Winter-season data were selected for this study as the anomaly between fire and non-fire zones will be conspicuous. Topographic factors like aspect, slope angle and morphology of the area have a strong relation with reflectance and radiant temperature of an object[4]. Raniganj coalfield has a subdued topo-

Figure 1. Location map of Raniganj coalfield, West Bengal.

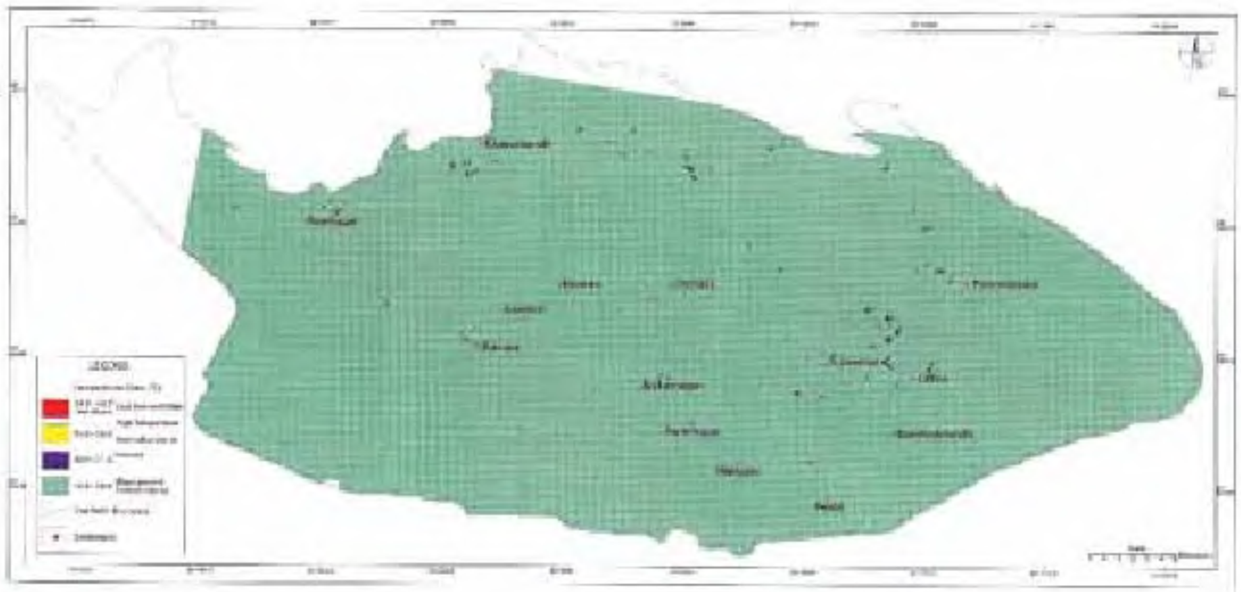

Figure 2. Coal-fire map of Raniganj coalfield.

Table 1. Classification of estimated temperature

Temperature class (°C)	Remarks
14.4–30.0	Background temperature
30.0–31.6	Coal fire and other high-temperature anomalies like industrial fire
31.6–38.0	
38.0–42.7 and above	

graphy and hence topographic factors have minimal influence on radiant temperature. Landsat-5 TM operates in seven bands and has 30 m spatial resolution in all bands except band-6, which has 120 m spatial resolution. It means that on the ground, information of 120 m × 120 m area is recorded as one pixel (picture element) with a digital number (DN) within 0 to 255 (for 8 bit data). Generally hot bodies are represented by higher DN values. Finally the temperature, which can be calculated from DN values, is the average temperature of the 120 m × 120 m area. Hence, fires of smaller size irrespective of their temperature, are likely to be missed out. In Raniganj coalfield, coal fires in open cast mines like Jambad and Ramnagar, which are of larger size are seen prominently in the satellite data, but fires near Dhadka and Dakshinkhanda village are almost insignificant in the satellite data due to their small sizes.

The information content of an area in band-6 of the satellite data is in the form of DNs. Conversion of these DNs to at-satellite temperatures is important for coal-fire mapping. This is done using Planck's radiation equation for black body for the bandwidth 10.4–12.5 μm.

$$L_\lambda = \int_{10.4}^{12.5} \left(\frac{2\pi hc^2}{\lambda^5}\right)\left(\frac{1}{e^{hc/\lambda\kappa T}-1}\right)\mathrm{d}\lambda, \quad (1)$$

where L_λ is the total spectral radiance in band-6 (W/m^2/Sr), λ the wavelength (m) in band-6, T the temperature (K), h the Planck constant (6.63×10^{-34} J s), c the speed of light (3.0×10^8 m/s), and κ the Boltzmann constant (1.38×10^{-23} J/K).

The inverse Planck equation will be:

$$T = \frac{C_2}{\lambda \ln(((\varepsilon C_1)/(\pi L_\lambda \lambda^5))+1)}, \quad (2)$$

where $C_1 = 3.742 \times 10^{-16}$ Wm^2, $C_2 =$ 0.0144 mK, and ε is the spectral emissivity.

Equation (2) to calculate the temperature can be simplified as:

$$T = \frac{14400}{\lambda \ln\left(\frac{3.742 \times 10^7}{\pi\lambda^5 L_6}+1\right)}, \quad (3)$$

where T is the radiant temperature in K (at-satellite), λ the average wavelength of band-6 (11.45 μm), L_6 the spectral radiance in band-6 (mW/cm^2/μm/sr).

L_6 can be calculated using the formula by Markham and Barker[5].

$$L_6 = 0.005632 \times \mathrm{DN} + 0.1238, \quad (4)$$

where DN is the digital number of the pixel for which calculation is being made. Using the above equations, radiant temperature was calculated for the terrain.

The temperature calculated from the satellite data depicts the radiant temperature of surface bodies. The heat generated by the underground coal fire is transmitted to the surface through the joints, fractures, faults and rock pores of the strata of Raniganj coalfield and is finally emitted to the atmosphere. Hence there exists a direct correlation between the underground coal fire and its surface manifestations.

The ambient temperature on 19 January 2001 was around 18°C. The land cover is mostly sandy soil and barren sandstone having high thermal capacity. The temperature was estimated using eq. (3) and then divided into four classes (Table 1) for preparation of coal-fire map using pseudo-colour encoding technique (also known as density slicing). Using trial and error technique during density slicing, DN values corresponding to background temperature of 30°C were considered as cut-off between fire and non-fire areas. The coal-fire map (Figure 2) gives an overview of

Table 2. Major thermally anomalous zones in Raniganj coalfield

Location	Longitude/ latitude	Temperature (°C) From satellite	Temperature (°C) On the surface	Fire zone dimension (in m × m)	Remarks
Ramnagar	86°50′40.6′E 23°45′26.6′N	42.7	143	300 × 300	Anomaly due to coal fire in the open cast coal mine
	86°50′22.8′E 23°45′21.5′N	34.1	86	80 × 80	
	86°50′44.1′E 23°45′18.3′N	34.1	76	110 × 110	
Khayerbandh	86°55′23.1′E 23°47′08.9′N	31.2	250	20 × 20	Anomaly due to coal fire in open cast mine
	86°55′56.0′E 23°47′15.0′N	31.2	145	40 × 40	
Burnpur	86°56′23.0′E 23°40′25.0′N	38.1	–	–	Anomaly due to chimney of IISCO steel plant
	86°56′00.0′E 23°40′36.0′N	31.2	–	–	
	86°56′28.8′E 23°41′01.3′N	31.2	–	–	
Jaykaynagar	87°04′06.3′E 23°39′17.4′N	31.2	–	–	Anomaly due to BALCO plant and adjacent mine boiler and chimney
Jambad	87°11′10.0′E 23°39′54.0′N	31.0	350	5 × 5	Anomaly due to coal fire in open cast mine
	87°11′26.0′E 23°38′02.0′N	31.0	150	10 × 10	
Jamuria	87°04′27.0′E 23°42′40.0′N	31.0	–	–	Anomaly due to burning of brick kilns
Pandaveswar	87°15′40.0′E 23°43′14.0′N	31.0	–	–	Not checked
Dhadka	86°59′40.1′E 23°42′01.4′E	25.7	550	3 × 4	Anomaly due to methane gas burning
Dakshinkhanda	87°14′01.6′E 23°37′22.7′N	25.7	500	3 × 4	Anomaly due to methane gas burning

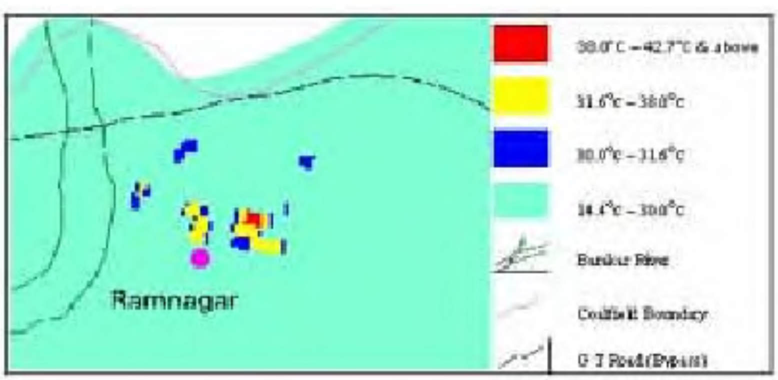

Figure 3. Coal-fire map of Ramnagar open cast colliery and its surroundings.

the fire-affected areas in Raniganj coalfield. Some of the major coal-fire affected/high thermal anomalous regions of Raniganj coalfield are mentioned in Table 2. Figure 3 gives in detail the coal-fire status of Ramnagar open cast colliery.

Ground-truth survey was carried out to verify the thermal anomalies, measure the temperature of fire and distinguish the anomaly between coal fire and domestic/industrial fire. A handheld infrared thermometer was used for the purpose.

The disparity between temperature observed on the surface and that measured from the satellite is because of the dimension of the fire zone and atmospheric absorptions.

In band-6, the highest DN value is 182 and the lowest is 115. Taking a contour interval of 10 DN, an isothermal map was prepared for the Ramnagar open cast colliery (Figure 4).

The present study demonstrates the application of remote sensing for coal-fire detection and monitoring, and also gives the status of the fire-affected areas in the Raniganj coalfield. Both coal-fire map

Figure 4. Isothermal map of Ramnagar open cast colliery and its surroundings.

and isothermal map give an overview of the fire-affected areas in Raniganj coalfield. Surface thermal anomalies are linked to the subsurface fire during field survey (Table 2). At-satellite temperature calculated may not match or correspond to the surface temperature, as conditions in the field vary from place to place and sometimes the fire zone dimensions are very small. However, this can be effectively and reliably used to demarcate the thermal anomalies and take precaution to prevent the fire from spreading further to adjacent areas. With the availability of Landsat-7 ETM + data with a spatial resolution of 60 m in band-6, detection and monitoring of coal fires can be carried out more precisely. At present, Raniganj coalfield is not severely affected by fire unlike other coalfields, but we will gradually be losing larger amount of coal if precautions are not taken now.

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