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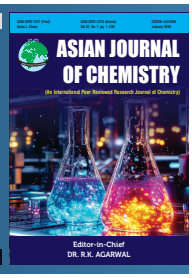

Soil Microbial Community Structure and Dynamic Enzyme Activity in the Degraded Soils of Paradeep Industrial Area

MANIKLAL GHOSH[1,*], AMARENDRA HARICHANDAN[2], PARESH NATH CHATTERJEE[1,3], MALAY KUMAR PRADHAN[4] and SOURAV BHATTACHARYA[5]

[1]Department of Chemical and Biological Sciences, National Institute of Technology Meghalaya, Saitsohpen Sohra-793108, India
[2]Department of Basic Science and Humanities, Hi-Tech Institute of Technology, Bhubaneswar-752057, India
[3]Department of Chemistry, National Institute of Technology Durgapur, Mahatma Gandhi Avenue, Durgapur-713209, India
[4]Directorate of Factories & Boilers, Government of Odisha, Bhubaneswar-751001, India
[5]Department of Basic Science and Humanities, Dr. B.C. Roy Engineering College, Fuljhore, Durgapur-713026, India

*Corresponding author: E-mail: maniklalghosh@nitm.ac.in; maniklal.ghosh05@gmail.com

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The surrounding land and waters are polluted by the industrial effluents of Paradeep. In this work, soil samples from seven locations around the Paradeep industrial area were investigated. The results found the overall average values of Fe, Cu, Zn, Cr, Ni and Pb were 149.24, 4.38, 4.69, 20.97, 2.98 and 7.41 mg/kg, which was lower than WHO guidelines except Mn (79.31 mg/kg). The soils under examination exhibit a pH range of 4.23-7.00, indicating the acidity to neutrality. The organic carbon content ranges from extremely low to high (0.17-1.76%). These soils have low to medium N, P and K values. High levels of hazardous Fe, Cr, Ni, Pb and Zn occur in the soils. Near Paradeep Phosphate Limited ash pond, the soil contains the highest amount of Cu (9.4 mg/kg). Heavy metals and low pH decreased the biological activities of several enzymes such as dehydrogenase, fluorescein diacetate and alkaline phosphatase, as shown by corelation studies (negative association). Industrialization has significantly contaminated the soil of the study region, requiring immediate restoration.

Keywords: Soil contamination, Soil nutrients, Microbes, Correlation, Industrial pollution.

INTRODUCTION

Throughout history, human beings have coexisted with the natural world. Unfortunately, surface and sub-surface soils of ecosystems now contain harmful trace metals from anthropogenic sources due to unregulated industrial and human activities. It is possible for these chemical compounds and hazardous trace metals to build up in water and soil. Hence, soil can be seen as a permanent repository for contaminants, from which these substances can enter food webs or seep into underground water sources [1]. Industrial waste is a common source of pollution due to irresponsible disposal practices. Non-point sources, such as pesticide residues or excessive use of fertilizers and specific sources, such as industrial emissions, effluents and solid waste disposal, vehicle exhaust and metal smelting or mining, are both contributors to pollution [2]. Although all these sources pose risks to humans, animals and plant health, the ones that leach heavy metal into soils are particularly worrisome because of how long these elements remain in the environment. They are immutable-all that can change is their state [3]. Soil environmental hazards are escalating due to causes such as heightened economic activity, rapid industrialization and negligent waste management, compounded by a lack of adequate knowledge regarding dangerous pollutants and their prevention [4,5].

The physico-chemical characteristics of soils are influenced by a combination of natural and human-caused variables that operate on time factors and space scales. The parent material, local geomorphology, vegetation, weather and other environmental factors all have a role in natural pedological processes including rock weathering and organic matter decomposition [6,7]. The intricate structure of soils reveals the consequences of these processes, which are time dependent. By contrast, the pedological properties are considerably impacted by soil management methods, which alter soil structure mechanically due

to urban and agricultural activities and because of pollution load the soil chemical composition is being altered. It is challenging to distinguish between natural and anthropogenic sources when determining the origin of an element's lethal concentration in the soil [8].

Among various industrial zones, the Central Pollution Control Board (CPCB) singled out the Paradeep industrial development area as particularly polluted [9]. Heavy metals, fly ash, nutrients (N, P, K), acid waste and zypsum pond waste all contribute to soil contamination in this region. Soil naturally contains heavy metals due to geological processes. However, human activities significantly contribute to soil contamination through various pollution sources, including agricultural practices, industrial operations, waste incineration, fossil fuel combustion and vehicular emissions. The industries located in the Paradeep industrial area include Paradeep Phosphates Ltd. (PPL), IFFCO, Paradeep Carbons Ltd., SKOL breweries, AMNS pellet plant, IOC refinery plant and other fish and prawn industries. Industrial solid waste is generated mainly from industries like PPL, IFFCO, AMNS pellet plant & ESSAR power plant, *etc*. These industries generate and dispose a major quantity of waste over to land as part of the process of waste disposal or waste treatment. The major waste generated from various units of the processing plant includes: phosphogypsum (contain sulphur mock, spent catalyst, acid residue, Cd, Cr, Cu, Mn, Zn, Pb and F), phosphoric acid tank sludge (hazardous waste), effluent treatment plant (ETP) sludge, fly ash from power plants, solid waste from industrial processing plants and power plants, ash from incinerator, spent clay containing oil, used oil and waste oil from petroleum industry and fertilizer industry. The geneated wastes disposal practice follows the process like gypsum pond, ash pond, disposal in secured land fill, solid waste disposal, wastewater disposal, *etc.* The disposed waste adversely impacted soil components of the surrounding area. In this pursuit, our research group set out to examine the soils near the Paradeep industrial area of Jagatsinghpur district and to determine the extent of heavy metal contamination in soil, as well as the relationship between soil parameters, diversity of organisms and enzyme activities. Also, this work has been conducted to address the issue related to sources of soil contamination and to help the policy maker to manage the impact with remediation.

EXPERIMENTAL

Study areas: Paradeep, one of the important industrial seaport cities in the eastern part of India, is located 53 km (33 miles) from Jagatsinghpur city of Odisha state, India. The city is located with the GPS coordinates of 20º18′59.5836″ N and 86º36′40.9176″ E. The spatial distribution maps are created using the ARC GIS software and inverse distance weighted (IDW) tool. The port is situated in the delta of Mahanadi river and the Bay of Bengal, which receives more than 57 million tons of cargo annually. The most common products exported through the port are minerals, coal and other natural resources. There are several manufacturing facilities in the town that contribute to its status as an industrial hub. These include the edible oil factory of Cargill, the pellet facility of Essar Steel, Paradeep Phosphates Ltd. (PPL), Paradeep Plastic Park Limited (PPPL), *etc*.

Resources and techniques: The soil analysis was done in 2023 and seven samples of soil were gathered from the Paradeep industrial area (Fig. 1), by driving a core-cutter into the ground to a depth of 25-30 cm. Multiple sub-samples were collected from different points within each sampling site, following a zig-zag pattern across a defined area (1 hectare field size, Table-1). Typically, six sub-samples were taken from each site, mixed thoroughly and composited into a single representative sample for that site for laboratory analysis. For the soil sampling approach, the standard soil sampling and testing practices as per ICAR and State Soil Testing Laboratory guidelines were followed [10,11]. This methodology ensures sampling strategy accuracy and average soil conditions at each site.

To conduct the microbe investigation, the soil samples from each site were passed through a 0.5 mm filter to remove gravel and other debris and then stored them in self-locking polythene bags at 4 ºC for three weeks. Nutrient agar, potato dextrose and starch casein agar were used for bacterial, fungal, and actinomycete isolations, respectively. The soil dilution plates were made using newly sampled soil on the same day. Following the serial dilution, 1 mL of appropriate dilution (10^{-4} for actinomycetes and fungi and 10^{-5} for bacteria) was added to the corresponding petri plates. Once the media was covered with the sample using a flame-sterilized bent glass rod, the plates were placed in an incubator set at 20 ºC and placed to incubate in the absence of light. Microbial colonies were counted and recorded after being visible for a minimum of 2 to 7 days (or 2 to 14 days for actinomycetes) and prior to their disappearance. The calculation of cfu/g of dry soil was based on the soil dilution parameters and the moisture content in the soil. The error associated with the count was ± 3%.

The soil samples collected from seven different sites were air dried before being oven-dried for 48 h at 60 ºC. Afterwards, the dried soil samples were finely ground using a pestle and mortar. To ensure that the samples were uniform in texture, they

TABLE-1
SAMPLING LOCATION DETAIL AND TERRAIN FEATURES

Location and source of pollution	Location	Terrain features
Musadia, Paradeep (IFFCO Plant)	**L1**	Industrial area
Baularia Palanda (Cargill India Pvt. Ltd.)	**L2**	Urban area
Jhimani, Paradeep (Oil Refinery)	**L3**	Industrial area
PPL Township, Paradeep (Paradeep Phosphates Ltd.)	**L4**	Residential area
Atharbanki (Gypsum storage site of IFFCO plant)	**L5**	Industrial area
Udayabata (Goa Carbon Ltd.)	**L6**	Industrial area
Near PPL ash pond	**L7**	Industrial area

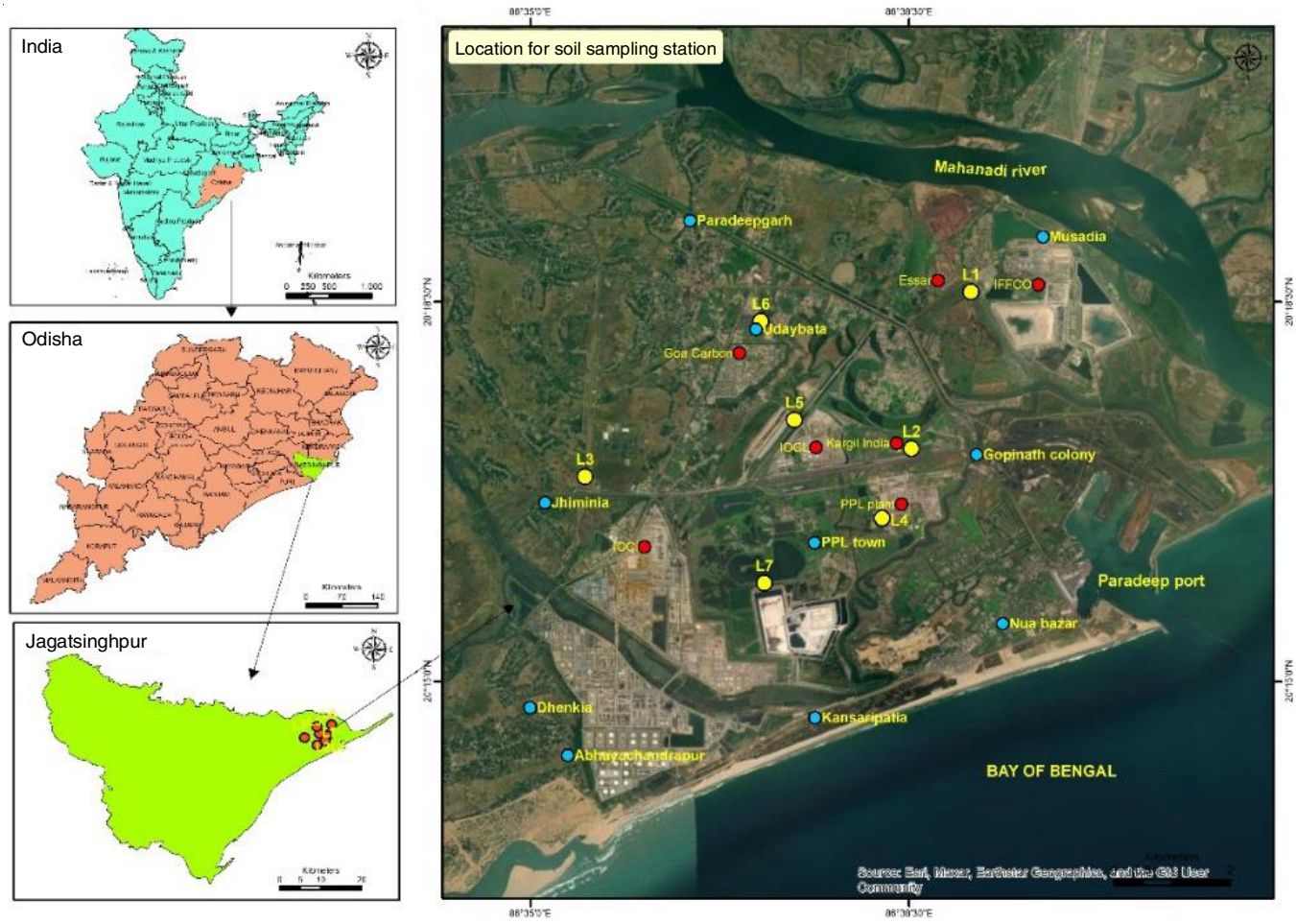

Fig. 1. Sampling map

were ground into a fine powder to a standard 250 mesh size using a swing grinding mill. A precise method for measuring the pH of soil suspensions prepared with a 1:1 ratio of soil to water. To test the air-dried soil samples for the physico-chemical properties including pH, electrical conductance (EC), organic carbon, accessible N, P and K, the the conventional procedures were followed [12]. To ascertain the concentrations of heavy metals (Fe, Cu, Mn, Zn, Cr, Ni and Pb) in the soil, the corresponding electrodeless discharge lamps in the atomic absorption spectrophotometer (AAS) were utilized [12]. In AAS analysis, 5-point calibration method or using 5 standards *i.e.* 0.0, 2.5, 5.0, 7.5 and 10.0 mg/kg, the standard calibration was plotted. For blank, double-distilled water was used for calibration. The error associated with the AAS analysis was ± 5%. The Pearson correlation matrix (eqn. 1) was used to conduct the correlation among the several soil parameters. To determine the relation between the heavy metals and soil characteristics and microbiological factors, the correlation coefficients were calculated:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (1)$$

where, n = sample size; x_i, y_i = the individual sample points indexed with i; $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$ (the sample mean) and $\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$ (the sample mean).

RESULTS AND DISCUSSION

Soils polluted by industrial effluents sampled from seven sites in the Paradeep region in Odisha, India, have pH values between 4.5 and 6.7 (Table-2). At locations **L4** and **L2**, the soils near Cargill India Pvt. Ltd. had relatively high pH value (pH 6.4 and 6.1, respectively), whereas at **L1**, the soils close to the Paradeep IFFCO facility were significantly acidic (pH 4.5) and at location **L5**, the soils from gypsum storage site of IFFCO industrial regions were relatively acidic (pH 4.7). This result was anticipated due to the industrial activity close to these two sites, which releases wastewater following the cleaning of acid storage tanks that hold acidic residues. Also, the disposal water from fertilizer industry containing phosphoric acid is the reason for acidic nature of soil and thereby confirmed the pollution of soil by fertilizer industry. In the studied locations, the soils do not contain any salt (0.102-0.911 dSm^{-1}).

The organic carbon levels in contaminated soils varied between 1.2% and 0.17%. Approximately 42.8% of the soils

TABLE-2
SOIL CHEMICAL PROPERTIES AT SELECTED SAMPLING LOCATIONS

Location	pH	EC (dSm^{-1})	Organic carbon (%)	N (kg/ha)	P (kg/ha)	K (kg/ha)
L1	4.5	0.911	0.42	229	23.0	467.1
L2	6.1	0.102	1.76	171	36.0	223.2
L3	5.4	0.131	0.66	158	11.8	108.4
L4	6.7	0.111	1.20	211	19.0	171.6
L5	4.7	0.312	0.23	238	13.0	323.4
L6	5.8	0.118	0.75	136	10.2	90.7
L7	5.2	0.171	0.17	254	43.0	267.3

were determined to be poor (< 0.50%), 28.6% of the soils are classified as medium (0.50-0.75%) and the remaining soils (28.6%) have significant levels of organic carbon (> 0.75%). The lowest soil organic carbon content (0.17%) was found at location adjacent to PPL ash pond industrial areas; however, it was medium in the soils from locations **L3** (0.66%), **L6** (0.75%). The soil sample collected from location **L2** had the highest average concentration of organic carbon, of 1.76% followed by **L4** (1.2%). The highest organic carbon value was expected at **L2** and was due the organic waste disposal from Cargill India Pvt. Ltd. Most of the soils in this study region have become barren as a result of the buildup of decomposition products in soils caused by the discharge of wastewater.

The soils in the present research site have an accessible nitrogen content ranging from 136 to 254 kg/ha, having an overall average of 201 kg/ha. A 85.7% of collected samples of soil detected a shortage in the availability of N (< 250 kg/ha). Soil had the least amount of accessible nitrogen at location **L6** (136 kg/ha) and from location **L3** (158 kg/ha), with the site of **L7** being the most elevated (254 kg/ha). At locations **L6** and **L3**, lower value of nitrogen in soil indicating less fertile nature due to addition of waste from oil refineries, Goa Carbon Ltd. industry that makes the environment unsuitable for growth of nitrogen fixation bacteria. The results revealed that nitrogen availability in the degraded soils is significantly low, whereas it is high in samples taken from a nearby fertilizer industry, as anticipated. This was due to the waste disposal of fertilizer industry to the nearby area. The reason for high and low values of nitrogen is cleared from spatial distribution map (Fig. 2a) indicating nearby industrial activities. Phosphorus availability in the investigated industrial zone varied between 10.2 and 43 kg/ha. The low value of phosphorous in the soils of studied area was obtained at **L6** whereas highest value of phosphorous was from location **L7**. From site **L6**, the soils showed the least average available potassium level (90.7 kg/ha), however, it was found medium in the soil sample from locations of **L2**, **L4**, **L5**, **L7** with values of 223.2 kg/ha, 171.6 kg/ha, 323.4 kg/ha and 267.3 kg/ha, respectively.

The area immediately around location **L1** had the highest average accessible potassium of 467.1 kg/ha. The deteriorated soils had a nutritional level ranging from poor to medium and were generally unfit for farming. The high and low values were expected from the above-mentioned location as these locations were close to fertilizer industry. The reason for high and low values of phosphorous and potassium are cleared from spatial distribution map (Fig. 2b-c) indicating nearby industries.

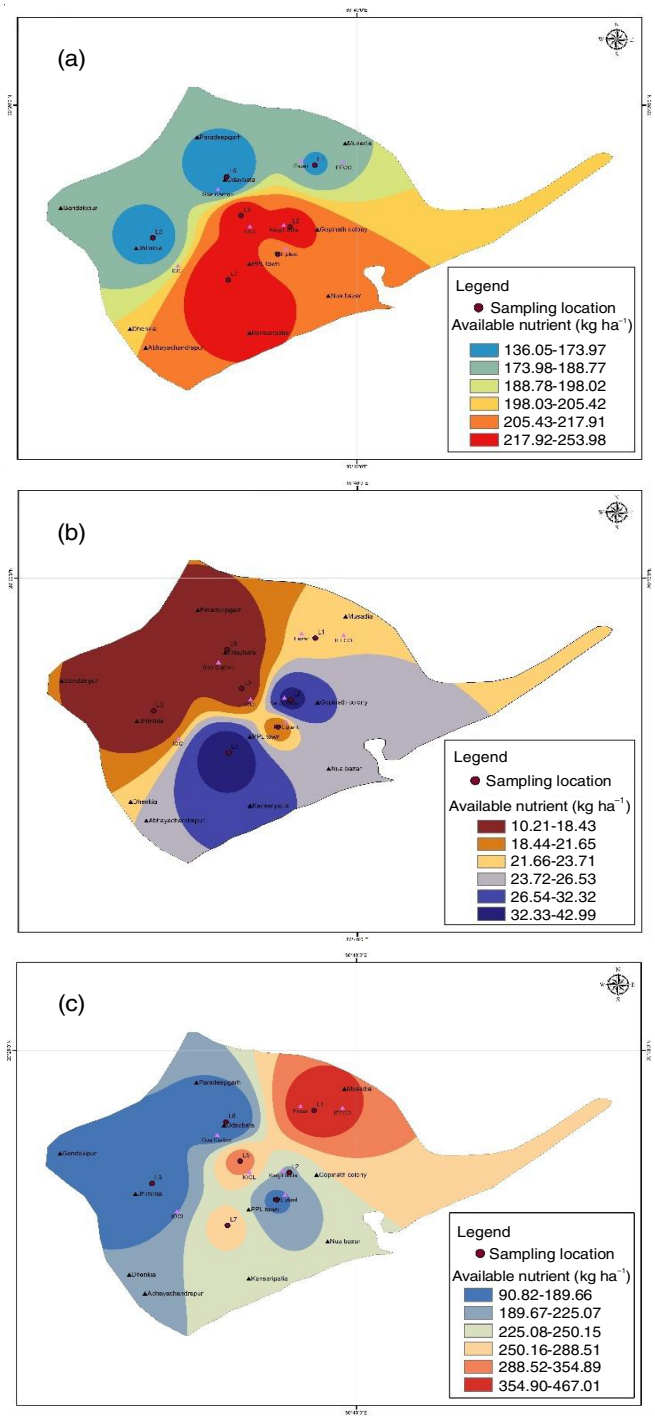

Fig. 2. Spatial distribution of (a) nitrogen (N), (b) phosphorous (P) and (c) potassium (K) throughout the study areas

Levels of micronutrients in soils near industrial zone: The studied areas are generally dominated by fertilizer industries, steel industries, coal-based power plants, petrochemicals and refineries. Excessive volumes of fly ash and ground fuel ash dumped onto land, emission of metal from smelters, input of pollutant from zypsum ponds, wastewater from fertilizer industries, transportation activities are the major input of both metal, nutrients (N, P, K) to soils. The available Fe in the soil sample collected ranged from 19.2-347 mg/kg (Table-3). The soils at site **L1** had the most elevated average accessible Fe levels (347 mg/kg) next to it at site **L5** (192 mg/kg) and at site **L7** (178.6 mg/kg). The high values of Fe were expected due to the nearby industrial activities like contribution from fly ash disposal and from nearby steel industry waste. Nevertheless, the total amount of available Fe in the soil samples taken from the research region was determined that greater above the essential threshold of 4.0 mg/kg. Specifically, 14% of the soil samples had an iron content of > 50 mg/kg and 71% had an iron content of > 100 mg/kg. The manganese availability in soils was found to be in the range between 12.4 and 142.5 mg kg^{-1}. Soil samples taken from site **L1** had the highest average available Mn level (142.5 mg/kg) followed from location **L5** (131.6 mg/kg) and, from **L7** (119.7 mg/kg). The amount of accessible Mn in soils was found to be more than 50 mg/kg in over 28.5% of soils and over > 100 mg/kg in 43% of soils. Available Mn levels in all soil samples are higher than the limit of detection, which is 2.0 mg/kg. Nearly every soil sample had concentrations of zinc and copper that were greater than the acceptable limits of 0.60 and 0.20 mg/kg, respectively. The zinc availability in this investigation was 4.7 mg/kg, with a variability of 0.58 to 11.22 mg/kg. The soil sample taken at site **L1** contained the highest mean accessible Zn (11.2 mg/kg) followed by at location **L7** (10.6 mg/kg) and at **L5** (6.2 mg/kg). These high values were due to the industrial activities like fly ash disposal, steel industry activities and gypsum ponds. The range of accessible Cu in the soils was between 0.23 and 9.4 mg/kg. The sample collected at site **L7** has the maximum mean concentration of presented Cu concentration (9.4 mg/kg) followed by sample from **L1** (9.1 mg/kg) and **L5** (7.1 mg/kg).

The obtained chromium level in the collected soil sample varied between 6.5-45.6 mg/kg. Highest chromium values (Fig. 3a) were observed in the soil sample near industrial area (**L1**) with value of 45.6 mg/kg. The soil sample also contains 2.3-11.3 mg/kg of Pb (Fig. 3a) and 0.44-6.7 mg/kg of Ni (Fig. 3b). As a result, research found that high levels of Cr, Ni and Fe (Fig. 3a-c) present in sample collected from location **L1** near the industrial areas. At these locations the high values of metal in soil were mainly due to fly ash disposal and steel industry activities. Many risks to crops, cattle and human being are caused by these heavy metals when they move through the soil-plant-animal ecosystem. All the high values of metal at mentioned location were due to nearby industrial and transportation activity in the study area, which is clear from correlation study.

Soil microbiology and biological processes in the industrialized regions: Table-3 displays the most abundant microbes found in the soil samples from site **L2** near Cargill India Pvt. Ltd. followed by site **L4**. Maximum fungal counts (55×10^4 cfu/g) were detected in location **L2**, while maximum bacterial counts (67×10^5 cfu/g) were observed in the same site which is adjacent to Cargill India Pvt. Ltd. followed by site

TABLE-3
SOIL MICROBIAL COUNTS, SOIL ENZYME ACTIVITIES AND HEAVY METAL AT SELECTED SAMPLING LOCATIONS

Location	Total microbial counts			Soil enzyme activities			Heavy metals						
	Fungi	Bacteria	Actino-mycetes	DHA	FDA	Acid phos-phatase (AP)	Fe	Cu	Mn	Zn	Cr	Ni	Pb
L1	14	18	15	0.221	0.613	22.24	347	9.1	142.5	11.22	45.6	6.7	11.3
L2	55	67	42	0.728	0.523	12.47	19.2	1.65	17.2	1.2	10.3	0.44	4
L3	31	30	24	0.577	0.311	19.12	113.8	0.23	75.6	1.5	15.2	1.4	7.7
L4	43	54	33	0.636	0.382	32.79	83.4	2.6	12.4	0.58	6.5	0.72	2.3
L5	16	17	23	0.191	0.211	11.21	192	7.1	131.6	6.2	25.8	4.6	9.8
L6	28	27	27	0.614	0.231	20.08	111.3	0.6	56.2	1.5	15.8	2.1	7.3
L7	20	20	18	0.321	0.162	14.07	178	9.4	119.7	10.6	27.6	4.9	9.5
Average	29.57	33.28	26	0.469	0.347	18.85	149.24	4.38	79.31	4.69	20.97	2.98	7.41

Note: All metal values are in mg/kg of soil, fungi count 1×10^4 cfu/g, bacteria count 1×10^5 cfu/g, actinomycetes count 1×10^4 cfu/g, DHA in $\mu gTPFg^{-1}h^{-1}$, FDA in µg/g/h and AP in $\mu gPNPg^{-1}h^{-1}$.

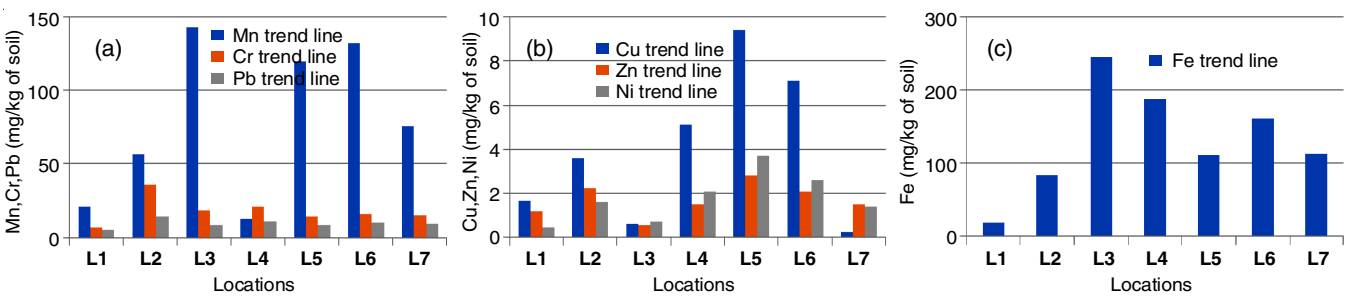

Fig. 3. (a) Mn, Cr and Pb metal content trend in the study areas, (b) Cu, Zn and Ni metal content trend in the study areas and (c) Fe metal content trend in the study areas

L4. At this location, these trends were expected as this location the terrain feature was residential area and contamination level is less. The lowest microbial counts were observed in the **L1** location sample soil, which is adjacent to IFFCO Plant industrial areas, which was expected as the industrial activities (fly ash disposal) influence surrounding soil quality. The variation in bacterial and fungal counts can be cleared also from Fig. 4a-b.

One way to measure the number of oxidative microbes in soil is to look at the activity of dehydrogenases, which are involved in the cellular energy transfer and oxidation processes. Out of the tested soils, the value at site **L2** had the maximum (0.728 μgTPFh^{-1}g^{-1}) dehydrogenase activity (Table-3) followed by site **L4** (0.636 μgTPFh^{-1}g^{-1}). This was expected as this location had a good number of microbial count and nearby terrain feature is residential area.

Dehydrogenase activity (DHA) and fluorescein diacetate activity (FDA) were ranged from 0.191-0.728 μgTPFh^{-1}g^{-1} and 0.162-0.782 μg/g/h, respectively, in the study areas. Highest FDA was observed at the location **L1** (0.613 μg/g/h) followed by **L2** (0.523 μg/g/h). Site **L3** had least levels of enzyme activity measured in DHA and FDA, where the soil was contaminated with oil and refinery industry waste. The increased dehydrogenase and fluorescein diacetate activity in these contaminated soils may result from enhanced microbial access to substrates for metabolic processes, while micronutrient supplementation significantly influences the cofactors of various enzymes [13].

Soil samples taken in close proximity to fertilizer factories showed a rising trends of acid phosphatase of the study area. According to Eivazi & Tabatabai [14], several soil-forming parameters, including pH and the parent substance influence the acid phosphatases' activity of soil. Maximum acid phosphatase activity (Table-3) levels were found in the soils (at **L4**: 32.79 μgPNPg^{-1}h^{-1}, **L1**: 22.24 μgPNPg^{-1}h^{-1}), which contaminated by wastes generated from the nearby fertilizer industrial area. However, site **L5** had the least acid phosphatase activity 11.21 μgPNPg^{-1}h^{-1}), which was expected.

Microbiological factors and their association with metals in soil: Fungi, bacteria and actinomycetes population of the soil showed a negative correlation with all studied heavy metals (Table-4). All the studied heavy metals (Fe, Cu, Mn, Zn, Cr, Ni and Pb) had significantly inversely related with soil actinomycetes (r = -0.876, -0.687, -0.899, -0.803, -0.827, -0.868 and -0.885, respectively), bacteria (r = -0.774, -0.582, -0.903, -0.689, -0.739, -0.814 and -0.913, respectively) and fungi (r = -0.862, -0.696, -0.938, -0.771, -0.819, -0.893 and -0.917, respectively) revealed that heavy metals were building up in soil samples as influenced by effluent/sludge emancipated by the industrial sectors. These industrial activities negatively impacted the soil bacteria. The foremost biota to experience both the immediate and long-term impacts of heavy metals are microbes. Even at very low levels, certain metals like Fe, Zn, Cu, Ni and Co play an important role in numerous microbiological processes. These metals participate in a wide variety of metabolic and redox reactions.

Metals help microbes together with fungi, actinomycetes and bacteria with their secondary metabolism [15,16]. Heavy metals aren't always poisonous, but they can impede or kill microorganisms when it at higher level [17]. Soil micro-

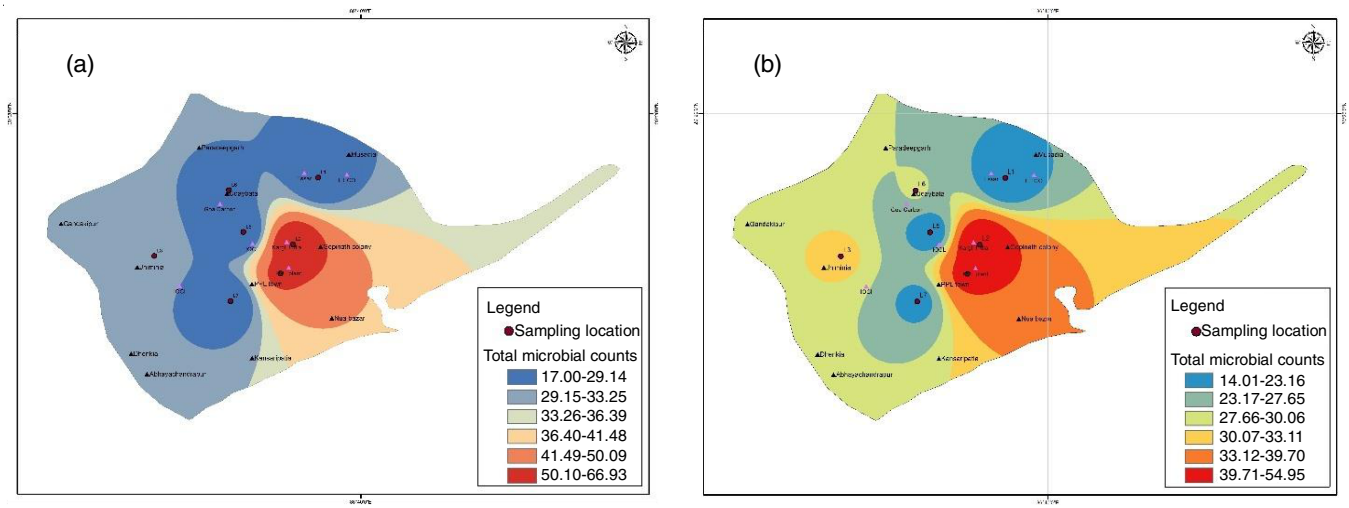

Fig. 4. Spatial distribution of (a) bacteria and (b) fungi throughout the study areas

TABLE-4
CORRELATION (r) AMONG HEAVY METALS, SOIL CHEMICAL CHARACTERISTICS AND MICROBIOLOGICAL FACTORS IN SOIL

Soil properties	Fe	Cu	Mn	Zn	Cr	Ni	Pb	pH	EC	Org. carbon	N	P	K
Fungi	-0.862	-0.696	-0.938	-0.771	-0.819	-0.893	-0.917	0.858	-0.604	0.962	-0.505	0.197	-0.526
Bacteria	-0.774	-0.582	-0.903	-0.689	-0.739	-0.814	-0.913	0.831	-0.485	0.969	0.379	0.248	-0.376
Actinomycetes	-0.876	-0.687	-0.899	-0.803	-0.827	-0.868	-0.885	0.802	-0.622	0.936	-0.500	0.085	-0.498
DHA	-0.866	-0.883	-0.953	-0.870	-0.858	-0.942	-0.858	0.883	-0.680	0.857	-0.768	-0.032	-0.781
FDA	0.207	0.001	-0.152	0.035	0.230	0.019	-0.134	0.018	0.574	0.494	-0.071	0.132	0.457
Acid phosphatase	0.013	0.235	-0.396	-0.278	-0.215	-0.239	-0.445	0.503	0.073	0.215	-0.101	-0.312	-0.182

organisms are negatively impacted by metals, resulting in less biological materials being broken down, metabolism, variety and the production of enzymes [18]. Due to the structural similarity between heavy metals and enzymes, a high dose of these metals can destroy enzymes and render them inactive [17]. The accumulation of heavy metals also has a major impact on soil enzyme activity, as shown by the adverse and/or marginal association among the two. Soil enzyme activities (FDA) of microbial mass showed positive and nonsignificant relationship with heavy metal like Fe, Cu, Zn, Cr, Ni (r = 0.207, 0.001, 0.035, 0.23 and 0.019, respectively). Also, the acid phosphatase activity of microbial mass showed positive and nonsignificant relationship with heavy metal like Fe, Cu, (r = 0.013 and 0.235 respectively). These findings showed that the soil condition in the current investigation degraded due to detrimental impacts on microbial activity brought about by elevated heavy metal levels in the soil.

Association of soil characteristics and microbiological factors: The association between soil pH and microbial biomass and activity was either non-existent or negative (Table-4). But direct association among pH-fungi (r = 0.858), pH-bacteria (r = 0.831), pH-actinomycetes (r = 0.802) and pH-acid phosphatase (r = 0.503) indicates the source of pH in soil might be due to microbial mass. While changes in soil response did not impact microbial's number multiplication, they did have a detrimental impact on soil enzyme activity. Nutrient levels following the addition of different organic amendments and changes in pH, which promote bacterial proliferation at the expense of fungal development, were found to be connected to alterations in the quantity and activity of microbes [19].

There was a strong link between the organic carbon and soil bacteria (r = 0.969), then fungi (r = 0.962) and finally actinomycetes (r = 0.936) (Table-4). Finally, it was found that the activities of dehydrogenase, fluorescein diacetate and acid phosphatase were all significantly related to soil organic carbon. The 'r' values for these were 0.857, 0.494 and 0.215, respectively. Multiple types of bacteria live in organic matter, so increasing organic matter had a big impact on the growth of microbes and enzymes which are involved in many biochemical processes in soil. There is a strong association between soil organic matter content and soil phosphatase function. This supports earlier claims that higher levels of organic matter boost soil phosphatase activity [20].

There was either no or a negative association between the amount of salt in the soil and microorganisms and biological processes. Direct correlation was found between DHA and soil microbes (Table-5). A direct association also among soil bacteria and accessible N and P (r = 0.379 and 0.248, respectively) was obtained (Table-4). There was also a positive but not significant relationship among soil fungi and presented P content (r = 0.197). In the heavy metal-contaminated soils of the study areas, this demonstrated that soil microbes played a more significant role in the transformation of nutrients than other microbes. The relationship between available N & K and dehydrogenase activity was significant and negative (r = -0.768 and -0.781, respectively). There was a positive link between available P and K with FDA (r = 0.132 and 0.457 respectively).

TABLE-5
ASSOCIATION (r) CONNECTING SOIL MICROBES TO ENZYME FUNCTION

Soil microbes	DHA	FDA	Acid phosphatase
Fungi	0.903	0.300	0.181
Bacteria	0.825	0.411	0.231
Actinomycetes	0.828	0.214	0.049

This showed that FDA enzyme is involved in changing nutrients. With a value of -0.312, acid phosphatase had a negative link with available P. This meant that industrial activity was to blame for the rise in available P levels in the soil. There is a strong negative connection between the amount of soil microbes, their biological activities and the amount of salt in soil. This indicates that the majority of soil nutrients originate due to human activities.

Conclusion

Analysis of heavy metals, soil health, microbial communities and actinomycetes showed that the soils in the study area surrounding Paradeep port city, India, are very vulnerable to heavy metal pollution as a result of rapid industrialization. Elevated concentrations of Fe, Mn, Cr, Pb and Ni in these soils have a negative correlation with the microbial health of the soil. Rapid industrialization in this area leads to heavy metal pollution in the soil due to their irresponsible disposal of waste or minimal care to ward off regional soil health, which eventually poison the microbial activity and negates the soil chemistry. The heavy metal content in the soil above the permissible limit in these soils pose significant risks, including the inhibition of essential soil enzyme activities and reduced crop yields. The accumulation of these toxic metals in the soil-plant-animal-human ecosystem or habitat chain is a growing health and occupational concern for the local community. Hence, continuous monitoring as well as possibly restricting the disposal of industrial waste in those industrial zones and surrounding areas is critical to ensure the compliance with environmental standards. Immediate remedial actions are essential to reduce heavy metal concentrations and prevent further damage to ecosystems and food chains. Moreover, research on microbial responses to heavy metal pollution is urgently needed to identify resistant microbes capable of restoring soil fertility and aiding in bioremediation efforts. The present findings underscore the necessity of implementing stringent waste disposal restrictions, conducting continuous monitoring of soil profiles and microbial health and adopting effective effluent treatment strategies to mitigate environmental pollution at Paradeep industrial zone.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

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