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Review Article

Geophysical Methods for Assessing Microbial Processes in Soil: A Critical Review

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Geophysical techniques have witnessed significant changes over the years and the applications are gradually shifting from its application in characterization of structure to characterization of processes. A comprehensive bibliometric analysis of the Geophysical tools in studying the microbial processes at subsurface level is presented here. Late 90s witnessed potential use of geophysical tools in characterization of contaminated lands for monitoring the changes taking place therein. Geophysical tools have achieved success in sensing the microbial processes that has stimulated the researchers' interest to study its possible application in monitoring bioremediation processes. Geophysical tools offer distinct advantages over the invasive point based methods deployed in monitoring the efficacy of remediation in view of their low cost, higher spatio-temporal resolution. A proper understanding of geophysical signatures *vis-à-vis* different controlling parameters is imperative to realize full potential of geophysical tool. Bibliometric analysis suggests different tools viz. DC resistivity, Self-Potential, Spectral Induced Polarization, Electro Magnetic, Ground Penetrating Radar have the potential to identify the changes in contaminated zones impacted by microbial processes. It is necessary that geophysical measurements should involve with the geochemical and microbiological measurements to avoid ambiguous results.

Keywords: Bioremediation; Biogeophysics; Geophysical methods; Soil remediation

1 Introduction

Geophysical methods have been steadily growing in their applications in diverse areas as attested by the research publications over the last 3 decades. The growing applications are stimulated by the development of powerful sensors as well as advancements in computing power, which has led to the development of efficient interpretation software. Till the late eighties, the geophysical tools were principally used for exploration of resources (oil, minerals, groundwater, geothermal) and the scale of application varied from hundreds of sq km (in air borne surveys) to tens of sq km (surface survey). However, late 1980s and 1990s witnessed the application of geophysical tools in engineering and environmental problems[1-4]. The growing interest of geophysics community in this area can be attested by establishment of professional societies like Environmental and Engineering Geophysical Society (EEGS) in US and its allied chapters in Europe. The growth in application of engineering and environmental applications of geophysics was primarily driven by the development of Electrical Resistivity Tomography systems and efficient 2D-3D inversion algorithms. It was also driven by stringent environmental regulations that were introduced during that time. The geophysical tools were found effective in view of their sensitivity to environmental target (such as mapping contaminated objects in the soil matrix *etc*.). This further led to significant research publications in mapping plumes from contaminated sites using geophysical tools. The significant contrast between the contaminated target and the host matrix enabled mapping the target through non-invasive tools like Resistivity, Electromagnetic (EM) and Ground Penetrating Radar (GPR)[5-7]. The environmental geophysics application ultimately paved the emergence of a new discipline, "Biogeophysics" which deals with the geophysical signature of microbial processes[8-9]. Linking the geophysical signature to microbial processes was beyond the conventional thinking of the geophysical community. Till 1990s, the geophysical signatures were linked to the factors like rock characteristics (porosity, extent of saturation, fluid property), metallic content of the soil/rock matrix, clay content in the formations. However, there was a paradigm shift towards the late 1990s, when field experiments demonstrated that microbial processes in the sub-surface can also contribute to geophysical

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signature. This led to a synergy of expertise of geophysicists, microbiologists and geochemists, which led to the development of "Biogeophysics" discipline that has seen a steady growth since 1997 when the 1st paper was published[10]. The number of articles published on geophysical signature of microbial processes are evidence of the growing interest in this emerging research area (Fig. 1) in the last two decades (since 1998). Fig. 1 illustrates the number of research publications on Biogeophysics, published in peer-reviewed journals in the domain of Earth and Environmental Sciences since 1998.

The present review attempts to analyze the efforts made so far using diverse geophysical tools, namely Resistivity, Induced Polarization (IP), Spectral Induced Polarization (SIP), which are being used to decipher the microbial signatures.

Despite the increasing popularity of the Biogeophysics discipline, to the best of our knowledge, there is no comprehensive review articles published to provide an overview of the development in the field of geophysical signatures of microbial processes since 2009, after the initial review published by 8-9. The present review explores the developments and provides an overview since 2009. We cover the basic concepts on Biogeophysics in this review that will be followed by the historical developments, wherein different studies are reviewed. The review covers the gaps and helps to identify the future directions of research.

2 Basic Concept and Historical Developments: geophysical response of microbial processes

The resistivity of rock matrix as defined by the Archie's law[11] is given by

$$\rho = a\rho_w \emptyset^{-m} S_w^{-n} \quad \dots (1)$$

Where ρ is the bulk resistivity of formation, ϕ is the porosity, ρ_w is fluid resistivity of the rock and S_w is the saturation. The values of "a, m and n" are saturation coefficient, cementation factor, and saturation exponent, respectively.

As per the equation (1), the resistivity signature is linked to different properties, viz. rock porosity, extent of fluid saturation in the pores, resistivity of the fluid (governed by the Total Dissolved Solids (TDS) of the fluid) in the pores of the rock matrix. The resistivity is also governed by the metallic content in the rock matrix.

As per the traditional approach, it is hypothesised that rock matrix contaminated by petroleum

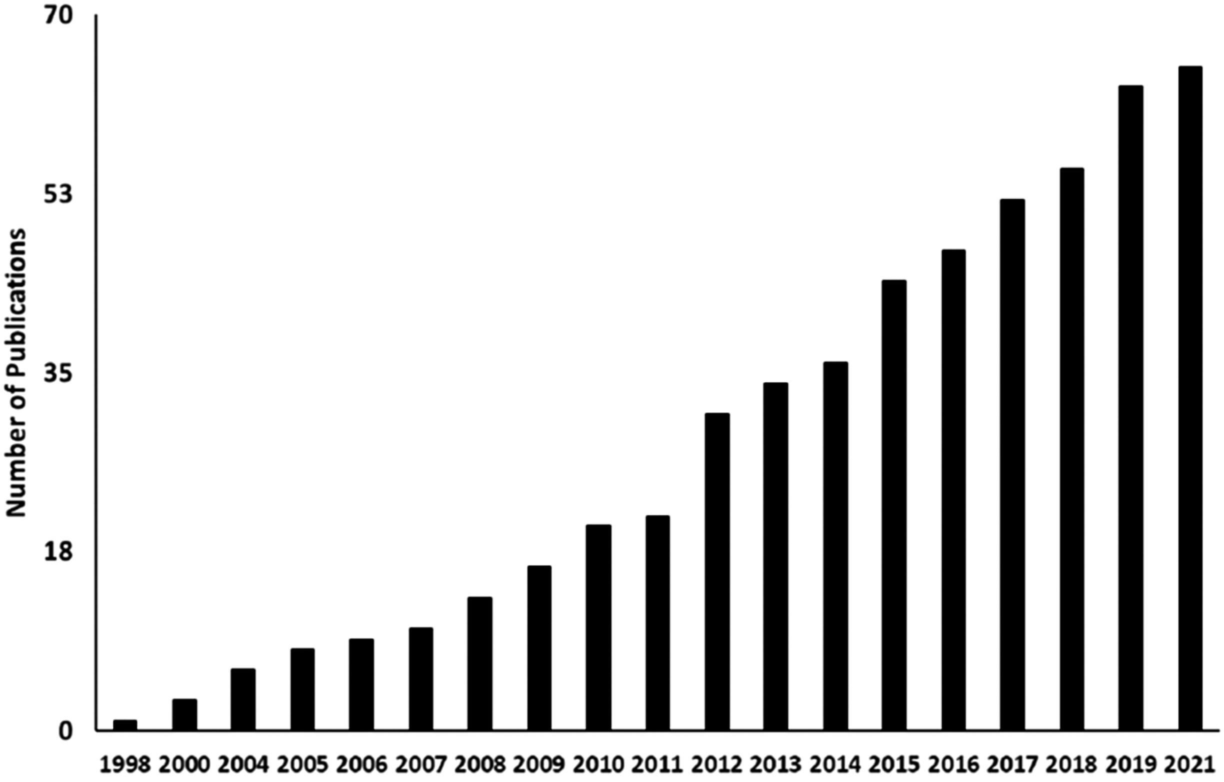

Fig. 1 — Growth in yearly publications in the field of Biogeophysics (retrieve Scopus database)

hydrocarbons will have higher resistivity, as hydrocarbon has significantly higher resistivity (10^6 ohm-m)[12]. However, the resistivity signature at the hydrocarbon contaminated site at (Carson in Michigan, USA.) provided contrasting response, where in relatively conductive response was observed as against the expected higher resistive response[10].The higher resistivity (lower bulk conductivity) of the matrix is expected in view of the insulating nature of the hydrocarbons[12]. To explain the elevated conductivity in the matrix, Sauck *et al.*[10] proposed a model wherein microbially mediated redox processes release CO_2 and Organic acids, which lead to mineral weathering and release of ions to the groundwater. As a consequence, increase in ions in groundwater leads to higher bulk conductivity of the matrix. Since the seminal work of Sauck *et al.*[10], there has been significant interest in the geophysical community to study the geophysical response of the microbial interactions with the geological media. The findings from Sauck *et al.*[10] had far reaching implications as the geophysical response from microbial processes was established for the 1st time in 1998. The subsequent works focussed on developing models to explain the geophysical response from microbial processes. Different tools, namely DC resistivity, GPR, EM and Spectral IP have been used to study the linkage between the geophysical signature and the microbial processes.

2.1 DC resistivity

The hydrocarbon, fuels, and some other organic contaminants exhibit high resistivity and low dielectric permittivity[10 & 12]. More importantly, water saturation in porous media plays a key role in the resistivity value of the matrix. If the water is replaced by more resistive fluid such as hydrocarbon, it will lead to higher bulk resistivity of the system.

Most of the researchers reported high apparent conductivity[10,13-15] and high-interpreted resistivity[16]in matrix contaminated by hydrocarbons. The increase in higher conductivity is attributed to the microbial degradation of a hydrocarbon producing carbonic and organic acid, which leads to the dissolution of minerals, and resulting in increasing TDS, and hence the conductivity. Hence, high resistivity associated hydrocarbon contamination is linked with younger oil spills whereas low resistivity (high conductivity) of the contaminated matrix is linked with older hydrocarbon contamination undergoing remediation[13, 17-19].Atekwana *et al.*[14] proposed that only TDS does not influence bulk conductivity, and surface conduction through the surface of mineral grain can occur instead of only electrolytic conduction in hydrocarbon contamination sites. It is also suggested that the transformation of physical properties in terms of elevation of TDS, production of acids is not only because of change in geoelectrical properties, but bacterial population have direct link to conductivity during remediation[20]. Allen *et al.*[21] studied the interdependence between the resistivity signatures of hydrocarbon contaminated site and the sub surface microbial communities. Measurements were made from a contaminated well and uncontaminated well and higher conductivity measurements were reported from the hydrocarbon contaminated site at Carson City in Michigan. The vertical changes in the resistivity signature were concomitant with substantial alteration in the microbial diversity structure. The high ratios of culturable hydrocarbon degrading microbes accorded with the peaks of hydrocarbon contamination and the higher conductivity. The spatial correlation in the changes in the resistivity and the changes in the microbial properties led to the suggestion that geoelectrical measurements can be a cost effective tool to guide microbiological sampling during natural or engineered bioremediation activity. It was one of the first attempts to study the composition of the microbial community distribution and its correlation with the elevated conductivity measurements. The higher electrical conductivity in the contaminated region was supported by the geochemical data of the water sample, wherein higher TDS was observed as against lower conductivity in the uncontaminated site close to it. Besides, lower pH (average pH: 6.5) was observed in the contaminated well while the pH in the uncontaminated well was higher (average pH: 7.1). The lower pH in the contaminated well can be attributed to the generation of weak acids during biodegradation.

Masy *et al.*[22] evaluated the potential of ERT to monitor enhanced biodegradation of hydrocarbons undergoing bioaugmentation at a controlled pilot site. The study was the 1st comprehensive attempt wherein the geophysical tool was attempted to decipher the changes in the aerobic hydrocarbon remediation wherein specific inoculated microorganisms were used. Besides, monitoring was also carried out for the physico-chemical parameters, and the microbial population for the soil and groundwater samples. The

ERT monitoring carried out for 126 days after inoculation indicated enhanced conductivity of the contaminated matrix during the initial phase of 50 days. However, after 50 days, the in-situ resistivity increased, and it was attributed to significant production of hydrophobic secondary metabolites. The increase in conductivity during the initial phase was attributed to the enhanced biomineralization due to the reduction in pH owing to the microbial action and the consequent release of ions from the matrix to the fluid in the matrix.

Johnson *et al.*[23] carried out ERT with the purpose of deciphering the changes in geophysical signature in a contaminated field site (trichloroethylene) subjected to biostimulation wherein a proprietary amendment, ABC® was emplaced in a field experiment of 12 months. The purpose was to decipher the geophysical response changes due to biogeochemical changes indicative of the progress of remediation. ERT, cross borehole Radar and geochemical fluid sampling from bore holes in the site were carried out for an integrated assessment. The efficacy of ERT in monitoring the transport of the amendment and subsequent biogeochemical alterations was validated. The calibration/validation exercise strongly supported the link between the bulk resistivity and the fluid conductivity. Subsequent to the post amendment emplacement, the variation in subsurface conductivity, and total organic acid changes over time can be explained by time-lapse ERT. The fluid conductivity showed high correlation to bulk conductivity ($R^2 = 0.79$) and the total organic acid ($R^2 = 0.89$).

2.2 Ground Penetrating Radar (GPR)

GPR has been found to be an effective tool in giving high resolution sub surface image (upto 30-40m)[24-25]. The depth of information from GPR measurement depends on the frequency of the antenna used and the properties (conductivity, dielectric constant) of the medium. Studies[26-27] has indicated that GPR reflections from gasoline contaminated sites shows different phases of the Light Non Aqueous Phase Liquid (LNAPL). One of the most relevant effects due to the organic contaminants into the soil is due to the microbial activity, which transforms the subsurface condition wherein changes in pore fluid conductivity, mineral precipitation take place. This results in alteration in permittivity causing attenuation of GPR signals. The depth of residual zones and unknown contamination sources can be investigated by employing GPR[28-29]. Bradford[30] reported loss of GPR reflection strength at the gasoline contaminated site. The GPR reflections essentially reproduced the results of Sauck[10] and it was observed that the zone of increased dispersion roughly coincided with the zone of increased conductivity.

Lane *et al.*[31] attempted mapping the spatio temporal variations of vegetable oil emulsion, in a contaminated site at Fridley, Minnesota in USA, where biostimulation was performed by injecting the latter. . The cross-hole radar travel time data enabled identifying the VOE distribution close to the injection wells. The attenuation of the Radar signal downgradient of the injection wells increased with time, which indicated the increase in conductivity, and consequently TDS. These changes are not only dependent on the tracers of colloidal iron or magnetite, but also the tracer-free injection at downgradient. At certain TDS and water specific conductance, the attenuation rate of GPR was consistent. This process usually includes the transformation of mineral constituents to aqueous form through oxidation-reduction reactions or biodegradation of chlorinated-solvent contaminants. Consequently, the GPR results enabled the development of several models to explain the spatial or temporal distributions of VOE and groundwater chemistry.

2.3 Self-Potential (SP)

The SP has come a long way since 1960, when the Geobattery model to explain SP mechanisms over ore bodies was generally accepted.

The detection and monitoring of microbial processes has gained lot of attention[7, 32-33]. Nyquist and Cory[34] established correlation between the depleted oxygen in the groundwater plume due to microbial action and the SP anomalies. It was observed that the negative anomalies coincided with the depleted Dissolved Oxygen (DO) in the groundwater plume at a field level experiment. The relationship between SP response and Redox potential (Eh) has been documented by Naudet *et al.*[35-36], and it was suggested that the Redox potential (Eh) can be derived from the SP response. Strong SP anomalies (upto -400 mV) were observed at the Entressen landfill site in Southern France[36], and it correlated well with the redox reactions driven microbial.

The findings of Naudet *et al.*[36] were explained by Arora *et al.* [37], wherein Geobattery model is proposed. The Geobattery model proposes a natural battery across the Water table boundary, which separates the reduced oxygen depleted zone with in the plume from the oxygen rich zone surrounding the plume. The Geobattery model suggested by Arora *et al.*[37] hypothesized presence of biomass/biofilms and metallic mineral precipitates, which serve as electron conductors. The oxidation of organic matter leads to concentration of Fe^{2+} and thereby creating a redox gradient. Arora *et al.*[37] documented the only field evidence, wherein large negative SP anomalies, were found to be microbial driven.

The effect of microbial processes on SP signal in a tank experiment (filled with water saturated quartz sand) was studied by Naudet and Revil[35]. The experiments involved 2 stages, wherein In Stage 1, the SP signal was monitored without the matrix containing the bacteria, while in the Stage 2, the monitoring was performed with the mixture containing the bacteria transferred to the tank. The difference between the measurements in the 2nd stage and that from the 1st stage was obtained. SP anomalies were observed above the treated zone containing the bacteria, which attests the impact of bacterial activity on the SP measurements. The results support the findings of Naudet *et al.*[36] wherein negative SP anomalies were observed above anaerobic contaminant plume rich in organic matter and heavy metals.

Large SP anomalies were observed in laboratory studies[38-39]. Ntarlagiannis *et al.*[38] performed column experiments, wherein Bacterial strains (cells of S. Oneidensis MR-1 and mutant strains) were used. Large SP anomalies (upto 600 mV) were recorded in column, inoculated with MR-1. However, the column inoculated with the mutant strain showed SP response, which was very less (average value was 10 mV). In similar experimental conditions, the abiotic control column did not have any SP anomalies. The SP response was attributed to electric current sources, originating from the microbial nanowires. The microbial nano wires were hypothesised as electron carriers from the microbial cells to remote electron acceptors[40]. Undergoing biodegradation of contaminated sites with hydrocarbons shows minimum SP irregularities reported by Che-Alota *et al.*[41].

It need to be noted that SP anomalies linked to the geobattery model are often masked by the electrode polarisation[39]. Revil *et al.*[42] proposed the biogeobattery model, wherein it is hypothesied that the SP signal is triggered by strong redox gradient generated due to the highly reduced contaminated plume under water-table, and an oxidized zone over the water table. The redox gradient was attributed to microbial activity[42]. It is reported that metal reducing organisms, namely Shewanella and Geobacter, produce bacterial nanowires(40&43). The latter enable the electron transfer to solid phase electron acceptors. There is less information about biofilms that transport electron over the scale of the groundwater interface. In spatially separated regions, according to Nielsen and Risgard-Petersen[44-45], the electrical coupling of biochemical processes transfers the electrons which can least cause at mm scales. Kato *et al.*[46] reported microorganisms utilizing conductive minerals such as magnetite, which can be conduits for electron transfer resulting in efficient inter species electron transfer contributing to the coupling of different biogeochemical reactions. The findings can be confirmed from contaminated sites, which are organic rich and undergoing biodegradation.

2.4 Spectral Induced Polarization (SIP)

The SIP is extension of the DC resistivity method. The frequency domain IP is also known as the Spectral IP or the Complex resistivity (CR) method. In the resistivity method, real conductivity is measured whereas the imaginary conductivity is measured in CR methods.

The spectral IP has been successfully implemented in mineral exploration[47-49]. However, its use in the monitoring of microbial processes has been appreciated as evident in the literature over the last 10-15 years[50-53]. The developments in multichannel instrumentation and computing power facilitated the growth of Spectral IP (SIP). Modern SIP instruments are now available, which combine the sensitivity of this spectroscopic method with respect to structural characterization with the spatial resolution of a geophysical field method.

In the frequency domain IP, the formation conductivity magnitude is measured at different frequencies and the percentage frequency effect gives the IP effect. From the variations in applied amplitude and phase shift, the complex conductivity is calculated[54]

$$\sigma^* = \sigma_{elect} + i\sigma^*_{surf} \qquad \text{... (2)}$$

where σ_{elect} is electrolytic conductivity of the matrix and σ^*_{surf} is surface conductivity. In the absence of metallic minerals, the conduction occurs as ionic conduction. Archie's Law can be derived as (Archie, 1942).

$$\sigma' = \frac{\sigma_w}{F} + \sigma'_{surf} \quad \ldots (3)$$

$$\sigma'' = \sigma''_{surface} \quad \ldots (4)$$

where single superscript (′) and double superscript (") represent the real part and imaginary part of the complex conductivity respectively.

The complex conductivity (In Eq 3) depends on electrolytic conductivity, interfacial conductivity, and electronic conductivity under 1 kHz. Specifically, interfacial conductivity is dependent on presence of the interfacial materials such as non-metallic mineral-fluid, metallic mineral-fluid, and microbial cell-fluid which produces low frequency polarization[55] under 1KHz. Electrical double layer (EDL) in interfacial layer can encourage randomly mixed redox active and inactive ions to diffuse linearly and transfer perpendicularly to the metal surface in the soil[56]. Ions movement especially active ions even at low concentration can effectively lessen the energy gap between electrolytic and electronic conductivity. The diffusive mechanism and electrochemical mechanism also depend on the sizes of metal particles.

It is well established fact that biodegradation alters the physical properties of subsurface as well as the composition of contaminants. In bioremediation activities, there is specific preference of removal of degrading compounds. In most cases, the microorganisms target weak bonds first and separate the compounds such as n-paraffins and acyclic isoprenoids in the case of oil degradations, Acetate, Bicarbonate ion, Iron, Hydrogen Sulfide and Methane in the case of ethanol degradation. In case of 2, 4-D herbicide, chloride are initially removed to form 4-chlorophenoxyacetate, 4-chlorophenol, and 4-chlorocatechol[57]. The degradation leaves polar compounds, acids, heavy metals, water and harmless gases in subsurface which affect SIP signatures. Laboratory studies have confirmed elevated imaginary conductivity and phase in samples collected from hydrocarbon contaminated sites against the samples collected from uncontaminated sites[58]. Davies *et al.*[60] reported the results from the laboratory columns (biostimulated and unstimulated) having silica sands. The imaginary conductivity measurements in the columns showed peak at the positions of the maximum microbial density. The Environmental Scanning Electron Microscope images also showed maximum biomass in day 23 and less in day 46, which indicated the death of the biomass due to limited nutrient/carbon source or excessive cell density. Davis *et al.*[60] investigated the effect of microbial growth on the CR measurements during stimulated microbial growth. The imaginary conductivity response is interpreted as different stages of biofilm development, with the maximum measured conductivity interpreted as maximum microbial growth while the decreasing imaginary conductivity representing microbial cell death or detachment.

Abdel Aal *et al.*[61] observed that microbial population, namely Pseudomonas aeruginosa adsorbed on the surface of mineral surfaces of clean quartz sands and iron oxide–coated sands led to increase in the imaginary conductivity as compared to real conductivity. No significant changes were observed in the real conductivity due to microbial adsorbtion. The polarization was attributed to the surface roughness and increase in the surface area due to microbial sorption. The larger surface area of the bacteria leads to the pronounced SIP effect, where in the imaginary conductivity was found significant. The imaginary conductivity, attributed to the microbial population was observed even when they were metabolically inactive.

The elevated imaginary conductivity and phase is linked to the change in pore geometry as an effect of ion selective biological membranes and bio metallic mineral precipitation during redox reaction[62-63]. Even SIP has proven its sensitivity to microbial abundance and cell surface charging properties at relatively low cell densities[53, 64-65].

Abdel Aal *et. al.*[66] attributes the major cause of alteration of SIP signature to the higher level of polar components produced during microbial process and its interface of water and mineral grains.

Orozoco *et al.*[67] found good correlation between imaginary conductivity and phase shift with Benzene, Toluene, Ethylbenzene and Xylene (BTEX) concentration. During the uranium degradation, spatiotemporal changes correlated with increases in Fe(II) and precipitation of metal sulfides[68].

3 Limitations and challenges

Geophysical thought process has dramatically changed with the growth of Biogeophysical studies in last two decades. The ability of geophysical techniques to image the subsurface structure/ process at microscale has been well established as attested by the literature in the last two decades. It is going to expand the applications of geophysical tools, in areas such as the life on other planets. Previously, geophysical tools were restricted to monitor the subsurface structure/ process at the scale of meter/ tens of meters. The advent of Biogeophysics has facilitated by giving insights on biofilms generation, redox reaction, biodegradation, and mineral precipitation. The link between microbial process and geophysical signature is well established in controlled experiments. The translation of the laboratory knowledge to the field has challenges due to heterogeneity in field conditions. There is a growing need for more field based experiments to provide informed understanding of the biological process in the subsurface and their geophysical signatures. For instance during the laboratory studies, surface charge density is less due to lesser area of the matrix. This leads to polarisation of electrodes and surrounding faces of the experimental column. Though, it is insignificant at laboratory scale, it is need to be studied extensively to strengthen this method for field scale experiments. It is necessary that electrode polarisation need to be minimized by injecting the current for sufficient duration.

It is evident that the polarization during microbial processes can be triggered by alteration in physical, chemical properties and microbes itself. If the changes are limited, the geophysical signature may not be discernible. The different geophysical methods differ in respect of resolution, uncertainty level and depth of investigation. In view of the complex nature of the microbial process, the uncertainty in the results can be minimised by combined use of different geophysical tools. Above discussed studies have shown that the geophysical tools can be used effectively to monitor changes in the contamination in the sub-surface rather than static detection of the contaminants. Time lapse data collection will remove the background heterogeneities and can be a useful proxy for the contaminant.

DC resistivity is often used in mapping the degradation of microbial processes (Fig. 2). The recent advancement in ERT such as inversion facility in 3D and 4D, optimized survey design strengthens the method and come up with the promising tool for remediation monitoring tools. At present, multiphase flow models are used for stimulating the transport of contaminants and they can be coupled to geophysical model to stimulate the geophysical response. Complex resistivity method is being used in the Biogeophysics community due its capability to relate surface-area to pore volume ratio to electrical polarization magnitude. The major drawback in using SIP in monitoring microbial process is time consuming field setup along with complex data analysis and processing compared to other geophysical methods. Besides, the inversion algorithms of other geophysical methods are straightforward and signal to noise ratio is higher as compared to SIP measurements. The capacitive coupling between the output, input and surface makes the data acquisition in SIP technique more challenging[69].The dependency of SIP signatures is higher on various factors other than microbial mediated changes such as lithology (polarized substances), subsurface flow and anthropogenic contaminants makes interpretation of SIP complex. Hence, there is a need for detailed studies by focusing on environmental parameter to minimize misjudgment in the interpretation. In addition, measurement errors have to be carefully evaluated during monitoring of the microbial process to prevent noisy data in order to prevent image artefacts. For the interpretation of SIP data, Cole-Cole resistivity model[70] is often used, the uncertainty of model is higher for weak polarization of samples and it should be avoided for weakly polarized samples[71]. SP measurements have come a long way in understanding the biogeochemical process. For interpretation of SP data, better understanding the quantification of electrokinetic coefficient as a function of the water content is highly

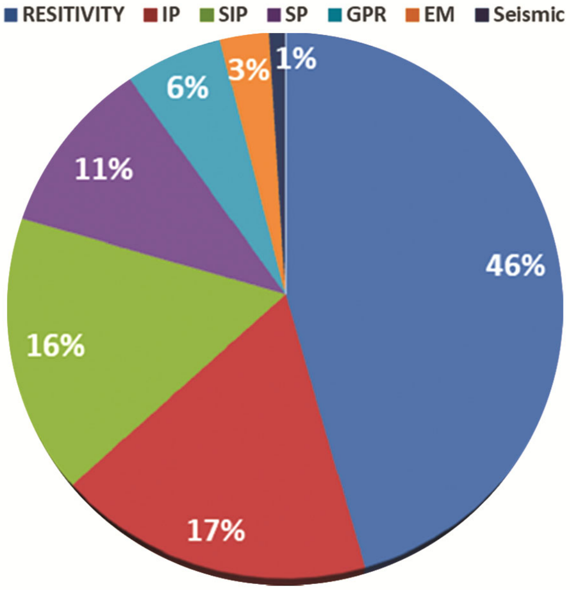

Fig. 2 — Percentage of Adapted Methods in Biogeophysics (retrieve Scopus database)

recommended[72]. The quantification of contamination and degraded products and its relationship to hydraulic properties are major challenges in SP measurements.

Environmental factors (temperature, rainfall) affect both geophysical signature and microbial activity in field conditions. Noel *et al.*[73] has addressed well the seasonal variation at hydrocarbon contaminated site. There is need for detailed studies to simulate the effect of temperature and rainfall on the geophysical response.

So far, geophysical tools are used to sense the geophysical signature of the remediation processes in respect of petroleum products. Contaminants like heavy metals, herbicides, pesticides, and chlorinated hydrocarbons contamination have not been addressed so far. The nature and behavior of these contaminants in the environment are different from petroleum products. Petroleum products are complex mixtures of hydrocarbons (aromatics, naphthenes, paraffins, and cycloparaffins) and they undergo natural attenuation processes such as chemical, photooxidation, vitalization, dissolution, and microbial degradation. However, most of the heavy petroleum hydrocarbons are accumulated in tarry masses above (Light Non-Aqueous Phase Liquid) and below (Dense Non-Aqueous Phase Liquid) groundwater. In the case of pesticides, its direct application leads to accumulation of pesticides in the soil for longer time (because if its persistent nature) further some of it migrates through rainwater runoff, contaminates groundwater and irrigation water and most importantly nearby surface water bodies vulnerable to contamination. Besides, the rate of pesticide degradation is significantly less[74]. As herbicides and pesticides are the serious concerns to environments, future attempts should be focused in this direction.

4 Conclusions

Present review attempts to critically explore and endorse the potential of different geophysical tools to sense the biological processes in the subsurface. After Atekwana *et al.*[8], major field implementing studies were carried out and it is discussed in the paper along with its limitations. The efficacy of geophysical tools in monitoring the changes of geophysical response from biological processes has been well established. Considerable success has been achieved in controlled lab experiments and limited field experiments. The developments in last two decades amply demonstrate the potential of geophysical tools in monitoring microbial process and its application in performance monitoring of remediation activities. This will go a long way establishing the geophysical tool as a substitute for invasive methods which are routinely used in the performance of remediation activities.

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