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Spectroscopic characterization of red latosols contaminated by petroleum-hydrocarbon and empirical model to estimate pollutant content and type

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ABSTRACT

This work assesses the applicability of reflectance spectroscopy to monitor petroleum hydrocarbon (PHC) leaks in petroleum facilities using the direct detection of the pollutant in bare soils. A controlled, lab-scale experiment is conducted, where red latosols are contaminated with several types of hydrocarbons (crude oils and derivatives) and in different concentrations, in order to simulate leaks. Results portray key spectroscopic characteristics of contaminated soils, spectral temporal variation patterns, and spectral detection limits considering visible–near infrared and short wave infrared wavelengths. Regression analysis models allow quantifying the pollution level and estimating the hydrocarbon type. This seamless method has a great potential to be used in environmental monitoring of bare soil along refineries and pipelines.

1. Introduction

Petroleum and refined petroleum products are significant pollutants of soils because storage tanks and pipelines can present leaks. Transport and transfer pipelines are critical points throughout the logistic processes. Leaks can be caused by several factors, such as pipeline aging and accidents. An accident interrupts the process producing damage, huge operational disruptions and environmental pollution. It may expose the population to risk of disease (Aislabie, Balks, Foght, & Waterhouse, 2004; Boffetta, Jourenkova, & Gustavsson, 1997; Freijer, de Jonge, Bouten, & Verstraten, 1996; Hutcheson, Pedersen, Anastas, Fitzgerald, & Silverman, 1996; Park & Park, 2011; Perez-Cadahia et al., 2007; Ziolli, 2009), fires and explosions. These risks are heightened in the view that pipelines run through vast distances, in areas where they are subject to physical and chemical changes, anthropic activities, and environmental influence such as temperature variations and soil dynamics. In this context, the early detection of petroleum hydrocarbon (PHC) leaks is imperative to minimize damage to the environment and human health and to improve remediation.

Conventional methods for monitoring PHC leaks are able to detect large spills, but small, progressive losses (below 1% of pipeline flow capacity) are difficult to be revealed in advance. Small losses are usually perceived by visual inspection — an unsuitable practice, considering the problems involved in accessing kilometers of pipeline and spotting a leak, which can be easily confused with wet soil and vice-versa.

PHC leaks affect soil and vegetation placed in their vicinity. Soils can be affected by bleaching (i.e., discoloration of red soils); neomineralization (e.g. clay, carbonate, sulphide); plus electrochemical, radiometric and microbiological changes (Oliveira, 1998; Schumacher, 1996, 1999; Souza Filho, Augusto, Oliveira, & Lammoglia, 2008; Thompson, Saunders, & Burson, 1994). Vegetation may suffer variations caused by an increase in the content of PHC-eating bacteria in the soil, which will reduce the available oxygen and increase the amount of organic acids and CO_2. Such changes may interrupt root breathing and, eventually, trigger the death of vegetation, interfering in its natural development. This forms geobotanical anomalies that can also be marked as vegetation blight, color variation due to the loss of photosynthetic pigments (chlorosis), falling of leaves, and lower density of plants (Li, Ustin, & Lay, 2005; Noomen, Skidmore, van der Meer, & Prins, 2006; Noomen et al., 2008; Sanches et al., 2013a, b; Smith, Steven, & Colls, 2004; White, Williams, & Barr, 2008).

Reflectance spectroscopy and remote sensing are promising tools for effectively detecting and monitoring PHC leaks, given their capability to detect the presence of PHCs exposed at surface and to map mineralogical and physiological changes in soil and vegetation submitted to PHC pollution. Reflectance spectroscopy (RS) is a method that has been used for decades to identify and quantify solid, liquid and gaseous

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materials (Clark, 1999). This is a non-destructive method that allows rapid and cost-effective measurements without any sample preparation. Imaging spectroscopy (IS), or hyperspectral remote sensing, is a technique that allows the analysis of large areas, without access restriction. Furthermore, it is possible to use sensor systems with spatial and spectral resolutions, and coverage over specific windows of the electromagnetic spectrum for each particular study. RS and IS in the VNIR–SWIR range (Visible Near Infrared–Short Wave Infrared: 0.35–2.5 μm) allow extracting several direct and indirect soil properties (Ben Dor, Ong, & Lau, 2015; Ben-Dor et al., 2008, 2009; Nanni & Dematte, 2006; Rossel & Behrens, 2010), as well as soil contamination characteristics (Chakraborty et al., 2010, 2012; Lubard, Krimmel, Thebaud, Evans, & Shemdin, 1980; Schwartz, Ben-Dor, & Esher, 2013). Cloutis (1989) demonstrated that PHCs are characterized by two main absorption bands centered at 1.730 μm and 2.310 μm. These spectral features have been used by several authors to directly detect soils contaminated with PHCs (Chakraborty et al., 2014; Hörig, Kühn, Oschütz, & Lehmann, 2001; Okparanma & Mouazen, 2013b).

RS and IS data and techniques have been used extensively in petroleum exploration (Chung, Choi, & Ku, 1999; Ellis, Davis, & Zamudio, 2001; Hörig et al., 2001; Kühn, Oppermann, & Hörig, 2004; Lammoglia & Souza Filho, 2011; Li et al., 2010; Lyder, Feng, Rivard, Gallie, & Cloutis, 2010; Noomen et al., 2008; Rivard et al., 2010; Smith et al., 2004; Souza Filho et al., 2008; Van Der Meer, Van Dijk, Van Der Werff, & Yang, 2002; Xu, Ni, Jiang, Jiang, & Chi, 2007) and environmental monitoring (Ayotamuno, Okparanma, Nweneka, Ogaji, & Probert, 2007; Kokaly et al., 2013; Lammoglia & Souza Filho, 2015; Noomen, Hakkarainen, van der Meijde, & van der Werff, 2015; Okparanma, Ayotamuno, Davis, & Allagoa, 2011; Okparanma & Mouazen, 2013a; Salem, Kafatos, El-Ghazawi, Gomez, & Yang, 2005; Van der Meer, Van der Meijde, Kooistra, Van der Werff, & Noomen, 2006; Van der Meijde et al., 2013; Winkelmann, 2005). However, specific studies to identify leaks and spills are rare in the literature. Most of the research is concentrated in countries with temperate climate and with focus on gaseous PHCs, light crude oil and its derivatives such as octane fuel, diesel and kerosene (Forrester et al., 2013; Schwartz et al., 2013). Soil characteristics and composition in these countries contrast evidently with those found in tropical and sub-tropical terrains, resulting in different spectral signatures for detection of PHCs and mixtures. Besides, it is important to consider the types of PCHs and derivatives that are transported along pipelines and refined in the oil facilities. Such parameters are typical for each oil facility and may differ among regions and countries.

In South America, work related to spectral sensing of PHCs is mostly focused on petroleum exploration, where tonal changes in soils and geobotanical anomalies have been used to pin down potential subsurface gas reservoirs. Research on detection of liquid PHC leaks considering soil, vegetation and temperature typically found in tropical regions is limited in the continent. Modern studies include only the development of macro and micro experiments, where different species of vegetation were grown in soils contaminated by PHCs (gasoline and diesel), aiming to identify spectral and morphological changes generated in vegetation and related to the presence of pollutants (Sanches et al., 2013a,b). Therefore, it is clear the need to advance knowledge in this field, considering the diversity and uniqueness of tropical plant species and soils. Moreover, it is critical to demonstrate whether a potential PHC leak detection method can be used in an operation fashion to monitor bare soils along pipelines and refineries.

In this context, this study provides information about early detection of PHC leakages in bare soils using direct spectral responses of PHC pollutants in the VNIR-SWIR range. The work comprises a laboratory-scale, controlled experiment where red latosol (typically found in tropical environments) is contaminated with several PHCs, and in different proportions, looking to understand how soil spectral signatures change due to the presence of PHC. Moreover, the study specifies optimal

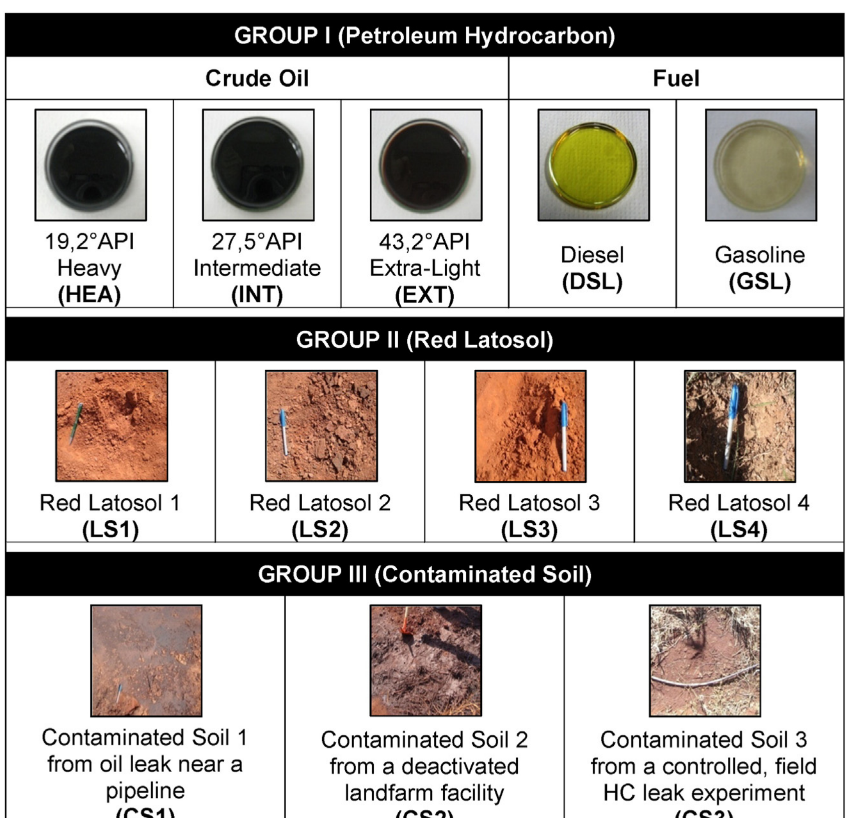

Fig. 1. Hydrocarbon and soil sample sets used in the experiment.