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Review

Plant–bacteria partnerships for the remediation of hydrocarbon contaminated soils

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HIGHLIGHTS

- ▶ Plant–bacteria partnerships is an emerging pollutant remediation approach.
- ▶ Plant associated rhizo- and endophytic bacteria can enhance pollutant degradation.
- ▶ Plant stimulates the bacteria to degrade organic contaminants in the soil.
- ▶ Plant associated-bacteria can reduce phytotoxicity and evapotranspiration of hydrocarbons.

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ABSTRACT

Plant–bacteria partnerships have been extensively studied and applied to improve crop yield. In addition to their application in agriculture, a promising field to exploit plant–bacteria partnerships is the remediation of soil and water polluted with hydrocarbons. Application of effective plant–bacteria partnerships for the remediation of hydrocarbons depend mainly on the presence and metabolic activities of plant associated rhizo- and endophytic bacteria possessing specific genes required for the degradation of hydrocarbon pollutants. Plants and their associated bacteria interact with each other whereby plant supplies the bacteria with a special carbon source that stimulates the bacteria to degrade organic contaminants in the soil. In return, plant associated-bacteria can support their host plant to overcome contaminated-induced stress responses, and improve plant growth and development. In addition, plants further get benefits from their associated-bacteria possessing hydrocarbon-degradation potential, leading to enhanced hydrocarbon mineralization and lowering of both phytotoxicity and evapotranspiration of volatile hydrocarbons. A better understanding of plant–bacteria partnerships could be exploited to enhance the remediation of hydrocarbon contaminated soils in conjunction with sustainable production of non-food crops for biomass and biofuel production.

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1. Introduction

Although petroleum is one of the main components of our modern industrial society, during the processes of extraction, refining, transport and use, an increasing number of sites is seriously contaminated by hydrocarbons (HCs) world-wide (Banks et al., 2003; Truu et al., 2007; Nam et al., 2008; Rojo, 2009). Presence of HC pollutants in the environment not only adversely affect human health but also plant growth and development (Joner et al., 2004; Meudec et al., 2007; Euliss et al., 2008; Peng et al., 2009; Nie et al., 2011; Rojo-Nieto and Perales-Vargas-Machuca, 2012). Furthermore, these strongly influence soil chemical properties, and soil microorganisms' population and activities (MacNaughton et al., 1999; Lapinskienė et al., 2006; Kisic et al., 2009; Barrutia et al., 2011; Guo et al., 2012; Leme et al., 2012). The toxicity of low molecular weight HCs is considered to inhibit plant growth and development. Furthermore, hydrophobic properties of HCs reduce the ability of plants and microorganisms to absorb water and nutrients from the soil (Kirk et al., 2005; Kechavarzi et al., 2007; Nie et al., 2011). Therefore, the remediation of HC contaminated soils is one of the hot topics in the field of environmental sciences and engineering (Ciric et al., 2009; Gan et al., 2009; Gurska et al., 2009; Kathi and Khan, 2011; Nie et al., 2011; Basumatary et al., 2012).

At present, remediation treatments available for HC polluted soils are usually expensive and environmentally invasive (Pandey et al., 2009; Weyens et al., 2009a, 2010b). As a complement to traditional remediation treatments, currently emerging phytoremediation technology might provide a more cost-effective and environmentally friendly HC remediation approach. Phytoremediation involves the use of plants to extract, sequester, and/or detoxify hazardous organic and inorganic contaminants from soil, water and air (Salt et al., 1995; Meagher, 2000; Pilon-Smits, 2005; Sandhu et al., 2007; Ali et al., 2012; Kabra et al., 2012). As plants use sunlight, water and carbon dioxide for their growth and development, the *in situ* application of this technology requires low inputs and maintenance. Furthermore, it causes minimum site disturbance, therefore it is highly acceptable in community (Weyens et al., 2010b, 2010c; Nesterenko-Malkovskaya et al., 2012). However, there are some disadvantages/limitations of phytoremediation, i.e. it is a long time process, not as efficient in the presence of high concentration of pollutants. The zone of effectiveness of phytoremediation is generally dictated by the depth of root growth, only the plant with extensive root system can be applied. Moreover, contaminants which are highly sorbed to soil particles may not be treatable due to limited bioaccessibility or bioavailability. More importantly, the effectiveness of phytoremediation varies with environmental conditions, including soil physicochemical properties and seasonal temperature fluctuations (Segura et al., 2009).

Although there have been some reports whereby plants alone were used successfully for bioremediation of HC from contaminated soils (Liste and Alexander, 2000; Newman and Reynolds, 2004; Euliss et al., 2008; Gerhardt et al., 2009; Peng et al., 2009; Zhang et al., 2012), the use of plants in conjunction with HC-degrading and/or plant growth-promoting bacteria (PGPB) offers much more potential for the remediation of HC contaminated soils (McGuinness and Dowling, 2009; Afzal et al., 2011; Teng et al., 2011; Yousaf et al., 2011). Bacteria possessing HC-degradation pathways and metabolic activities improve plant tolerance to HC pollutants by degrading these organic compounds (Escalante-Espinosa et al., 2005; Alarcón et al., 2008; Robert et al., 2008). Additionally, PGPB mitigate plant stress responses, and enhance plant growth and development (Weyens et al., 2009c, 2009d; Golubev et al., 2011; Afzal et al., 2012). Beside the fact that bacterial application to plants vegetated in contaminated soil enhances biomass production, for the purposes of its use in different industries, the exploration of plant–bacteria associations for the reclamation of polluted environments is an emerging field (Weyens et al., 2010a, 2010b, 2010c). Due to high potential of plant–bacteria partnerships to remediate contaminated soil and water, the use of this technology to remediate different environmental pollutants has been increasingly investigated (Germaine et al., 2006, 2009; Weyens et al., 2009c, 2010b, 2010c; Glick, 2010; Yousaf et al., 2010b; Afzal et al., 2011, 2012).

Plant-associated bacteria, such as rhizobacteria (RB) and endophytic bacteria (EB), have been shown to contribute to biodegradation of toxic organic compounds in polluted soil and could have potential for improving phytoremediation (Siciliano et al., 2001; Germaine et al., 2006, 2009; McGuinness and Dowling, 2009; Weyens et al., 2009c, 2009d; Yousaf et al., 2010a; Afzal et al., 2012). RB colonize the root environment, where they can involve in the degradation of organic contaminants including HCs (Alkorta and Garbisu, 2001; Glick, 2003; Abhilash et al., 2011; Afzal et al., 2011). RB which exert a beneficial effect on the plant being colonized are termed 'plant growth promoting rhizobacteria' (PGPR). PGPR may benefit the host by causing plant growth promotion or biological disease control. EB colonize in the internal tissues of the plant and generally do not confer pathogenic effects to their host (Compant et al., 2010). HC-degrading EB can produce various enzymes to degrade HCs and reduce both the phytotoxicity and evapotranspiration of volatile HCs (Germaine et al., 2009; Weyens et al., 2009d; Yousaf et al., 2011; Li et al., 2012). Recently, HC-degrading bacteria (up to 9×10^7 cells g^{-1}) were isolated from the surfaces of leaves of two legumes, peas and beans (Ali et al., 2012). It was recommended that phytoremediation through phyllosphere technology could be useful in remediating atmospheric HC pollutants.

Although plant–bacteria partnerships have been extensively investigated; most of the studies aimed to explore either plant–pathogen interactions or nitrogen fixation. From the last decade, the ecology of bacteria in the rhizosphere and endosphere of different plants was focused to improve the phytoremediation of soil contaminated with different organic pollutants including HCs (Siciliano et al., 2001; Yousaf et al., 2010a). More recently, many reports pointed out that successful colonization of inoculated RB and/or EB in different compartments of plant is an important factor to enhance the efficiency of phytoremediation (Nie et al., 2011; Yousaf et al., 2011; Afzal et al., 2012; Wang et al., 2012a). In this paper, we review the current knowledge about the plant–bacteria partnerships that can be applied for the remediation of HCs from the polluted environment. Furthermore, colonization and metabolic activities of plant growth-promoting and HC-degrading RB and EB regarding phytoremediation of HCs will be addressed.

2. HC remediation by plants

It is a general concept that plants are basic source of fiber, fuel and food. However, their possible roles to remove contaminants from the soil and water have been recognized in the last two decades. The particular tendency to tolerate, immobilize, accumulate, degrade and remove large amount of organic pollutants from the soil and water has opened up the possibility to use plants for the remediation of HCs polluted environment (van der Lelie et al., 2001; Garbisu et al., 2002; Peña-Castro et al., 2006; Ying et al., 2011). Plants can absorb minute quantity of HCs from the soil and translocate them into their different parts (McCrady et al., 1987; Sheng et al., 2008a). HCs uptake and accumulation in the root and shoot of plants vegetated in contaminated soil are associated with contaminant concentration in the soil (Brooks et al., 1998; Wild et al., 2005; Parrish et al., 2006; Lu et al., 2010b). Once