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Review

Efficient phytoremediation of organic contaminants in soils using plant–endophyte partnerships

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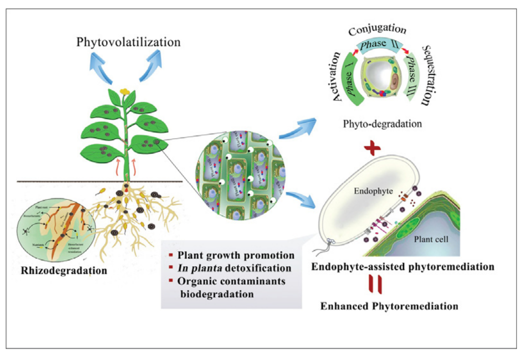
HIGHLIGHTS

- Endophytes are valuable bio-resources for enhancing phytoremediation efficiency.
- The superiority of endophyte-assisted phytoremediation is assessed.
- Mechanisms adopted by plant and endophyte for xenobiotic removal are summarized.
- Cometabolism of plant and endophyte serves a main route for xenobiotic degradation.
- "Omcs" techniques open up new perspectives for plant-endophyte interactions.

GRAPHICAL ABSTRACT



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ABSTRACT

Soil pollution with organic contaminants is one of the most intractable environmental problems today, posing serious threats to humans and the environment. Innovative strategies for remediating organic-contaminated soils are critically needed. Phytoremediation, based on the synergistic actions of plants and their associated microorganisms, has been recognized as a powerful *in situ* approach to soil remediation. Suitable combinations of plants and their associated endophytes can improve plant growth and enhance the biodegradation of organic contaminants in the rhizosphere and/or endosphere, dramatically expediting the removal of organic pollutants from soils. However, for phytoremediation to become a more widely accepted and predictable alternative, a thorough understanding of plant–endophyte interactions is needed. Many studies have recently been conducted on the mechanisms of endophyte-assisted phytoremediation of organic contaminants in soils. In this review, we highlight the superiority of organic pollutant-degrading endophytes for practical applications in phytoremediation, summarize alternative strategies for improving phytoremediation, discuss the fundamental mechanisms of endophyte-assisted phytoremediation, and present updated information regarding the advances, challenges, and new directions in the field of endophyte-assisted phytoremediation technology.

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Contents

1. Introduction

Industrialization, urbanization, and changing agricultural practices have greatly increased the release of anthropogenic hazardous organic contaminants into soils (Table 1), posing a serious threat to the global environment and human health (Kang, 2014). Novel cost-effective and sustainable remediation strategies for removing or detoxifying organic contaminants in soils are urgently needed. Phytoremediation, using plants and their associated microorganisms to eliminate soil contaminants, is a cost-effective, reliable, and promising technology (Arslan et al., 2015; Fester et al., 2014), particularly when the harvested plant biomass can be utilized for bioenergy production (Pandey et al., 2016).

Plants are inhabited by diverse microbial communities, ranging from the rhizosphere and phyllosphere to the endosphere (Compant et al., 2010). These microorganisms maintain contact with their host plants and play vital roles in plant development, growth, and fitness, as well as decontaminating polluted soils. Endophytes engage in these intimate interactions with their host plants without inflicting infections or other negative effects, resulting in mutualistic relationships in most cases (Hardoim et al., 2015). Endophytic microorganisms harbor a plethora

Table 1
Common anthropogenic hazardous organic contaminants detected in soils.

Types	Concentrations	Research areas	Sources of samples	References
Persistent organic pollutants (POPs)				
Petroleum hydrocarbons	400–40,000 μg g^{-1}	Dongying, China	Oilfield	Shi et al., 2015
Polycyclic aromatic hydrocarbons (PAHs)	892–3514 ng g^{-1}	Gdańsk, Poland.	Municipal solid waste landfill	Melnyk et al., 2015
	14.78–2084 ng g^{-1}	Kumasi, Ghana	Communities in metropolis	Bortey-Sam et al., 2014
Polychlorinated biphenyls (PCBs)	11.26–21.89 ng g^{-1}	Oued Souhil, Tunisia	Waste water irrigated soil	Haddaoui et al., 2016
Tetrabromobisphenol A (TBBPA)	ND - 2900 ng g^{-1}	Bui Dau, Vietnam	Electronic (e)-waste recycling workshop	Matsukami et al., 2015
Polybrominated diphenyl ethers (PBDEs)	0.004–4.78 ng g^{-1}	South Korea	Industrial, urban and agricultural soils	Kim et al., 2014
		13.9–13,251.2 ng g^{-1}	Qingyuan, China	E-waste recycling area
Wang et al., 2014				
Polychlorinated dibenzo-p-dioxins/dibenzofurans (PCDD/Fs)	11.5–59.6 pg g^{-1}	Riyadh, Dammam, Saudi Arabia	Industrial area	Al-Wabel et al., 2016
Endosulfans	0.058–8.42 ng g^{-1}	South Korea	Industrial, urban and agricultural soils	Kim et al., 2014
Organochlorine pesticides (OCP)	12.49–310.54 ng g^{-1}	Oued Souhil,Tunisia	Waste water irrigated soil	Haddaoui et al., 2016
	3.22–24.56 ng g^{-1}	Taurus Mountains,Turkey	Forest soil	Turgut et al., 2012
Perfluorinated compounds	5.5-483 ng g^{-1}	Chicago, USA	Biosolid-amended soils	Sepulvado et al., 2011
Endocrine disrupting chemicals (EDCs)				
Phthalic acid esters (PAEs)	0.2–4820 ng g^{-1}	Novi Sad, Serbia	Recreational, residential and industrial area, schools	Škrbić et al., 2016
Bisphenol A (BPA)	12.89–167.9 ng g^{-1}	Hartwood, Lanarkshire, UK.	Sewage sludge amendment	Zhang et al., 2015
Nonylphenol	ND-7.22 ng g^{-1}	Pearl River Delta, Southern China	Vegetable farms	Cai et al., 2012
Nonylphenol monoethoxylate	ND-8.24 ng g^{-1}			
Pharmaceuticals andpersonal care products (PPCPs)				
Acetaminophen	ND-1.8 ng g^{-1}	Valencia, Eastern Spain	Soils irrigated with contaminated waters	Vazquez-Roig et al., 2012
Carbamazepine	ND-1.5 ng g^{-1}			
Tetracycline antibiotics	0.04–184.8 ng g^{-1}	Guangzhou, South China	Organic vegetables farms	Xiang et al., 2016
Clotrimazole	6.5–8.3 ng g^{-1}	Zhejiang, Hunan, Shandong province, China	Biosolid-amended soils	Chen et al., 2013a
Micronazole	7.4–12.5 ng g^{-1}			
Triclocarban	1.20–65.10 ng g^{-1}	Michigan, USA	Municipal biosolid-amended soils	Cha and Cupples, 2009
Tonalide	24.4–67.5 ng g^{-1}	Hunan, Zhejiang province, China	Biosolid-amended soils	Chen et al., 2014

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