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Review

Bioaugmentation as a strategy for the remediation of pesticide-polluted soil: A review

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HIGHLIGHTS

- Concept of bioaugmentation of pesticide-polluted soils is presented.
- The degradative potential of pesticide-degrading microorganisms is characterised.
- Case studies on bioaugmentation of soils contaminated with different pesticides are described.
- Factors affecting bioaugmentation of pesticide-polluted soils are discussed.

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ABSTRACT

Bioaugmentation, a green technology, is defined as the improvement of the degradative capacity of contaminated areas by introducing specific microorganisms, has emerged as the most advantageous method for cleaning-up soil contaminated with pesticides. The present review discusses the selection of pesticide-utilising microorganisms from various sources, their potential for the degradation of pesticides from different chemical classes in liquid media as well as soil-related case studies in a laboratory, a greenhouse and field conditions. The paper is focused on the microbial degradation of the most common pesticides that have been used for many years such as organochlorinated and organophosphorus pesticides, triazines, pyrethroids, carbamate, chloroacetamide, benzimidazole and derivatives of phenoxyacetic acid. Special attention is paid to bacterial strains from the genera *Alcaligenes*, *Arthrobacter*, *Bacillus*, *Brucella*, *Burkholderia*, *Catellibacterium*, *Pichia*, *Pseudomonas*, *Rhodococcus*, *Serratia*, *Sphingomonas*, *Stenotrophomonas*, *Streptomyces* and *Verticillum*, which have potential applications in the bioremediation of pesticide-contaminated soils using bioaugmentation technology. Since many factors strongly influence the success of bioaugmentation, selected abiotic and biotic factors such as pH, temperature, type of soil, pesticide concentration, content of water and organic matter, additional carbon and nitrogen sources, inoculum size, interactions between the introduced strains and autochthonous microorganisms as well as the survival of inoculants were presented.

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1. Introduction

Pesticides are important components of many agricultural management systems because they allow pests, diseases and weeds to be prevented or controlled, yield losses to be reduced or eliminated and high product quality to be maintained. The application of integrated approaches including the use of pesticides with other technologies such as newly developed crop varieties, application formulations and farm equipment have resulted in the greatest capacity to produce food in human history. However, the continuous and widespread use of agrochemicals raised the question of their potential effects on public health and the environment (Damalas and Eleftherohorinos, 2011).

Pesticides undergo many different pathways once they enter the environment, including transformation/degradation, sorption-desorption, volatilisation, uptake by plants, runoff into surface waters and transport into groundwater (Chowdhury et al., 2008). Transformation or degradation is one of the key processes that governs the environmental fate and transport of a pesticide, which also comprises different processes including abiotic degradation (*e.g.* oxidation, hydrolysis and photolysis) and biodegradation. During these processes, a pesticide is transformed into a degradation product or is completely mineralised to a carbon field (Karpouzas and Walker, 2000a; Singh et al., 2006). Although abiotic degradation plays a role in many cases, the biodegradation of pesticides by microorganisms is usually the most important and dominant process (Chen et al., 2012; Cycoń et al., 2014; Karpouzas and Walker, 2000a; Silva et al., 2015). However, the structure of a pesticide molecule determines its physico-chemical properties and inherent biodegradation. Some pesticides are insoluble in water and sorb tightly to soil particles. Thus, these pesticides are relatively unavailable for biodegradation and their residues can remain in the soil for a long time, thereby adversely affecting the ecosystem (Chowdhury et al., 2008; Purnomo et al., 2011; Wang et al., 2013). The results of many studies have shown that pesticides can have many harmful effects on soil biology, which involve quantitative and qualitative changes in the soil microflora, changes in the activity of enzymes, alterations in the nitrogen balance of the soil (inhibition of N_2 fixing and nitrifying microorganisms as well as interference with ammonification) and adverse effects on mycorrhizal symbiosis and nodulation in legumes. The indirect and direct impact of pesticides on the microbiological aspects of soil then affect plant growth and soil fertility (Chowdhury et al., 2008; Cycoń and Piotrowska-Seget, 2007; Das et al., 2016).

The increasing awareness of the risks to humans related to pesticides has forced us to limit their application, to design new more environmental friendly agricultural chemicals and to develop effective strategies including biological technologies to clean-up soil contaminated with persistent pesticides. Among the biological approaches, which include attenuation, biostimulation and bioaugmentation, the last one seems to be the most promising for the removal of pesticides and their residues from soil (Fig. 1).

The aim of this review is to present the results of recent experimental studies on (1) the potential of selected microorganisms for pesticide degradation in liquid media, (2) the bioaugmentation of pesticide-contaminated soils with appropriate bacterial and fungal strains, their consortia as well as genetically engineered microorganisms (GEMs) to enhance the degradation of various pesticides that belong to different chemical groups and (3) the biotic and abiotic factors that determine the final results of bioaugmentation.

2. The concept of bioaugmentation

Bioaugmentation belongs to the green technologies that are used to remove organic contaminants from environments. It is the compelling method of engineered bioremediation, based on the inoculation of given environments (*e.g.* soil, activated sludge, sediments, water, *etc.*) with microorganisms characterised with desired catalytic capabilities. Bioaugmentation is mainly recommended for sites where the number of autochthonous microorganisms that enable contaminants to be degraded is insufficient and/or those in which native populations do not have the catabolic pathways necessary to metabolise pollutants (Forsyth et al., 1995; Gentry et al., 2004; Mrozik and Piotrowska-Seget, 2010). Bioaugmentation relies on the enhancement of the catabolic potential of soil microbial communities for the degradation of pollutants. This goal may be achieved by soil inoculation with selected single strains of bacteria and/or fungi or their consortia with desired catabolic capabilities. Moreover, genetically engineered microorganisms (GEMs), which exhibit an enhanced ability to degrade a wide range of toxic pollutants, also have the potential for bioaugmentation (Fig. 1). The selection of the appropriate strains for bioaugmentation should take into consideration the following features of microorganisms: a high potential for contaminant degradation, fast growth, ease of cultivation, the ability to withstand high concentrations of pollutants and to survive in a wide range of environmental conditions (Mrozik and Piotrowska-Seget, 2010; Singer et al., 2005; Thompson et al., 2005) (Fig. 2).

Three approaches can be distinguished depending on the origin of the inoculants: autochthonous, allochthonous and gene bioaugmentation (Fig. 1). In the first method, microorganisms are isolated from the contaminated environments (mainly using an enriched culture) and re-injected onto the same site. For allochthonous bioaugmentation, microorganisms are recruited from another site after which they are introduced on to the polluted site (Semrany et al., 2012). Gene bioaugmentation involves the use of GEMs equipped with genes encoding the enzymes responsible for some desired functions as well as the introduction of catabolic vectors directly into the environment (Gao et al., 2015; Pieper and Reineke, 2000; Zhang et al., 2012) (Fig. 1). Genes for the degradation of pesticides are frequently found on broad-host-range plasmids such as pV2 for dichlorvos (Tang et al., 2009), pVAG33 for γ-HCH (Zhang et al., 2010), pADP1 for atrazine (Devers et al., 2007), pJP4 for 2,4-D (Innoue et al., 2012) and pDOC for chlorpyrifos (Zhang et al., 2012).