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Bioremediation of pesticide-contaminated water resources: the challenge of low concentrations

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The use of pesticides in agricultural and urban environments has improved quality of life around the world. However, the resulting accumulation of pesticide residues in fresh water resources has negative effects on aquatic ecosystem and human health. Bioremediation has been proposed as an environmentally sound alternative for the remediation of pesticide-contaminated water resources, though full-scale implementation has thus far been limited. One major challenge that has impeded progress is the occurrence of pesticides at low concentrations. Recent research has improved our fundamental understanding of pesticide biodegradation processes occurring at low concentrations under a variety of environmental scenarios and is expected to contribute to the development of applied bioremediation strategies for pesticide-contaminated water resources.

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Introduction

Approximately 2.4 million metric tons of pesticide active ingredients are applied annually worldwide to control the occurrence of weeds, insects, fungi, and other unwanted organisms in agricultural and urban environments [1]. Decades of monitoring studies have documented the occurrence of pesticide residues at trace concentrations (on the order of μg/L and lower) in water resources around the world (e.g. [2•]). One potential pathway of human exposure to pesticides is through drinking water. Even at trace concentrations, pesticides may exceed regulated drinking water concentration thresholds [3] and remediation may be required to protect public health (see Box 1 for summary of key legislation and guidelines for pesticide occurrence in drinking water). Traditional drinking water treatment processes do not effectively remove pesticides from water [3]. Advanced water treatment processes such as activated carbon target pesticides for removal, but are expensive to operate and are not suitable or feasible for all situations [3]. Therefore, alternative strategies are needed to effectively remove pesticides from drinking water resources and limit human exposure.

Engineered bioremediation processes have a long history of application for environmental restoration, however there are unique challenges to consider when designing bioremediation strategies for pesticide-contaminated water resources. Traditional bioremediation processes typically target specific chemical contaminants that are confined in the subsurface at high concentrations. In contrast, bioremediation of pesticide-contaminated water resources must target soluble pesticide residues that are transported in the aqueous phase at low concentrations. Further, pesticides occur in water resources along with other carbon substrates that are present at similar or greater concentrations; pesticide degraders must compete with indigenous microbial communities for these carbon substrates while maintaining biodegradation activity towards pesticides. In this review, the recent literature on pesticide biodegradation and bioremediation is explored while focusing on these unique challenges. First, the kinetic and physiological factors that determine the extent of pesticide biodegradation under a variety of environmental scenarios are considered. Then, the general strategies that have been proposed for the bioremediation of pesticide-contaminated water resources are introduced. Finally, the main challenges limiting the application of specific techniques are discussed.

Factors that determine the extent of pesticide biodegradation

Biodegradation is regarded as the most important means for natural attenuation of pesticides in the environment [9]. However, pesticide biodegradation will only occur under favorable environmental conditions [10]. One critical factor that determines the extent of pesticide biodegradation is the interaction between the pesticide degrader and the indigenous microbial community along with the consequent competition for other assimilable organic carbon (AOC) substrates. These interactions are presented schematically in Figure 1. There are two limiting scenarios that can reduce the complexity of these interactions. The first scenario is delineated on the left side of Figure 1 and is characterized by relatively high growth

Box 1 Summary of key legislation and guidelines for pesticide occurrence in drinking water

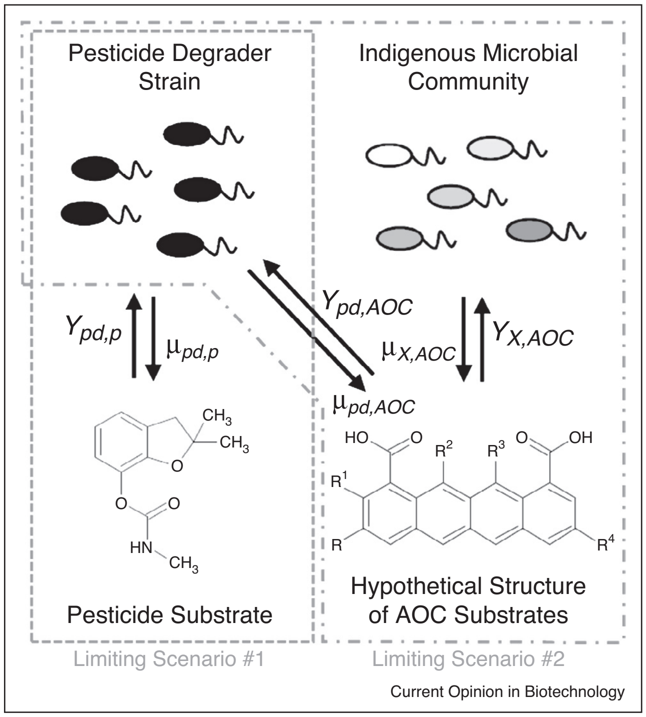
World Health Organization (WHO) Guidelines for Drinking Water Quality [4]
- Establishes guideline values (GVs) for 32 individual pesticides that are of health significance in drinking water.
- GVs range between 0.03 and 200 μg/L.

European Union (EU) Groundwater Directive [5]
- Stipulates maximum allowable concentration of all individual pesticides in drinking water is 0.1 μg/L.
- Stipulates that the sum of all pesticide concentrations is less than 0.5 μg/L.
- Stipulates maximum allowable concentration of aldrin, dieldrin, heptachlor, and heptachlor epoxide is 0.03 μg/L.

Australian Drinking Water Guidelines 6 [6]
- Establishes guideline values (GVs) for 153 individual pesticides.
- GVs range between 0.0003 and 9 μg/L.

United States Environmental Protection Agency (USEPA) Safe Drinking Water Act
- Stipulates maximum contaminant levels (MCLs) for 21 individual pesticides [7].
- Stipulates MCLs for the 21 pesticides in the range of 0.2–700 μg/L.
- Identifies 43 additional pesticides and pesticide degradation products on a contaminant candidate list (CCL) that may require an MCL in future regulations [8].

Figure 1



Schematic of interactions between pesticide degraders and indigenous microbial communities along with the consequent competition for other assimilable organic carbon (AOC) substrates. Key parameters that determine the extent of pesticide biodegradation are the growth rate and yield of the pesticide degrader on the pesticide ($\mu_{pd,p}$, $Y_{pd,p}$), the growth rate and yield of the pesticide degrader on other AOC substrates ($\mu_{pd,AOC}$, $Y_{pd,AOC}$), and the growth rate and yield of the indigenous microbial community on other AOC substrates ($\mu_{X,AOC}$, $Y_{X,AOC}$). The limiting scenarios described in the text are delineated by the dashed lines. Schematic is adapted from Liu et al. [18•].

rates of the pesticide degrader on the pesticide substrate. This can occur when pesticide concentrations are high or when enzyme affinities for the target pesticide are greater than enzyme affinities for other AOC substrates. For example, agricultural soils are generally characterized by high concentrations of pesticides following application; under these conditions, significant biodegradation and mineralization of pesticides has been reported (e.g. [11]). Bacterial enzymes may also evolve in response to prolonged exposure to high concentrations of specific pesticides which can lead to the construction of novel metabolic pathways [12] or enhanced metabolic activity [13]. In this limiting scenario, interactions with the indigenous microbial community or other AOC substrates are not expected to have a significant effect on pesticide biodegradation. The second scenario is delineated on the right side of Figure 1 and is characterized by relatively high growth rates of either the pesticide degrader or the indigenous microbial community on other AOC substrates. This can occur when the concentration of AOC substrates is high or enzyme affinities for the target pesticide are relatively low. For example, wastewater treatment plant influents are generally characterized by high concentrations of other AOC substrates and low concentrations of pesticides [14]. Under these limiting conditions, the environment selects for microorganisms that grow on the abundant AOC substrates and pesticides are typically recalcitrant [14]. Pesticide removal reported in these types of environments is generally attributed to fortuitous metabolism [9] evidenced by the formation of pesticide degradation products [15].

Pesticide-contaminated water resources are not generally characterized by one of these limiting scenarios and therefore the complement of interactions presented in Figure 1 are important for determining the extent of pesticide biodegradation. The co-occurrence of indigenous microbial communities and other AOC substrates can have either positive or negative effects on the extent of pesticide biodegradation [16,17]. A recent model developed and validated using literature reported biodegradation data demonstrated that the effects of interactions with indigenous microbial communities or other AOC substrates can largely be predicted by considering the kinetics of those interactions [18•]. The key parameters