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Transport Behavior of Microorganisms in Porous Media

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ABSTRACT

The study of pathogenic microorganism transport in porous media is of great significance for protecting drinking water resources. On the basis of summarizing existing research data at home and abroad, the transport behavior of microorganisms in porous media was analyzed. Research has shown that pathogenic microorganisms, as a type of biological colloid, are subject to multiple transport mechanisms during their transport process. In addition to common hydrodynamic and hydrochemical conditions, microorganisms are also influenced by their own properties, medium particles, and chemotaxis during transport. This review aims to summarize the relevant research on the transport of microorganisms in porous media in recent years, gain a deeper understanding of the transport behavior of microorganisms in porous media, and provide theoretical basis for their practical application in groundwater and soil pollution remediation.

KEYWORDS

Microorganism; Porous media; Transport mechanism; Influence factors.

1. INTRODUCTION

Groundwater is one of the main sources of drinking water for humans and plays a crucial role in maintaining human production and daily life. However, groundwater quality surveys conducted over the past few decades have shown that groundwater is suffering from severe contamination by pathogenic microorganisms such as viruses and bacteria[1]. The sources of pathogenic microorganisms are complex and diverse, such as septic tanks, the use of animal manure in agricultural activities, and leachate from landfills, all of which can become sources of pollution[2-4]. They can enter groundwater through rainwater runoff or infiltration, thereby endangering human health through drinking water. Previous studies have shown that there are a large number of pathogenic microorganisms in the excrement of humans and animals, which can penetrate into soil ecosystems through the application of animal manure and recycled water systems[5-7], and migrate and spread in soil and water environments, thereby causing outbreaks of human or animal borne diseases through drinking water and food.

It is worth noting that there have been multiple public health incidents worldwide caused by contamination of drinking water sources with pathogenic microorganisms. In 2016 and 2018, Finland experienced two outbreaks of drinking water epidemics due to the rupture of drinking water pipelines and the invasion of wastewater into distribution systems, resulting in approximately 450 infections. Subsequently, the main pathogenic microorganisms detected in patient samples were adenovirus, norovirus, enterotoxigenic intestinal tract, and hemorrhagic Escherichia coli[8]; Cun et al.[9] found that the detection rates of Escherichia coli and Legionella pneumophila in 49 samples from a sewage treatment plant during summer and winter seasons were both 100%, and there was no significant seasonal difference. It can be seen that preventing pathogenic microorganisms from contaminating water bodies is crucial for ensuring public health and drinking water safety. In order to explore the transport process of microorganisms in porous media, scholars at home and abroad have conducted a large number of indoor column experiments and field experiments, and found that the research on the influencing factors of microbial transport in porous media mainly focuses on the properties of pathogenic microorganisms themselves, the properties of porous media, hydraulic conditions, ion strength, and other factors[10]. Gannon et al.[11] found that the important factor affecting bacterial transport is the size of the bacteria; Bai et al.[12] found that under unsaturated conditions, some pores cannot contribute to the retention of bacteria, and the deposition of bacteria at the gas-liquid interface increases; Dong et al.[13] found that water salinity significantly reduced the distribution and relative abundance of plastic degrading bacteria during their transport from rivers to oceans.

Based on the search of relevant research at home and abroad, this article mainly summarizes the current research status and progress of microbial transport in porous media, and discusses the sedimentation and transport mechanisms of microorganisms in porous media. At the same time, the transport behavior of microorganisms in saturated and unsaturated porous media was analyzed, and the research hotspots of microorganisms in porous media were summarized, providing a basis and reference for future research on microbial transport in porous media.

2. THE TRANSPORT MECHANISM OF MICROORGANISMS IN POROUS MEDIA

The transport process of microorganisms in porous media can essentially be regarded as the transport behavior of colloidal particles in the pore structure driven by water flow. The transport process is the result of multiple mechanisms working together, such as water flow velocity, colloid particle size, medium particle size, surface roughness, pore size, and pore water chemical properties, all of which have significant impacts on it. Zhong et al.'s[14] research shows that the transport process of microorganisms in porous media can be divided into four types: convection dispersion, pore blockage, adsorption, and deposition (as shown in Fig. 1).

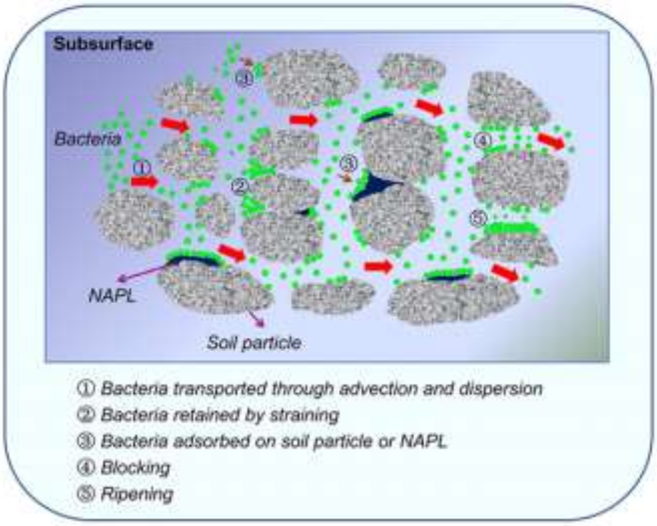

Fig 1. Schematic diagram of bacterial transport processes in subsurface porous media[14].

2.1. Advection-dispersion

In porous media, the transport process of microorganisms is similar to solute transport, both of which are controlled by groundwater dynamic conditions. The main mechanisms include advection and hydrodynamic dispersion. Among them, advection refers to the phenomenon of microorganisms migrating as a whole with the liquid phase in the pores of porous media under the push of water flow, and its transport direction and rate are positively correlated with the direction and velocity of pore water flow. Hydrodynamic dispersion is composed of both molecular diffusion and mechanical dispersion. The former is driven by the concentration gradient caused by the Brownian motion of colloidal particles, and molecular diffusion plays an important role when the pore water flow is in a static or low velocity state. The latter is caused by the heterogeneity of pore structure, resulting in longitudinal and transverse mixing caused by differences in pore water flow direction and velocity.

2.2. Pore blockage

Pore blockage is an important mechanism for controlling the transport of biological colloids in porous media. When the diameter of the biological colloid approaches or exceeds the pore size it needs to pass through, its transport path will be physically blocked, resulting in the inability of the biological colloid to pass through and forming a retention effect[15, 16]. The efficiency of pore blockage mainly depends on the ratio of colloid particle size to medium pore size. The shape, size irregularity, and surface roughness of porous media can all affect the process of pore blockage[17]. It is worth noting that natural porous media typically exhibit a wide range of pores and particle size distributions[18], and their complex surface roughness can also affect the transport of colloids[19].

2.3. Adsorption

Adsorption refers to the phenomenon in which colloidal particles deposit on the surface of a porous medium when the pore size of the medium is larger than the colloidal particle size, due to the combined effects of electrostatic interactions, van der Waals forces, and hydrophobic interactions between the colloidal particles and the surface of the medium[20, 21]. Due to the fact that the size of microorganisms typically corresponds to the colloidal particle size range, their adsorption behavior in porous media can be explained by the DLVO theory (Derjaguin Landau Verwey Overbeek theory). This theory suggests that the interaction between colloidal particles is mainly determined by two forces: van der Waals attraction and double-layer repulsion. The potential energy of DLVO is related to the distance between colloidal particles. As the distance between colloidal particles decreases, the potential energy of DLVO will appear successively as a secondary potential energy trap (negative value), a maximum potential energy barrier (positive value), and a primary potential energy trap (negative value). According to the DLVO theory, the adsorption behavior of microorganisms on porous media surfaces can be divided into two types: reversible adsorption and irreversible adsorption. Reversible adsorption refers to the temporary capture of microorganisms by short-range forces (such as van der Waals attraction) when they approach the surface of a medium under hydrodynamic action (such as fluid shear force), Brownian motion, or self flagellar drive, resulting in a weak binding state. Irreversible adsorption refers to the strong binding state between microorganisms and the surface of a medium, which requires overcoming the maximum potential energy barrier in order to detach.

2.4. Sedimentation

Sedimentation is a key factor in regulating the transport of microorganisms in porous media, mainly including two mechanisms: blocking and ripening[22]. Blocked deposition refers to the reduction of available attachment sites for other cells after microorganisms attach to the surface of a medium, thereby lowering the overall deposition efficiency. Research has shown that when the concentration of cells in the inflow is high, the blocking effect is significantly enhanced, leading to a gradual increase in the concentration of cells in the outflow[23]. Ripening deposition refers to the use of attached microorganisms as new adsorption sites, which promote the subsequent deposition of other colloidal particles. This process gradually reduces the concentration of effluent cells by increasing the effective deposition sites.

3. FACTORS AFFECTING THE TRANSPORT OF MICROORGANISMS IN POROUS MEDIA

The soil and groundwater environments are complex and varied, with significant differences. The transport behavior of microorganisms in porous media is influenced by various factors, including the activity status of microorganisms, the properties of porous media, and the properties of groundwater environmental solutions. In recent years, numerous scholars have studied the mechanisms by which different factors affect the transport behavior of microorganisms in porous media. The following provides a systematic explanation of the factors that affect microbial transport behavior.

3.1. Particle size of porous media

The particle size of porous media is one of the important factors affecting microbial transport. Research has shown that particle size not only affects the interaction between microorganisms and media particles, but also affects the transport process of microorganisms in porous media. Smaller particle size usually represents smaller pores and larger specific surface area, which can inhibit microbial transport by increasing the contact opportunities between microorganisms and the medium surface. Studies have shown that the removal rate of Escherichia coli bacteriophages in sandy soil is significantly higher than that in river sand, mainly due to the larger pore particle size in sandy soil enhancing the virus's transport ability, thereby improving its removal rate in the medium[24]. Bai et al.[25] studied the transport behavior of Klebsiella in fine sand (0.25-0.54 mm) and coarse sand (0.58-1.48 mm), and found that bacterial sedimentation decreases with increasing sand particle size.

3.2. Surface roughness and moisture content of porous media

The surface roughness of porous media can reduce the maximum potential energy barrier height at the solid-liquid interface, increase the collision frequency between microorganisms and the medium, and thus inhibit the transport of microorganisms[26]. Lu et al.[27] found that the sharp convex structure on the surface of quartz sand media can significantly reduce the maximum potential energy barrier threshold at the solid-liquid interface, thereby enhancing the retention efficiency of colloidal particles in the primary potential energy trap. The study also found that particles located in the grooves on the surface of the media are less affected by fluid shear and are more likely to be trapped in the capture area of the secondary potential energy trap.

The saturation of porous media has a significant impact on the transport and retention behavior of microorganisms in porous media. Jewett et al.[28] studied the retention of Pseudomonas at saturation levels of 100%, 84%, and 46% and found that the retention of Pseudomonas in soil columns increased with decreasing saturation levels. When the saturation level decreased from 100% to 46%, the retention of Pseudomonas in soil columns increased from 50% to 95%. Research has found that in saturated systems, the reaction of viruses at the solid-liquid interface dominates their transport; In unsaturated systems, the decrease in water saturation and the increase in gas-liquid interface promote the retention of viruses and inhibit their transport[29, 30].

3.3. Velocity of flow

Flow velocity is the main driving force for the transport of microorganisms and other colloids in porous media. Generally speaking, the transport ability of microorganisms increases with the increase of flow velocity, and the transport amount of microorganisms in soil columns also increases. Huysman et al.[31] confirmed that the transport of Lactobacillus in unsaturated porous media significantly increases with increasing flow velocity (from 0.8 cm/h to 4.7 cm/h). Sasidharan et al.[32] systematically studied the regulatory mechanism of flow velocity on the transport behavior of Escherichia coli in porous media from the aspects of DLVO energy, cell retention time, and torque balance. The research results showed that as the flow velocity decreased and the retention time increased, the viscous force between cells and the media surface increased.

3.4. Ionic strength and type

Ionic strength regulates the electrostatic interaction between microorganisms and the surface of the medium by compressing the double layer, thereby affecting their adsorption and transport behavior. Chen et al.[33] studied the mechanism of the effect of ion strength on the retention behavior of bacteria in quartz sand and found that as the ion strength increased (from 1 mM to 100 mM), the Zeta potential between bacteria and quartz sand decreased, the electrostatic repulsion between the two decreased, and the amount of bacteria retained in quartz sand increased. Torkzaban et al.[34] found that increasing ion strength leads to the generation of interparticle tension, resulting in an increase in the number of colloids trapped in secondary potential energy traps. Ions of different valence states significantly alter the transport behavior of microorganisms through charge neutralization or bridging. Zhang et al.[35] found that the deposition of bacteria in porous media increases with the increase of ion concentration. In addition, they also found that the bacterial deposition rate in CaCl2 solution is significantly higher than that in NaCl solution at the same ion strength. This is because compared to monovalent ions, divalent cations (such as Ca^{2+}, Mg^{2+}) have higher charges and stronger ability to neutralize the charges between colloids and the surface of the medium, which can significantly enhance the deposition of colloids in the medium; Divalent/multivalent ions can also connect colloids to the surface of the medium through ion bridging, promoting the deposition behavior of colloids.

3.5. pH

The influence of pH on microbial transport is mainly achieved by affecting the surface properties of microorganisms and porous media. Jiang et al.[36] studied the adsorption characteristics of Pseudomonas putida on minerals such as montmorillonite, kaolinite, and goethite, and found that the bacterial adsorption capacity decreased with increasing pH (from 3.0 to 10.0). This phenomenon is consistent with the research findings of Kim et al.[37]: experiments on the transport behavior of Bacillus cereus showed that increasing the pH value from 7.2 to 8.5 can increase its transport efficiency by about 50%, which is attributed to the strengthening of the negative surface charge of the bacterial cells and the enhancement of their electrostatic repulsion with the medium.

3.6. Organic compound

The organic matter attached to the surface of porous media can inhibit the sedimentation behavior of microorganisms through various mechanisms. Yang et al.[38] found that humic acid changes the surface potential of the medium by adsorbing hematite in the fluid, weakening the electrostatic attraction between microorganisms and the medium, and enhancing the transport ability of Escherichia coli. Foppen et al.[39] found that humic acid enhances bacterial transport in porous media by altering the surface charge and steric hindrance effect of goethite coating media.

3.7. The size and shape of microorganisms

The size and shape of microorganisms are the main factors limiting their filtration, adsorption, and other processes in porous media. Research has shown that the shape of bacteria (defined as the aspect ratio of cells) can affect their transport in porous media. Weiss et al.[40] studied the transport behavior of 14 bacterial strains suspended in artificial groundwater through quartz sand column experiments. By comparing the differences in bacterial morphology and particle size distribution between the initial state of the bacterial suspension and the effluent, they found that the cells in the effluent were smaller and rounder. Mallén et al.[41] studied the transport behavior of bacteriophage viruses, odorous pseudomonas, and Escherichia coli in sand and gravel aquifers under natural flow conditions, and found that bacteriophage viruses had the strongest transport ability, followed by odorous pseudomonas, and Escherichia coli had the weakest transport ability. These research results indicate that microorganisms with smaller sizes and shapes closer to circles have stronger transport abilities in porous media.

3.8. Chemotaxis

Bacterial chemotaxis is the fundamental physiological mechanism by which bacteria dynamically adjust their movement direction by sensing changes in chemical concentration gradients in the environment[42, 43]. It plays a key role in survival strategies that seek benefits and avoid harm. When pollutants (such as naphthalene, phenol, aspartic acid, etc.) are present in the system[44, 45], bacteria will aggregate around the pollutants through chemotaxis reactions, affecting their transport behavior. Wang et al.[46] found in heterogeneous sand columns that Escherichia coli moved towards the central chemotactic source in the presence of chemotactic substances, and exhibited a higher peak of breakthrough with larger pore flow velocity in the inner layer of coarse quartz sand. Adadevoh et al.[47] found that in quartz sand columns with dispersed pollution sources (naphthalene crystals), the transport of Pseudomonas putida G7 increased and the recovery rate decreased.

3.9. Extracellular polymeric substances

Extracellular polymeric substances (EPS) are high molecular weight polymers secreted and encapsulated on the surface of cells by microorganisms during their growth process. The main components are proteins, polysaccharides, deoxyribonucleic acid (DNA), and humus. EPS affects the transport behavior of microorganisms in porous media by altering their surface potential and hydrophobic interactions[48]. After selectively removing some EPS components using proteolytic enzymes, Kim et al.[49] found that the transport ability of Escherichia coli was significantly improved, indicating that the presence of EPS has an inhibitory effect on microbial transport; Removing EPS treatment can inhibit the formation of bacterial aggregates and further reduce their sedimentation probability. Tong et al.[50] found that the transport rate of EPS free bacteria was significantly higher than that of the control group by comparing the sedimentation kinetics of bacteria wrapped in natural EPS and EPS removing strains, confirming the regulatory effect of EPS on microbial retention.

4. DISCUSSION AND PROSPECT ON THE TRANSPORT OF MICROORGANISMS IN POROUS MEDIA

This article reviews the transport mechanism of microorganisms in porous media and summarizes the factors that affect microbial transport behavior. Due to the complex structure and surface characteristics of microorganisms, as well as the co-transport of pollutants, mineral particles, etc. in the environment with microorganisms in porous media. Based on this, the following research needs to be conducted in the future:

(1) At present, research on the transport behavior of microorganisms in porous media mainly focuses on pathogenic microorganisms such as Escherichia coli, and experimental media are mostly homogeneous quartz sand or glass beads, often ignoring the heterogeneity and complexity of porous media in actual environments. Therefore, it is urgent to further prove whether the research results and patterns obtained in the laboratory are applicable to practical environments.

(2) The research methods mainly focus on indoor soil column simulation experiments under a single influencing factor, but the transport of microorganisms in actual soil or groundwater environments is often affected by multiple factors. Therefore, conducting research on the combined effects of multiple factors is essential for accurately understanding the transport behavior of microorganisms in underground environments.

(3) The porous media system in the laboratory always plays the role of a "black box" and cannot visually display the transport process of microorganisms in the porous media. It is urgent to develop a real-time visualization system for pore scale to achieve real-time observation of microorganisms in porous media, and further reveal the transport behavior of microorganisms in porous media from the micrometer scale.

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