

## Review paper

# The trapping of colloid particles in porous media: Mechanisms and applications, review

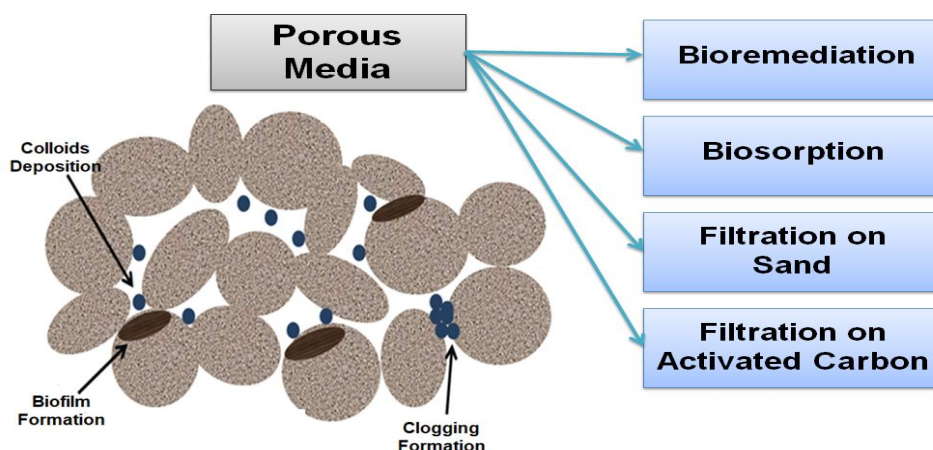
Bouchenak Khelladi Racha Medjda<sup>1\*</sup>, Chiboub Fellah Abdelghani<sup>1</sup>, Pontié Maxime<sup>2</sup>, Guellil Fatima Zohra<sup>3</sup>

<sup>1</sup>Department of Hydraulics, Faculty of Technology, University of Tlemcen, Tlemcen, Algeria.

<sup>2</sup>Department of Chemistry, Group Analysis and Processes, Faculty of Sciences, University of Angers, Angers, France.

<sup>3</sup>Department of Chemistry, Faculty of Chemistry, University of Tlemcen, Tlemcen, Algeria.

## GRAPHICAL ABSTRACT



## ARTICLE INFO

### Article history:

Received 13 September 2020

Reviewed 18 November 2020

Received in revised form 26 December 2020

Accepted 27 December 2020

### Keywords:

Retention  
Biofilms  
Biofilm  
Clogging  
Bioremediation

## ABSTRACT

This review paper will serve to explain how a particle is trapped on a porous media, and describe the mobility of those particles when passing through a media. It also presents the different parameters that play an important role on the trapping mechanism and the role of biofilm formation. The deposition and trapping mechanism of particles in porous media is governed by the action of different mechanisms such as interception, sieving, diffusion, gravitational and Van Der Waals forces, Brownian diffusion, and inertia. The particle retention through the porous media leads to the formation of a biofilm and the clogging of the media. The understanding of particle retention, clogging, and biofilm formation is interesting because it plays a major role in soil recovery process such as bioremediation, biosorption and filtration (on sand and activated carbon) used for degradation of particles (colloids and microorganisms) and harmful contaminants (heavy metals, drugs) by microorganisms.

©2020 Razi University-All rights reserved.

## 1. Introduction

The transport of solid particles in porous media, subject to fluid flow occurs in many natural or artificial processes. For example in the field of civil engineering, the transport of particles leads to the clogging of draining materials, reduction of soil permeability, soil erosion, or degradation of materials, and water treatment (filtration on sand or activated carbon). Knowing the mechanisms of interaction at the pore scale between the different phases composing the porous material is essential to determine the macroscopic sizes or behaviors of the particles that might be useful in different applications (Benmezroua, 2011). Organic, inorganic, and microbiological colloids exist in natural and contaminated aquifer and also in vadose zone environments.

\*Corresponding author Email: [rashamajda@hotmail.fr](mailto:rashamajda@hotmail.fr)

These colloid particles can be released into groundwater and soil through various hydrologic, geochemical, and microbiological processes. Knowing the processes that control colloid transport is required to assess the potential of contamination and to protect drinking water supplies from pathogens, in order to develop strategies for bioaugmentation and bioremediation, and devise microbially enhanced oil recovery systems (Wollesen de Jonge et al. 2004). Colloid transport in porous media has been catching considerable scientific attention due to potentially enhanced transport of contaminants associated with mobile colloids that also enhance the transport of dissolved contaminants in groundwater. The interest in colloid transport grew due to the importance of predicting and

understanding microorganism, colloids and nanoparticle transport in natural porous media (Molnar et al. 2015). For the purpose of treating contaminated soils, various technologies have been developed over the years. Among those techniques for soil recovery we cite bioremediation using microorganisms to eliminate and transform contaminants into harmless substances. This process depends on soil porosity and permeability, soil's ability for adsorption of microorganisms, and soil properties.

In this article, we review the main transport, mobility, trapping and retention mechanisms associated with colloid behavior in porous media. We begin our review by giving the characteristics of a porous media, then summarizing the main factors and mechanisms influencing colloid retention and transport at the microscale and exploring the clogging phenomena and biofilm formation. Finally, we continue by giving applications for soil remediation and recovery.

## 2. Porous media characteristics

Porous media can be defined as solid bodies having pores which represents void spaces frequently distributed through the material, whose size is intermediate between very small voids, which are present in solid at the molecules scale, and very large, which may be called "caverns" (Catalano. 2012). Any biotic or abiotic material, which contains a fluid-filled voids network can be considered as a porous medium, however, the fluid-filled channels in many porous media have non uniform shapes and size and are commonly referred to as pores (Dullien. 2012; Larue. 2018). In a porous system, pores may be non-interconnected or interconnected (Fig. 1); where the part of the pore space interstitial fluid flow is possible, which represents the effective pore space of the porous media (Catalano. 2012). Two major quantities are used to characterize porous structures, which are porosity; the ratio of the void space to the total volume of the medium, and permeability, which is the conductivity of the flow across the porous media, which depends on both particle size and porous media structure, and also on its degree of saturation in water (Khaled and Vafai. 2003; Gette-Bouvarot. 2014).

The reduction of permeability is mainly controlled by friction between grain surfaces and particles. Therefore, the roughness of particles and grains surfaces is the major clogging parameters. The permeability alterations can be attributed to the attached particles as well as the moving ones with different velocities, it is suggested that the ratio of the moving particles to the number of settled particles is a key parameter to characterize permeability reduction which could not only be due to changes in volume fraction of the fine particles to the pore volume, but also to the size distribution of the fine particles (Parvan et al. 2020). Two other geometrical parameters characterize a porous medium; the first one is the specific internal area, defined as the ratio of internal area to bulk volume and expressed as a reciprocal length, and for the second one is the tortuosity, defined as a geometrical property equal to the relative average length of the flow path of a fluid particle from one side of the porous medium to the other (Catalano. 2012).

The study of the porous media hydrodynamics requires focusing on the mechanical and physical properties of each component; including the solid skeleton, which characterizes the intrinsic structure of the porous media and the fluids which are flowing within it. However, for a complete description of such complex material, the analysis of the interaction between the fluid and solid phases in dynamic and static conditions is required (Catalano. 2012). Interactions between soil porous media surface and mobile colloids may be more important than those between colloids in limited pore space, therefore, physicochemical surface and pore structures characteristics have an important influence on colloid mobility (Bin et al. 2011).

## 3. Mobility mechanism in porous media

In the subsurface environment, colloids (with an effective diameter of 1 nm to 10 µm) comprise many natural substances such as; organic compounds, clays, mineral precipitates, and metal oxides as well as biological organisms such as viruses, pathogenic bacteria, and protozoa. Compared to larger particles, colloids show higher rates of diffusive flux (e.g., Brownian motion) and higher reactivity (because of higher surface areas) and are more strongly influenced by short-range surface forces. However, colloids have more deterministic trajectories than smaller particles, and their forces of interaction can be greater than smaller particles.

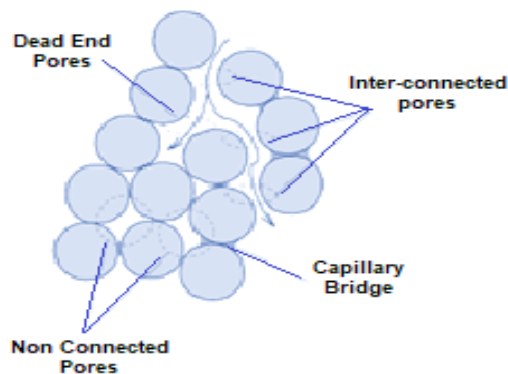


Fig. 1. Different types of connections between pores in a porous media are considered as spherical (Gette-Bouvarot. 2014).

Defining colloids on the basis of transport properties suggests that larger aerosols may have the same diffusivity (inversely proportional to fluid viscosity) of smaller aerosols, but different reactivity or specific surface area (Molnar et al. 2019). Colloid mobility (Table 1) in porous media is mainly controlled by the net rate of colloid deposition and release, which can be divided into a two-step process; transport of colloids from bulk solution to the porous media surface and then their attachment to the surface, which depends on the nature of the interaction between particles-surface (Bradford et al. 2006; Bin et al. 2011). The trapping mechanism of fine particles is directly related to the pore throat size, pore size, and connectivity of the granular porous medium, therefore, the percolation or trapping process can potentially be used to deduce information about the geometrical properties of the porous medium (Kerimov et al. 2018).

Table 1. Model for colloids motion.

Colloid motion (Lazouskaya et al. 2011)

$$m \frac{dv}{dt} = -\frac{1}{2} m_f \frac{dv}{dt} + F_D + F_{col} + F_{Br} + F_G$$

$$F_D^B = 6\pi\mu r \left[ \frac{v_n - v_{front} \cos\alpha}{F_1} - (u_n - v_{front} \cos\alpha) F_2 \right]$$

$$F_1(H) = \frac{19H^2 + 4H}{19H^2 + 26H + 4}$$

$$F_2(H) = 1 + \frac{1.79}{(0.828 + H)^{1.167}}$$

|                   |                                                                                 |
|-------------------|---------------------------------------------------------------------------------|
| Symbol definition | $F_D$ = The drag force                                                          |
|                   | $F_{Br}$ = The force due to Brownian diffusion,                                 |
|                   | $F_G$ = The net gravity force,                                                  |
|                   | $F_{col}$ = Colloid forces including electrostatic ( $F_{el}$ ),                |
|                   | VanDer Waals ( $F_{vdW}$ ), hydrophobic ( $F_h$ ) forces,                       |
|                   | $m$ = The particle mass,                                                        |
|                   | $m_f$ = Mass of the fluid,                                                      |
|                   | $v$ = The particle velocity.                                                    |
|                   | $(v_n - v_{front} \cos\alpha)$ and $(u_n - v_{front} \cos\alpha)$ = Colloid and |
|                   | fluid relative velocities in the normal direction,                              |
|                   | $F_1$ and $F_2$ = Universal hydrodynamic functions of                           |
|                   | the dimensionless separation $H$ between the                                    |
|                   | particle and the surface                                                        |

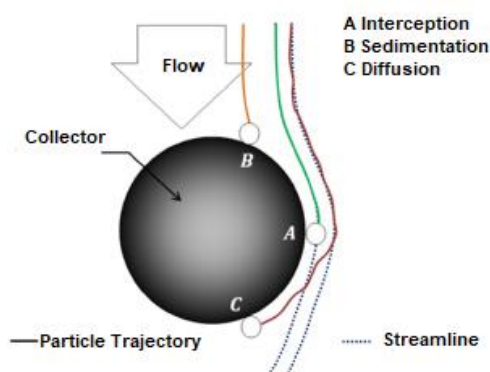


Fig. 2. Mechanisms of colloid contact to a collector (Daalach. 2017).

The main mechanisms of colloid contact to a collector (Fig. 2) are interception, inertial impaction, sedimentation, attachment at the air-water interface, Brownian diffusion, electrostatic forces, adsorption, and "straining" (Bradford et al. 2006; Bin et al. 2011; Prédélus et al. 2014). For small particles, Brownian motion, electrostatic forces, and double layer forces are the primary factors that dominate particle motion, however for larger particles; the leading factors are generally hydrologic interactions and gravity (Liu et al. 2016).

### 3.1. Inertial impaction

Whenever the current lines change direction and if the particles have a considerable inertia, then the particle comes into contact (shock-rebound) with the closest surface to the granular filter before being driven by other flow lines. The importance of this mechanism (Fig. 3) can be verified by the number of Stokes. The typical values for the Stokes number are from  $1 \times 10^{-9}$  to  $2 \times 10^{-3}$ , the highest value corresponds to an inertial impaction due to dominant inertia (Papineau. 2013; Benmezroua. 2011).

### 3.2. Interception

Interception (Fig. 3) occurs when the particle remains in its flow line in absence of surface forces and inertia, and if the radius of the suspended matter is bigger than the distance between the flow lines which contains the particle and the granular filter, then the particle comes enough closer to the grain to collide with the granular filter surface where they are stopped (Papineau, 2013; Benmezroua, 2011; Carre, 2017). During this process the removal efficiency of the filter is enhanced by decreasing of the pore size due to the accumulation of the deposited particles on the filter media, as suspended particles travelling in roughing filter are obstructed to move forward due to the reduction of pore size and due to collision are packed together and lose energy to go forward (table 2) (Haider, 2018).

### 3.3. Brownian diffusion (diffusion)

Colloidal diffusion is the movement of colloids from regions of high particle concentrations to regions of low particle concentrations, similar to individual molecules diffusion. However, unlike individual molecules, colloids movement is due to their random walk behavior 'Brownian motion,' which leads the particle to contact with the surface of the grain of the porous media. The magnitude of Brownian motion increases with decreasing particle size. In the absence of surface forces, the deposition of Brownian particles in the granular media filter can be considered as a mass transfer process. Brownian motion affects the individual colloids trajectories during transport which impacts how far they may be transported through porous media. The diffusion (Fig. 3) action becomes important with the decrease in the diameter of the particle ( $d < 1 \mu\text{m}$ ) (Molnar et al. 2019; Benmezroua, 2011).

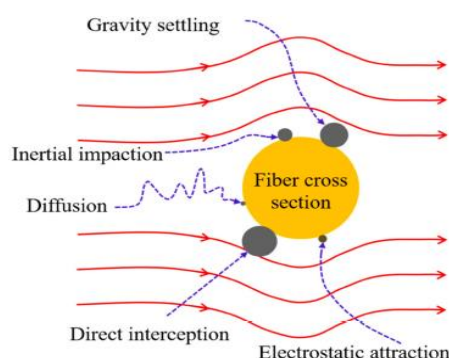


Fig. 3. Inertial impaction, interception and diffusion mechanisms of particle deposition on a fiber (Chao et al. 2020).

### 3.4. Electrostatic forces

Most microparticles in suspension develop an electrostatic charge; because of these charges they can form agglomerations, as they can be separated by repulsion. All this depends on several parameters (the pH of the fluid, the type of material of the particles and the granular filter ...) (Benmezroua. 2011). According to the theory of Derjaguin, Landau, Verwey and Overbeek (DLVO), the interactions between a colloidal particle and a collector surface can be defined as

the sum of the electrostatic double layer and the attractive Van Der Waals interactions, which can be either repulsive or attractive, and short-range forces such as hydration and steric repulsion (Jeremy et al. 2004; Chung, 2015). This theory describes the interactions existing between the free ions and the electrochemical double layer to generate a  $W_{DLVO}$  energy which takes into account an  $F_{VDW}$  attractive force and an electrostatic force (Table 2). The ions adsorbed on particle surfaces lead to an agglomeration of particles attached to the surface of a grain of the porous medium (Benmezroua. 2011). Van Der Waals interactions exist between all atoms and molecules are of low intensities, the charged particles immersed in the fluid adsorb ions and by compensation, a second layer richer in ions of opposite charge is formed. Three types of interactions can be differentiated; the first one, Keesom interactions which result from the interaction between two permanent dipoles, like two magnets, this interaction causes the alignment of one or both dipoles, the second one, Debye interactions resulting from the interaction between a permanent dipole and an induced dipole. The deformation of an electron cloud caused by an electric field (of the molecule) makes polar a second molecule, and the third one, London interactions resulting from the fact that the electron density is not totally homogeneous around an atom which creates a weak dipole moment. This dipole moment interacts with the dipolar moments of the other molecules and a force is created (Masson. 2015; Benmezroua. 2011).

### 3.5. Sedimentation

During this process, the particles having greater mass density than of water settle onto the media surface. Those particles are susceptible for gravitary forces that they go out from the flow lines to the media filter. For effective sedimentation and natural agglomeration of smaller particles in larger and heavier particles, laminar flow conditions are necessary, which are ensured by low roughing filtration rates. This process is not effective for colloidal particles ( $< 100 \text{ nm}$ ) due to their low density (Haider, 2018; Papineau, 2013).

Table 2. Capture coefficient for colloid transport mechanism.

|                                                | Equation (Hakobyan. 2015)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Aerosol Filtration theory                      | $LF = \frac{\Delta p}{U \mu}$ and $L = \alpha H / \pi a^2$                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
| Capture coefficient for interception mechanism | $\eta_R = \frac{1}{2(2 - \ln Re)} [2(1 + R) \ln(1 + R) - (1 + R) + 1/(1 + R)]$                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| Capture coefficient for inertial impaction     | $\eta_{I-} = \frac{St}{2 Ku^2}$<br>$f = (29.6 - 28\alpha^{0.62})R^2 - 27.5R^{2.8}$ for $R < 0.4$<br>$f = 2$ for $R > 0.4$                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
| Capture coefficient for diffusion mechanism    | $\eta_D = 2.9 k^{-\frac{1}{3}} p_e^{-\frac{2}{3}} \left( 1 + 0.39 k_p^{\frac{1}{3}} k_n \right)$<br>$k = Ku + 1.15 Kn$                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| Capture coefficient for sedimentation          | $\eta_G = \frac{U_G}{U} = \frac{2r_p^2 g (\rho_p - \rho_{gas})}{9\mu U}$                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| Capture coefficient for Van Der Waals Forces   | $\eta_W = 0.573 \left( \frac{A^7 Cc r_p^3}{a^5 U \mu k u^{5/2}} \right)^{2/7}$                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| Symbol definition                              | <p><math>L</math> = The length of fibers per unit area of filter material,<br/> <math>\alpha</math> = The filter packing density (solid fraction),<br/> <math>H</math> = Filter thickness,<br/> <math>a</math> = Radius of the fiber,<br/> <math>F</math> = The dimensionless resisting force acting on a unit length of fibers<br/> <math>Re</math> = Reynolds number,<br/> <math>R</math> = The interception parameter,<br/> <math>St</math> = Stokes inertial parameter,<br/> <math>Ku</math> = Kuwabara hydrodynamic factor,<br/> <math>Kn</math> = Knudsen number for fiber,<br/> <math>Pe</math> = Peclet number of aerosol particle transportation<br/> <math>\rho_{gas}</math> = Gas density,<br/> <math>g</math> = Free fall acceleration,<br/> <math>\rho_p</math> = Density of captured particles,<br/> <math>r_p</math> = Radius of captured particles,<br/> <math>U_G</math> = The particle deposition rate,<br/> <math>\mu</math> = Dynamic viscosity of the flow,<br/> <math>U</math> = Filter face velocity,<br/> <math>A^7</math> = The constants of VanDer Waals interaction,<br/> <math>Cc</math> = Cunningham slip factor correction for slip effect vanishing between gas and particle</p> |

### 3.6. Adsorption

Adsorption is defined as the physicochemical interactions with porous media (Fig. 4), it is also a mass transfer from a liquid phase to a solid phase. It implements attractive forces between a solute and a solid surface, it occurs when colloidal particles are close to the surface of soil particles. Interactions on the surface of colloidal particles lead to permanent or temporary attachment to the solid phase of porous media (Tahar. 2013; Prédélus. 2014).

Depending on the nature of the forces, there are two types of adsorption, often involved simultaneously; physical adsorption which is governed by Van Der Waals forces, and which therefore does not imply any chemical alteration of the adsorbed substances; it therefore represents a reversible reaction and weak energies, and the chemical adsorption which involves the formation of chemical bonds; it therefore represents an irreversible reaction and strong energies (Tahar. 2013).

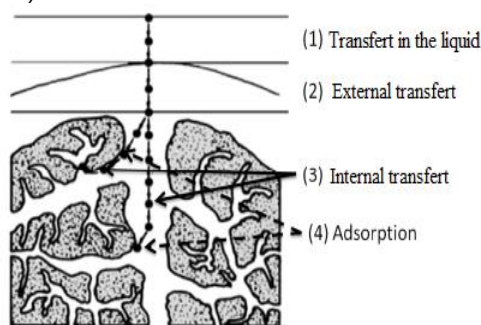


Fig. 4. Adsorption mechanism (Masson. 2015).

### 3.7. Attachment

Particle attachment on media surface is partly dominated by DLVO forces, expressed as the sum of electrostatic double layer repulsive forces and Lifshitz-Van Der Waals attraction forces. The magnitude of energy interaction is substantially reduced when surface roughness is reduced by only a few nanometers, thereby enhancing particle deposition on the media surface (Chao et al. 2015). The attachment of colloidal particles at the air-water interface depends on ionic strength, surface properties of colloidal particles, and pH (DeNovio et al. 2004; Hahn et al. 2003). Surface roughness to particle deposition can be explained by the contribution of surface charge heterogeneity, hydration, attachment within the secondary energy minimum, and hydrophobicity (Chao et al. 2015). Constriction occurs when the pore diameter is inferior to colloidal particles, which provides sites for depositing, including areas where local water flow is not null. This type of deposit is called "straining", which concerns mainly larger colloidal particles (Prédélus. 2014). More a colloid get closer to a grain, more the resulting force is attractive, until the colloid reaches a distance equivalent to the second minima energy. Once this distance is crossed, at the moment when the colloid continues its trajectory towards the grain, it is exposed to repulsive forces. If the particle has enough kinetic energy to cross the energy barrier; the distance from the grain at which the repulsion forces are maximum, and continues its trajectory towards the grain, this will be exposed to an attractive resulting force increasing up to that this one reaches the first minima energy. The first energy minima are defined as the distance at which the colloid undergoes a maximum attractive force. The attachment of a colloid can take place at a distance equivalent to the first or second minima energy (Papineau. 2013; Hahn et al. 2003). Since the attractive force resulting from the second minimum energy is less, the attachment is said to be reversible and the colloids retained at this distance from the grain are more vulnerable to detachment (Tufenkji et al. 2005). The attachment of particles to filter materials is partly governed by electrostatic interactions as presented above, but also by hydrophobic and steric interactions. These hydrophobic interactions take place between two hydrophobic surfaces in an aqueous medium. The resulting long-range attraction forces (up to 80 nm) exceed those of Van Der Waals interactions. For their part, steric interactions result from interactions between macromolecules on the surface of biocolloids and surrounding surfaces. Compression of these macromolecules causes an increase in repulsive forces and thereby decreases attachment (Jegatheesan et al. 2005; Tufenkji et al. 2007). The description of a successful attachment (Table 3) is the transport over an existing energy barrier to contact in the primary well. This type

of attachment is considered as irreversible due to the great energy barrier that is released from this primary energy minimum. The deposition rate is unfavorable or slow when the net repulsive interaction energy is low compared to the mass transport rate, however the deposition process is favorable or fast when there is no net repulsive interaction, and is set by the mass transport rate (Hahn et al. 2004).

### 3.8. Straining

Straining is defined as the trapping of colloid particles in down-gradient pore throats that are too narrow to allow the passage of the particle through the media (Mc Dowell-Boyer et al. 1986). The retention of colloids by straining is dominated by both porous media and colloids properties. Straining occurs when colloids are retained in dead-end pores which are smaller than some critical size, however colloid transport may still occur within pores larger than the critical size (Wollesen de Jonge et al. 2004). In addition, the straining effect is more important in unsaturated media; when the water flow is towards the smallest pore, it drives colloidal particles to where they are blocked (Prédélus et al. 2014). The straining phenomenon is mainly dominated by the porous media structure; where the geometric criteria depend on the relative size of the colloidal particles to those of soil pores. This phenomenon becomes significant when the ratio between the colloidal particles size and the media pore size is greater than 0.05. The straining depends not only on the sizes ratio but also on the particles irregularity, the ionic strength, and the concentration of colloidal particles in solution (Tufenkji et al. 2004; Torkzaban et al. 2010; Foppen et al. 2007). Another mechanism of colloid contact to a collector is sieving mechanism, which occurs when the particles that have their radii more than half the distance between the fibers that are completely retained by their frontal layer (Fig. 5). But this mechanism becomes valid and notable only when density of fibers is high. Also such filters become useless after a short time of the gas flow regime (Hakobyan. 2015).

Table 3. Model for different mechanism of colloid transport.

|                                   | Equation (Bai et al. 2018)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
|-----------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Total bacterial adsorption energy | $\Delta G_{adh} = \gamma_{sm} - \gamma_{sl} - \gamma_{ml}$                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| Advection-dispersion              | $\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} - v \frac{\partial C}{\partial x}$                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| Modeling colloidal transport      | $\theta_m \frac{\partial C_m}{\partial t} + \theta_{im} \frac{\partial C_{im}}{\partial t} = \theta_m D_m \frac{\partial^2 C_m}{\partial z^2} - q \frac{\partial C_m}{\partial z}$                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| Adhesive torque                   | $T_{adhesive} = \min(2) = a_0 F_A$                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| Total vertical capillary          | $F_{v,tot} = \sigma_{aw} 2\pi \sqrt{r_p^2 - (h_f - r_p)^2} \cos \left[ \beta + \frac{\pi}{2} - \cos^{-1} \left( \frac{h_f - r_p}{r_p} \right) \right]$                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
| Symbol definition                 | <p><math>\gamma_{sm}</math>, <math>\gamma_{sl}</math> and <math>\gamma_{ml}</math> = The solid-cell, solid-liquid, and cell-liquid interfacial free energies, respectively.</p> <p><math>C</math> = The bacterial concentration in the aqueous phase at a distance <math>x</math> and time <math>t</math>,</p> <p><math>D</math> = The hydrodynamic dispersion coefficient,</p> <p><math>v</math> = The interstitial bacteria velocity,</p> <p><math>F_A</math> = The DLVO force of adhesion in the secondary minimum,</p> <p><math>a_0</math> = The radius of the colloid surface contact area,</p> <p><math>\sigma_{aw} = 0.0718 \text{ N/m}</math> at <math>25^\circ\text{C}</math> = The surface tension at air-water interfaces,</p> <p><math>\beta</math> = The contact angle between water and colloids,</p> <p><math>r_p</math> = Radius for a spherical colloid which is captured within a water film,</p> <p><math>h_f</math> = Height</p> <p><math>\theta_m</math> and <math>\theta_{im}</math> = The volumetric water content in the mobile water region and in the immobile water region respectively,</p> <p><math>C_m</math> and <math>C_{im}</math> are the concentrations of mobile and immobile region, respectively,</p> <p><math>q</math> = The Darcy flow rate,</p> <p><math>D_m</math> = The dispersion coefficient of the mobile region,</p> |

The structure of a porous media also plays an important role in the colloidal particles retention process; it is able to generate areas of low flow where the hydrodynamic effect is less important than the electrostatic attachment (Prédélus et al. 2014).

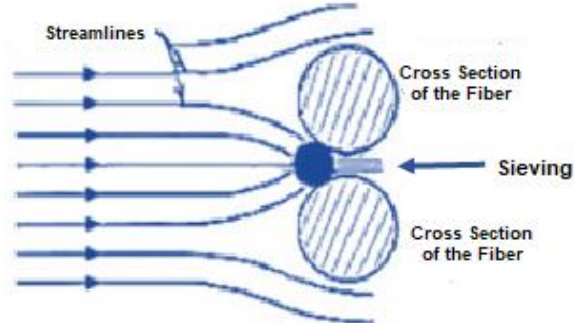


Fig. 5. Sieving mechanism of a particle deposition (Hakobyan. 2015).

#### 4. Biofilm

Biofilms or biological membranes are one of the oldest forms of life on earth, they are formed of a very thin layer of microorganisms that stick and grow to the surface of any material. Although biofilm development is desirable in some systems, there are many concerns with regard to biofilms in medicine, industry, and aquatic systems (Reyhani and Khoshnood. 2020).

Biofilms that develop in porous media are a key process to various engineering applications and natural phenomena, their presence can be either associated to negative or positive effects. Microorganisms that are also considered as to be colloidal particles have the ability to adsorb to the media surface and form biofilm, while porous media offers accessible pore that can be colonized (Fig. 6). Porous media have high ratios of surface area to volume where microorganisms could adhere to the pore surface and form biofilms, rather than remaining in a planktonic state compared to non-porous structures. However, the formed biofilm can progressively accumulate and fill the pore space, leading to permeability and porosity distribution reduction, and making fluids to flow through the porous structure increasingly difficult, it also affects mass transport of non-reactive and reactive solutes within the porous structure (Dullien. 2012). The biofilm plays an important role on the ability of bacteria to colonize the solid surface to survive and protect themselves from the environment (Wang. 2015).

Within subsurface rocks or soil, biofilm growth induces to substantial modifications to macroscopic mass and momentum transport dynamics, this type of modification has observed in variation overtime of macroscopic parameters; permeability, hydraulic conductivity, dispersion, and porosity, in conjunction to the presence of biofilm induces bioclogging leading to head loss increase and consequently the permeability reduction (Davit, 2010). When bacteria adhere to the biofilm surface, they will secrete a matrix called exopolysaccharides (EPS) which will help increasing the surface affinity of the bacteria and construct a protein structure (pili and fimbriae) that will enhance their adhesion to the surface. One of the major characteristic of biofilms compared to their singular counterparts is for example, if *E. coli* bacteria is alone, it may be quickly washed away, however, a biofilm formed of *E. coli* requires extensive treatment to kill. This property has made biofilms one of great interest in many research fields. (Tovey. 2019). Another class of colloids called "Biocolloids" exists, formed by protozoa, bacteria, and viruses, are a source of water-borne diseases and pose serious health hazards if they occur in drinking water wells. Bacteria are living organisms capable of moving through pore sizes smaller than their body size in the subsurface, which makes their transport more complex than in the case for colloidal transport. Several environmental factors that have strong effects on bacterial fate and transport in porous media have been identified such as substrate and concentration of cells, growth and inactivation, dispersion, advection and chemotaxis.

Properties of the porous media strongly affect biocolloids release, attachment, and inactivation. The initial attachment of these microorganisms to porous media is controlled by electrostatic interactions between the surfaces of the biocolloids and the grains that comprise the porous media and the solution chemistry. In this way, "biocolloids transport" is quite similar to colloid transport. (Tushar and Kartic. 2006; Molnar et al. 2019). The attachment mechanism in porous media is strongly related to biological processes (microbial

growth), where during metabolism, cells produce EPS, that forms a biofilm that reduces permeability and pore size of porous media. Moreover, the mechanical trapping or straining process occurs when the pore throats are too narrow for microorganisms to flow. The ratio between pore size and bacteria diameter is the primary determinant for straining to occur (the ratio must be higher than 1.5) (Gaol et al. 2020).

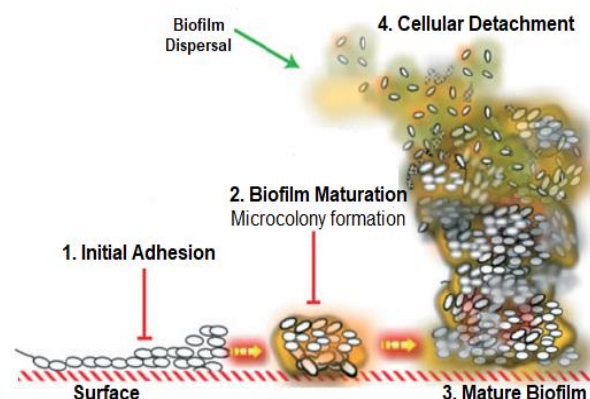


Fig. 6. Biofilm formation (Rendueles & Ghigo. 2012).

#### 5. Clogging

Two main types of mechanical ways exist to trap particles in the pore space of porous media. When particles size is equal or larger than the host particle, it will be trapped above the granular media. As a result of a continuous accumulation of particles within the media, an external (Fig. 7b) cake above the host matrix will be formed, however an internal cake (Fig. 7a) is formed when particles are small enough to pass through the porous media, and then trapped either mechanically inside the porous media or pass through it (Kerimov et al. 2018).

Particle and grain sizes play an important role in the deposition and transportation process. When the particle size is bigger than the pore during a filtration (Table 4), it will be intercepted or deposited under the gravity effect and hydrodynamic forces. Hence, the pore becomes narrower or even gets blocked, which make the subsequent particles transport more difficult through this pore, and the particles that deposit behind the blocked pore will cause the clogging (Liu et al. 2016).

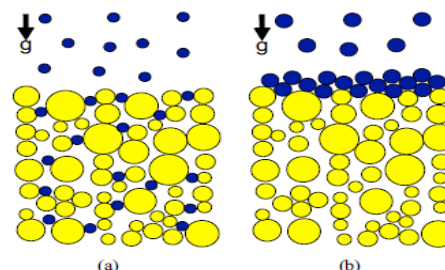
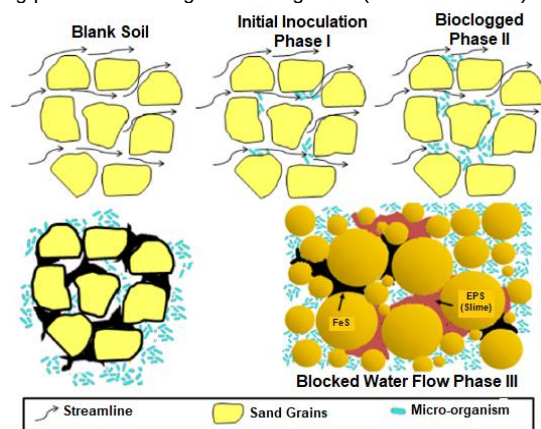


Fig. 7. Mechanical trapping mechanisms: (a) internal filter cake, (b) external filter cake (Hua et al. 2017).

During transportation organic particles deposit on the filter material and a sticky layer consisting of bacteria and other microorganisms (biofilm) is formed around the gravel, when the particles travel in water, they adhere to this organic material and are retained in the filter. The biofilm on the filter media improves the removal ability of the filter initially for all particles but become effective for small particles only with the running of the filter; the captured particles restrict the pore size and the passage through the pores allowing the collection of subsequent particles. As time passes between collisions of particles on the media surface and those in solution, the first intercepted particle migrates to the bottom of the media, which reduce the possibility for interaction with the next incoming particle (Haider. 2018). The main mechanism of biological clogging consists of biofilm formation which leads to the pores space decrease resulting in clogging. The main cause of the biological clogging is the network surrounding the microcolonies with extracellular polymers substances that adhered to material grains (Kim et al. 2010; Wang. 2015). Clogging in porous media is a complex process governed by chemical (physicochemical), physical, and

biological processes, which are related to each other in most cases. Physicochemical clogging is mainly generated by suspended particles, mineral precipitation, fine aquifer sediments, air and biogenic gases, while biological clogging is mainly due to biomass accumulation and microorganisms' growth (Fig. 8). The physicochemical process is mainly governed by rock properties such as permeability and pore size. However, these rock properties can be affected or altered by transport in porous media, physical filtration and straining processes during microbial growth (Gaol et al. 2020)



**Fig. 8.** Bioclogging process from the initial inoculation of the porous medium which does not alter the flow pattern (Phase I) to the increase in microcolonies density causing bioclogging of the pores and change of the flow pattern (Phases II and III) (Tahani et al. 2016).

**Table 4.** Models for colloids transport mechanism.

| Mechanism                              | Equation                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | References           |
|----------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------|
| Particle clogging model                | $-\frac{d_p}{dz} = K'S^2_p \mu \frac{(1-\varepsilon)^2}{\varepsilon^3} u$                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | (Richards. 2010)     |
| Colloid filtration theory              | $\frac{\partial C}{\partial t} + \nabla \cdot J = Q$                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | (Richards. 2010)     |
| Colloid transport through porous media | $\frac{\partial C}{\partial t} \phi = -\nabla \cdot (vC)\phi + \nabla \cdot (D_{disp} \nabla C)\phi - \rho_b \frac{\partial S}{\partial t}$                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | (Molnar et al. 2019) |
| Pore scale model (Navier-Stokes)       | $\rho \left( \frac{\partial v}{\partial t} + v \cdot \nabla v \right) = -\nabla p + \mu \nabla^2 v + \rho g$                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | (Wang et al. 2018)   |
| Symbol definition                      | <p> <math>C</math> = The concentration of colloids suspended in fluid<br/> <math>t</math> = Time<br/> <math>\phi</math> = The medium's porosity,<br/> <math>v</math> = The pore velocity vector,<br/> <math>D_{disp}</math> = Dispersion<br/> <math>\rho_b</math> = The bulk density of the medium,<br/> <math>S</math> = The mass of colloids retained per mass of porous medium<br/> <math>J</math> = The particle flux vector<br/> <math>Q</math> = The source<br/> <math>K'</math> = The Kozeny constant,<br/> <math>p</math> = The static pressure,<br/> <math>z</math> = Spatial co-ordinate,<br/> <math>Sp</math> = The specific surface area of the solid material,<br/> <math>\mu</math> = The fluid viscosity,<br/> <math>\varepsilon</math> = Bed porosity<br/> <math>u</math> = The superficial velocity<br/> <math>k_f</math> = The deposition rate,<br/> <math>U</math> = Darcy velocity of the water<br/> <math>dc</math> = The diameter of the collector<br/> <math>\rho</math> = The fluid density<br/> <math>g</math> = The gravitational acceleration vector         </p> |                      |

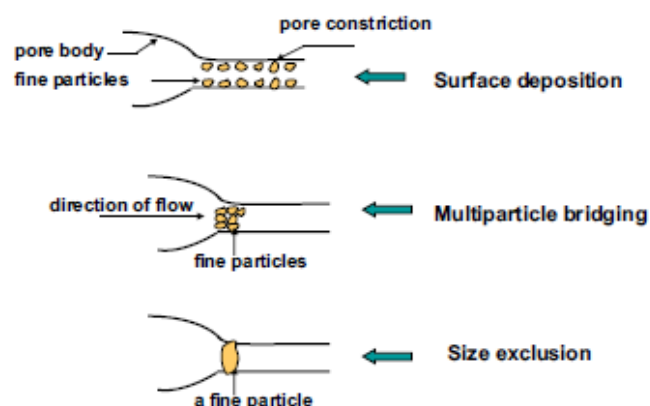
## 6. Application

Many industrial processes use porous media filters to recover valuable colloidal materials or to purify liquid streams of unwanted materials. The reduction of pore space leading to a decrease in porous media permeability, referred as clogging, can be seen as problems for some applications or as benefits for others, depending

on its objectives (Molnar et al. 2019; Gaol et al. 2020). With the understanding of clogging and biofilm development, three applications are presented to explain the interest and benefit of the topic currently being discussed. Various factors impact the clogging process which can be environmental, operational, and bacteriological; feeding water and materials characteristics and surface properties of bacterial stains. The interactions are mainly observed between the particulate or colloids matters, material surface and the microorganisms. The filter media has a great impact on the clogging development, not only on the physical process including particulates size versus pore space, but also on the adhesion of bacteria and further biofilm formation including cell surface versus sand grain surface (Wang. 2015).

### 6.1. Filtration

Solid particle retention and transport in porous media is a very complex process due to the variability of the velocity field in the pore space, the different forces acting on particles, and the complex interaction particle-surface and particle-particle. The main mechanisms for particle trapping in porous media are (Fig. 9); a) surface deposition, which occurs when the pore size is bigger than the particle size but the density of the carrying fluid is smaller than the particle density which allow to the particle to settle on pore surface due to gravity, b). Particle bridging or jamming is the formation of a 'bridge' structure at the pore throat by several particles, which occurs when the particle density is high and the particle size smaller than the pore size, c) size exclusion is when the pore size is smaller than the particle size leading to the particles capture at the pore inlets (Hongtao. 2018).



**Fig. 9.** Fine particle trapping at the pore constriction (Gavrilescu. 2014).

#### 6.1.1. Slow sand filtration (SSF)

SSF is a simple and easy-to-operate process that allows water to pass through sand media with a filtration rate of 0.1–0.3 m/h. The SSF uses physical, chemical and biological processes to purify water, as the water passes through the media, solids, microorganisms and heavy metals are removed. The biological filtration and physical process works in parallel with filtration within the same filter bed then followed by processes of adsorption, mechanical filtration and degradation (Hoslett et al. 2018; Verma et al. 2017)

Biofilm formation plays a key role in the transport of suspended particles, and it is interesting when using the slow-sand filtration technique which includes two mechanisms; mechanical filtration done by bacteria through the sand grains, and the bacteria adsorption to the biofilm layer 'Schmutzdecke'. Adsorption and mechanical trapping of suspended particles could be the mechanism for turbidity reduction. As water passes through the Schmutzdecke, particles may be trapped in the media and dissolved, and organic material is adsorbed and metabolized by microorganisms (Timoteo et al. 2013; Collin. 2009) Schmutzdecke is a biological and gelatinous layer formed on the SSF surface that provides the effective water purification. This sticky biofilm, consists of decomposing organic matter, manganese, iron and silica, metabolizes incoming bacteria and acts also as a fine filter media that contributes to turbidity removal in the raw water (Collin. 2009; Prem et al. 2018)

Excess of biofilm development and surface deposit is the biggest operational problem causing the filter clogging. Clogging is caused by finer sand particles than the pore size originates from the

hydrodynamic bridging in dead end filtration. As the particles accumulated in the sand media, the flow path became narrower which increases simultaneously the shear rate, and the shear stress. As a result, the particles that have been retained on the filter could be swept away and the flow path be widened again which leads to the particles accumulation difficult and lessen the efficiency of the filter (Verma et al. 2017; Youngseok et al. 2017). However, the presence of slight clogging generated by the accumulation of biomass and particulate matters could be favorable for the filter performance at the early stage of operation; the pore size in the upper layer is partially reduced by the retained particles and the surface coating on the grains, and the network among these retained particles and newly generated biomass benefit to achieve more uniform infiltration (Wang, 2015).

Bio-filters are employed as secondary treatment a system that receives the effluent from septic tanks and treat it through physical, chemical and biological treatment processes. Bio-filters are the modification form SSF which are extremely effective and reliable for removing biological oxygen demand, total suspended solid, Turbidity and ammonia from wastewater. Biological processes are the main mechanism of pollutants removal in bio-filters. A thin layer of microorganisms (biofilm) attaches and grows on the filter media surface, and absorbs soluble and colloidal waste materials in the wastewater as it percolates over the sand surfaces (Jamshidzadeh and Tavangari Barzi. 2019).

### 6.1.2. Granular activated carbon (GAC)

Granular activated carbon is widely used in water treatment as the fixed bed media since it is extremely porous (specific area of about 600 to 1000 m<sup>2</sup>/g) and slightly electro-positively charged, that can physically adsorb (attract) electro-negatively charged water contaminants (adsorbate), such as soluble organic matter.

Activated Carbons are made of a variety of materials such as ; nutshells, wood, coal and petroleum. Moreover, they differ in terms of characteristics such as; number of micro and macro-pores, surface area, and functional groups. In addition, the pores of the GAC are able to remove particulate matter from the source water by entrapment, and microorganisms are capable to colonize the GAC media surfaces by biosorption and proliferate into the biofilm (Simpson, 2008). GAC is considered as a good solid surface for biofilm attachment and also for biofilm protection against shear stress or toxic substances. The attachment of the microorganisms to a solid surface is governed by various types of interactions; including electrostatic forces, VanDer Waals forces, steric interactions, hydrogen bonds and hydrophobic bonding. Besides the chemical characteristics of the GAC surface, its physical structure may also affect the biofilm adhesion. The irregular surface and macroporous structure of GACs are suitable sites for bacterial attachment, giving a good protection from shear stress, while microporous GACs may not be adequate because of the small pores that do not allow the penetration of microorganisms that are larger than the pores (Dos Santos and Daniel, 2019)

In the initial stages, GAC removes organic matter through adsorption, and as the water passes through the GAC the biofilm proliferates, the bacteria and exopolymeric substances form a relatively porous structure separated by open channels and interstitial voids. Due to this porosity, some microorganisms and waterborne nutrients can pass through the biofilm of the GAC surface. If the size of the waterborne substances is too large, some of the channels within the biofilm may become completely or partially saturated. This saturation can generate problems such as an aerobic/dead zone, clogging, and detachment of bacteria from the GAC, leading to an efficiency reduction of the process which requires a cleaning and/or regeneration (Simpson. 2008; Hoslett et al. 2018)

### 6.2. Bioremediation

Bioremediation is a non-invasive and eco-friendly method commonly used to restore the contaminated sites using microorganism that are able to degrade, transform, or chelate various toxic compounds into harmless or less toxic forms (Dzionek al. 2016) Therefore, knowledge about biocolloids transport in porous media is necessary for secure disposal of wastewater and for the development of effective bioremediation strategies of contaminated soils and groundwater using microorganisms' strains (Tushar Kanti and Kartic. 2006).

Composting is a biological process which consists on treating municipal and agricultural solid wastes and sewage sludge using

microorganisms under aerobic and thermophile conditions. Composting has been applied to bioremediation of soils contaminated with chlorophenols, herbicides, pesticides, and petroleum hydrocarbons that are used in industrial activities along with the activities associated with extracting the petroleum from reservoirs and transportation process that have led them to be identified as the most widespread environmental contaminants with solvents, petroleum hydrocarbons (Dzionek et al. 2016; Partovinia and Behnam. 2018)

Bioremediation requires cell immobilization techniques that are classified in four groups on the basis of physical mechanisms (Fig. 10); adsorption or attachment on a solid surface (hydrogen bonding, gravitational forces, Van Der Waals forces, electrostatic charge, and hydrophobic interactions), entrapment and encapsulation inside a porous matrix, cell protection back of a barrier (keeping cells inside a membrane or capsule), and aggregation (flocculation, crosslinking) (Partovinia and Rasekh. 2018).

Natural biofilms may also be observed attaching to the GAC surfaces. The formation of a natural biofilm takes some time depending on the strain and support matrix. The biofilm formation is influenced by different factors such as concentration of the contaminant, hydrophilic-hydrophobic nature, efficiency of the microbial strain, electrostatic, and adhesive properties of surface, conditions during degradation, retention time, pH and temperature. The thickness of the produced biofilm depends on cell growth on surfaces of support materials that can form less than a monolayer to several layers (Partovinia and Rasekh. 2018; Silva et al. 2019).

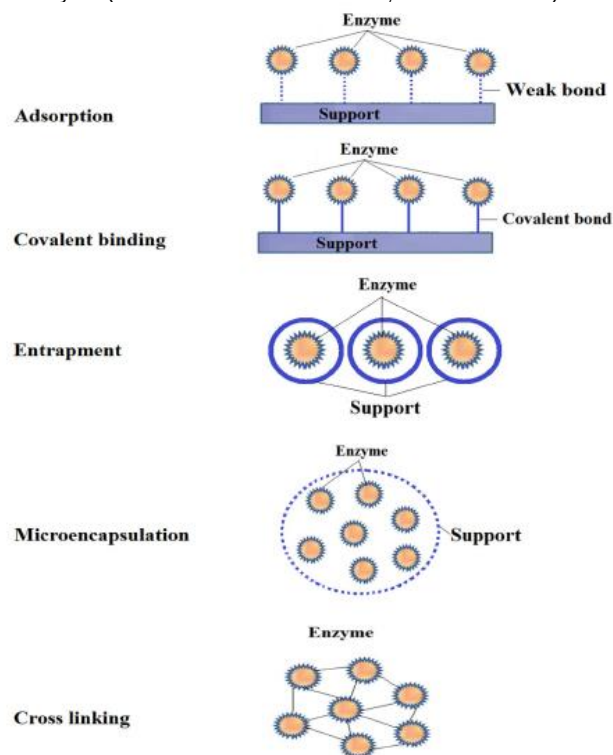


Fig. 10. Methods of immobilization (Hassan et al. 2019).

### 6.3. Biosorption

The ability of biological materials to capture heavy metals from wastewater is recognized as biosorption. Biosorption is a physiochemical process that naturally occurs in specific biomass that passively concentrates and binds the cellular structure with contaminants (Ubandoa et al. 2020). There are many ways for the contaminants to be captured by the microorganisms' cells due to their structure complexity. The cell wall is the first component that meets the pollutants, where the solutes can be deposited on the surface or within the cell-wall structure. Fungal cell have excellent adsorption properties because of their several functional groups such as hydroxyl, carboxyl, amino, sulfonate, and phosphonate (Silva et al. 2019).

Microalgae can also be used as a method for biosorption because of its high adsorption capacity of metals, cost-effectiveness, and high efficiency in dilute sewage. Another advantage in using microalgae for heavy metal removal is their ability to also remove other elements such as nitrogen, phosphorus, potassium, and enabling multiple bio-

removals (Ubandoa et al. 2020). Biosorbent process has to be regenerated after saturation which can be done by specific methods involving chemical reagents use. During repeated biosorption-desorption for five cycles, no loss in the efficiency of heavy metals removal was noted (Al-Mulla et al. 2018).

## 7. Conclusions

Investigations into colloid transport and retention in porous media have yielded indispensable information for various fields of study. The retention and migration of fine particles in porous media are very important to natural processes and engineering applications such as groundwater flow, soil erosion, and oil production, but also for environmental applications such as soil and groundwater contamination, and landfill leachate infiltration, because many environmental pollutants can attach to colloids and move in different subsurface environments. This process is referred as colloid-facilitated transport, which is one of the most important mechanisms for heavy metals mobility in soils. Other pollutants transported by colloid-facilitated transport including; organic compounds (pesticides and herbicides) from agricultural land, excess nutrients (phosphorous, nitrogen) from farmland, and biocolloids (microbes and pathogens) known to threaten public and environmental health (eutrophication, poisoning, and waterborne). Therefore, understanding colloid transport in subsurface and surface environments is essential to protect public health and aquatic ecosystems from potential contamination. The accumulation of colloids at the surface of porous media leads to the formation of the clogging layer which reduces the permeability and porosity of the media, however it can also act as a barrier to prevent the intrusion of colloids and microorganisms inflow by forming a blanket layer above the porous media named biofilm. The biofilm is composed of microorganisms that biodegrade the contaminant and plays a major role in slow sand filters for purifying water. Understanding the colloid transport, clogging and biofilm formation is the key for new methods of green route for remediation to eliminate contaminants and pollutants (heavy metals) in soil. Among those methods we cite bioremediation, biosorption, filtration and adsorption, which are based on microorganisms transport, adsorption and retention in the soil to be treated.

## Acknowledgments

We would like to thank all the co-authors for their contribution in the writing of this article and for Maxime Pontié for his proof reading.

## References

- Al-Mulla Emad Abbas J., Jabbar F.H., AL-Hamadani Rawaa Fahim C., Porous media for removal of organic and inorganic contaminants, *Nano Biomedicine and Engineering* 10 (2018) 104-116.
- Aristotle T., Ubandoa, Aaron Don M., Africab Marla C., Maniquiz-Redillas Alvin B., Culabaa Wei-Hsin C., Jo-Shu C., Microalgal biosorption of heavy metals: A comprehensive bibliometric review, *Journal of Hazardous Materials* 402 (2021) 1-15.
- Bai Hongjuan, Lassabatere Laurent, and Lamy E., Colloid transport in aggregated porous media with intra- and inter-aggregate porosities, *Industrial & Engineering Chemistry Research* (2018).
- Benmezroua B., Numerical and experimental study at the microstructural scale of the granular transport in saturated porous media, Ph. D Thesis, University of Rennes, France (2010).
- Bin G., Xinde C., Yan D., Yongming L., Lena Q.M., Colloid deposition and release in soils and their association with heavy metals, *Critical Reviews in Environmental Science and Technology* 41 (2011) 336-372.
- Bradford S.A.; Simunek J.; Bettahar M., Van Genuchten M.T.; Yates S.R., Significance of straining in colloid deposition: Evidence and implications, *Water Resources Research* 42 (2006) 1-16.
- Carre E., Microbiological quality of treated wastewater for reuse, Autre, Université de Lyon, France, (2017).
- Catalano E., Physical and numerical modeling for the micro-mechanical on saturated granular media, application to the stability of substrates, Ph. D Thesis, University of Grenoble, France (2017).
- Chao J., Stefano D.N., Monica B.E., Surface roughness impacts on granular media filtration at favorable deposition conditions: experiments and modeling, *Environmental Science & Technology* 49 (2015) 7879-7888.
- Chao L., Zijian D., Bin H. Qin-Fei K., The effect of temperature and humidity on the filtration performance of Electret Melt-Blown nonwovens, *Materials* 13 (2020) 1-12.
- Chung Jae W., Pathogen removal using saturated sand columns supplemented with hydrochar, 1<sup>st</sup> Ed., Delft, the Netherlands, (2015).
- Collin C., Biosand filtration of high turbidity water: modified filter design and safe filtrate storage, University of Sydney, Australia (2009).
- Daalach S., Study of the performance of Vortisand filters with the presence of surface scanning, Ph. D Thesis, University of Québec, Canada (2017).
- Davit Y., Multiple-scale analysis of transport phenomena in porous media with biofilms, University of Toulouse, France (2010).
- De Novio N.M., Saiers J.E., Ryan J.N., Colloid movement in unsaturated porous media, recent advances and future directions, *Vadose Zone Journal* 3 (2004) 338-351.
- Dos Santos P.R., and Daniel L.A., A review: organic matter and ammonia removal by biological activated carbon filtration for water and wastewater treatment, *International Journal of Environmental Science and Technology* 17 (2020) 591-606.
- Dzionek A., Wojcieszńska D., Guzik U., Natural carriers in bioremediation: A review, *Electronic Journal of Biotechnology* 23 (2016) 28-36.
- Foppen J.W., Van Herwerden M., Schijven J., Transport of *Escherichia coli* in saturated porous media: Dual mode deposition and intra-population heterogeneity, *Water Research* 41 (2007) 1743-1753.
- Gaol C.L., Ganzer L., Mukherjee S., Alkan H., Investigation of clogging in porous media induced by microorganisms using a microfluidics application, *Environmental Science: Water Research & Technology* 7 (2021) 441-454.
- Gavrilescu M., Colloid-mediated transport and the fate of contaminants in soils, the Role of Colloidal Systems in Environmental Protection (2014) 397-451.
- Gette-Bouvarot M., The role of biological compartment in the clogging and unclogging process in infiltration basin, Ph. D Thesis, Institute of Lyon, (2014).
- Hahn M.W., and O'Melia C.R., Deposition and reentrainment of brownian particles in porous media under unfavorable chemical conditions: some concepts and applications, *Environmental Science and Technology* 38 (2003) 210-220.
- Hahn Melinda W., and O'melia Charles R., Deposition and reentrainment of brownian particles in porous media under unfavorable chemical conditions: some concepts and applications, *Environmental Science & Technology* 38 (2004) 210-220.
- Haider R., Performance of up-flow roughing filters at high altitude for removal of particles in glacial drinking water in Mominabad Hunza, Ph. D Thesis, University of Surrey, England UK, (2018).
- Hakobyan N.A., Introduction to basics of submicron particles filtration theory, *Armenian Journal of Physics* 8 (2015) 140-151.
- Hassan M.E., Yang Q., Xiao Z., Liu L., Wang N., Cui X., Yang L., Impact of immobilization technology in industrial and pharmaceutical applications, *Biotechnology* 9 (2019) 440-456.
- Hongtao Y., Pore-scale modeling of particle filtration in porous media, Thesis, The University of Texas at Austin, (2018).
- Hoslett J., Massara T.M., Malamis S., Ahmad D., Van den Boogaert I., Katsou E., Ahmad B., Ghazal H., Simons S., Wrobel L., Jouhara H., Surface water filtration using granular media and membranes: A review, *Science of the Total Environment* 639 (2018) 1268-1282.
- Hua Z., Guansheng L., Yongbing J., Jinzhon Y., Yang L., Xin Y., Zhifeng L., and Guangming Z., Transport of bacteria in porous media and its enhancement by surfactants for bioaugmentation: A review, *Biotechnology Advances* 35 (2017) 490-504.

- Jamshidzadeh Z., Tavangari Barzi M., Substrate removal kinetics and performance assessment of recirculation sand filters for treating restaurant greywater, *Journal of Applied Research in Water and Wastewater* 6 (2019) 56-61.
- Jegatheesan V., and Vigneswaran S., Deep bed filtration: mathematical models and observations, *Critical Reviews in Environmental Science and Technology* 35 (2005) 515-569.
- Jeremy A.R., Sharon L.W., Menachem E., Bacterial adhesion and transport in porous media: role of the secondary energy minimum, *Environmental Science & Technology* 38 (2004) 1777-1785.
- Kerimov A., Mavko G., Mukerji T., Al Ibrahim M.A., Mechanical trapping of particles in granular media, *Physical Review* 97 (2018) 1-19.
- K. Mohanty K., Porous media: fluid transport and pore structure By F. A. L. Dullien, Academic Press, *AIChE Journal* 38 (1992) 1303-1304.
- Khaled A.R., and Vafai K., The role of porous media in modeling flow and heat transfer in biological tissues, *International Journal of Heat and Mass Transfer* 46 (2003) 4989 –5003.
- Kim J.W., Choi H., Pachepsky Y.A., Biofilm morphology as related to the porous media clogging, *Water Research* 44 (2010) 1193-1201.
- Larue A., Experimental methods for the study for the 3D development of biofilms in porous media, Ph. D Thesis, University of Toulouse, INP Toulouse, (2018).
- Lazouskaya V., Wang L.P., Gao H., Shi X., Czymmek K., and Jin Y., Pore-scale Investigation of colloid retention and mobilization in the presence of a moving air–water interface, *Vadose Zone Journal* 10 (2010) 1250–1260.
- Liu Q., Cui X., Zhang C., Huang S., Experimental investigation of suspended particles transport through porous media: particle and grain size effect, *Environmental Technology* 37 (2016) 854-864.
- Masson S., Study of the adsorption of emergent micropollutants on activated carbon textile, Ph. D Thesis, University of Grenoble Alpes, (2015).
- Mc Dowell-Boyer L.M, Hunt JR, Sitar N., Particle transport through porous media, *Water Resources Research* 22 (1986) 1901–1921.
- Molnar I.L., Johnson W.P., Gerhard J.I., Willson C.S., O'Carroll D.M., Predicting colloid transport through saturated porous media: A critical review, *Water Resources Research* 51 (2015) 6804–6845.
- Molnar I.L., Pensini E., Asad Md A., Mitchell C. A., Nitsche Ludwig C., Pyrak-Nolte L.J., Miño Gastón L., Krol M.M., Colloid transport in porous media: a review of classical mechanisms and emerging topics, *Transport in Porous Media* 130 (2019) 129–156.
- Papineau I., Influence of the variation of the raw water quality and the aging of the media filter on the performance of the granular filtration, Ph. D Thesis, Institute of Montreal (2013).
- Partovinia A., and Rasekh B., Review of the immobilized microbial cell systems for bioremediation of petroleum hydrocarbons polluted environments, *Critical Reviews, Environmental Science and Technology* 48 (2018) 1-38.
- Parvan A., Jafari S., Rahnama M., Norouzi Apourvari S., Raoof A., Insight into particle retention and clogging in porous media; a pore scale study using lattice Boltzmann method, *Advances in Water Resources* 138 (2020) 103530-10343.
- Prédélus D., Lassabatrere L., Paiva Coutinho A., Louis C., Brichart T., Ben Slimène E., Winiarski T., and Angulo-Jaramillo R., Tracing water flow and colloidal particles transfer in an unsaturated soil, *Journal of Water Resource and Protection* 6 (2014) 696-709.
- Prem R., and Manjeet P., Schmutzdecke- A filtration layer of slow sand filter, review article, *International Journal of Current Microbiology and Applied Sciences* 7 (2018) 637-645.
- Rendueles O., and Ghigo J-M., Multi-species biofilms: how to avoid unfriendly neighbors, *FEMS Microbiology Review* 36 (2012) 972–989.
- Reyhani Z.S., and Khoshnood Z., Study of biofilm creating bacteria in drinking water of Ahvaz city in Iran, *Journal of Applied Research in Water and Wastewater* 7 (2020) 163-166.
- Richards T., Particle clogging in porous media Filtration of a smectite solution, Ph. D Thesis, Chalmers University of Technology, Sweden, (2010).
- Silva A., Delerue-Matos C., Figueire do Sónia A., Freitas O.M., The use of algae and fungi for removal of pharmaceuticals by bioremediation and biosorption processes: A review. *Water* 11 (2019) 1555-1591.
- Simpson D.R., Review, biofilm processes in biologically active carbon water purification, *Water research* 42 (2008) 2839 – 2848.
- Tahani F., Souli H., Fleureau J.M., Kermouche G., Fry J.J., Girar B., Aelbrecht D., Lambert J., and Harkes M., Durability of bioclogging treatment of soils, *Geotechnical and Geoenvironmental Journal* 142 (2016) 1-11.
- Tahar A., Amelioration of the elimination of organic micropollutants from wastewater by secondary and tertiary, Doctoral thesis. University of Montpellier I, France, (2013).
- Timoteo B.B., Anthony L.A., and Enguito M.R.C., Efficiency of slow sand filter in purifying well, *Water Journal of Multidisciplinary Studies* 2 (2013) 86-102.
- Torkzaban S., Hassanizadeh S.M., Schijven J.F., Van den Berg H.H.J.L., Role of air-water interfaces on retention of viruses under unsaturated conditions, *Water Resources Research* 44 (2006) 1-11.
- Torkzaban S., Kim H.N., Simunek J., Bradford S.A., Hysteresis of colloid retention and release in saturated porous media during transients in solution chemistry, *Environmental Science & Technology* 44 (2010) 1662-1669.
- Tovey S., Transport and accumulation of bacteria in porous media, Handout, Seminar, Institute for Computational Physics, (2019) 1-14.
- Tufenkji N., and Elimelech M., Deviation from the classical colloid filtration theory in the presence of repulsive DLVO interactions, *Langmuir* 20 (2004) 10818-10828.
- Tufenkji N., and Elimelech M., Spatial distributions of *Cryptosporidium* oocysts in porous media: evidence for dual mode deposition, *Environmental Science and Technology* 39 (2005) 3620-3629.
- Tufenkji N., Modeling microbial transport in porous media: traditional approaches and recent developments, *Advances in Water Resources* 30 (2007) 1455-1469.
- Tushar Kanti S., and Kartic C.K., Review on subsurface colloids and colloid-associated contaminant transport in saturated porous media, *Advances in Colloid and Interface Science* 119 (2006) 71- 96.
- Ubandoa A.T., Africab A.D.M., Maniquiz-Redillas M.C., Culaba A.B., Chen W-H., Chang J.S., Microalgal biosorption of heavy metals: A comprehensive bibliometric review, *Journal of Hazardous Materials* 402 (2021) 1-11.
- Verma S., Daverey A., Sharma A., Slow sand filtration for water and wastewater treatment—a review, *Environmental Technology Reviews* 6 (2017) 47-58.
- Wang C., Comparative study of materials in the filtration reactors for the non collective sewage system, Ph. D Thesis, University of Limoges, France (2015).
- Wang C., Wang R., Huo Z., Xie E., Dahlke H.E., Colloid transport through soil and other porous media under transient flow conditions-A review, *WIREs Water* 7 (2020) 1-33.
- Wollesen de Jonge L., Kjaergaard C., Moldrup P., Colloids and colloid-facilitated transport of contaminants in soils: An introduction, *Vadose Zone Journal* 3 (2004) 321-325.
- Youngseok K., Kyung Hyun A., Seung Jong L., Clogging mechanism of poly(styrene) particles in the flow through a single micro-pore, *Journal of Membrane Science* 534 (2017) 25-32.