Clogging in subsurface wastewater infiltration beds: genesis, influencing factors, identification methods and remediation strategies

Ying-hua Li, Lin-lin Peng, Hai-bo Li and De-ze Liu

ABSTRACT

Subsurface wastewater infiltration (SWI) is an environmentally friendly technology for the advanced treatment of domestic sewage. Clogging (including physical, chemical and biological clogging) of the porous medium not only directly reduces the hydraulic load (treatment efficiency), but also reduces the service life. Although clogging has become one of the key issues discussed in several reports, there are still several gaps in understanding, especially in its occurrence process and identification. SWI clogging causes, development process and solutions are different from those of constructed wetlands. This article quotes some reports on constructed wetlands to provide technical ideas and reference for revealing SWI clogging problems. Based on the analysis of the clogging genesis, this review gathers the main factors that affect the degree of clogging, and new methods for the identification of clogging conditions. Some preventive and unclogging measures/strategies are presented. Finally, it is suggested that to effectively alleviate the clogging phenomenon and extend the service life, priority should be given to the comprehensive analysis of wastewater quality and solid constituents accumulated in the pores. Then, the effectiveness of in-situ strategies, such as alternating operation will be the main focuses of future research.

Key words | clogging, genesis, influencing factors, remediation, subsurface wastewater infiltration

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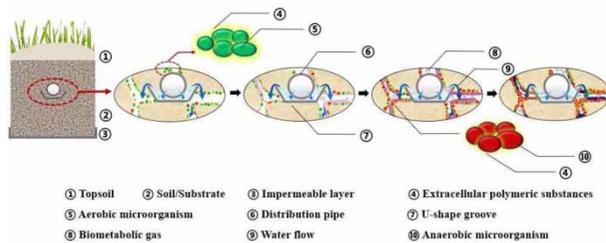China
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HIGHLIGHTS

- Up to dated methods for the identification of clogging conditions were compared.
- Main factors that affect the probability and degree of clogging were gathered.
- Different preventive and unclogging measures/strategies were compared.
- Priority unclogging measurements are proposed.

GRAPHICAL ABSTRACT

① Topsoil   ② Soil/Substrate   ③ Impermeable layer   ④ Extracellular polymeric substances
⑤ Aerobic microorganism   ⑥ Distribution pipe   ⑦ U-shape groove
⑧ Biometabolic gas   ⑨ Water flow   ⑩ Anaerobic microorganism

SUBSURFACE WASTEWATER INFILTRATION

Subsurface wastewater infiltration (SWI) technology is an improved process of soil capillary infiltration trench, as shown in Figure 1 (Li et al. 2011; Lopez-Peña et al. 2019). The medium is specially configured, thus the pollutants are filtered, adsorbed and degraded, and the effluent can be recovered and recycled. According to the effluent reuse situation and water quality requirements, SWI can be flexibly matched with a variety of pre-treatment processes, highlighting their great efficiency in pollutants removal, low operation cost and simple management. Since its development in the 1960s, SWI has been increasingly applied throughout the world in treating wastewater (Tang et al. 2018; Xia et al. 2020).

The medium is expected to have a strong biological respiration capacity, so the service life of SWI is estimated to be 50 to 70 years (Li et al. 2011). However, large amounts of long-term observation data indicate that the main problem resulting in the malfunction of SWI is clogging. Despite specific recommendations for design and operation described in the scientific literature, clogging will still inevitably occur. Clogging can directly reduce the hydraulic load (treatment efficiency) of the percolation process. Also, clogging leads to an uneven distribution of the wastewater, followed by the exclusion of filter zone, surface ponding and overflow (Vymazal 2018). Siegrist (1987) reported that clogging is related to the composition of organic matter and loading rates. Subsequently, scholars have conducted a large number of beneficial explorations, revealing the clogging problem of the SWI systems. Most conclusions pointed out that the particulate matter and the biofilm formed in the matrix layer are the root causes of clogging. Whether from the perspective of biological metabolism-mass transfer or Darcy's law, this view has been widely accepted. However, with research progress, some different academic views began to emerge. As a consequence, genesis, influencing factors and identification methods regarding the clogging phenomena are still a matter of controversy. The understanding of development of clogging is shown in Table 1. Some scholars believe that the problem of clogging will still be the focus of SWI technology research for a long time (Tatoulis et al. 2017; Tang et al. 2018; Pucher & Langergraber 2019). Although there have been reviews on clogging (Alem et al. 2015; Berlin et al. 2015; Chu et al. 2019), with the continuous deepening of research, the understanding of clogging genesis has evolved from physical and biological clogging to gas clogging. In recent years, the clogging theory of SWI has been continuously improved. Starting from the internal principles, this review comprehensively reveals the causes of SWI clogging and the main factors. On this basis, new identification methods of matrix clogging in recent years are summarized, and new findings regarding the prevention and remediation techniques/strategies are also put forward. Finally, new feasible suggestions are provided for the alleviation of clogging in the operational phase, providing reference for future research and practical operation of SWI technology.

CLOGGING GENESIS

Physical retention

Early research has mainly focused on the physical clogging process and its mechanism, claiming that physical retention is the main cause of clogging in the matrix layer, mainly including: (1) clogging of suspended solids (SS), as seen in Figure 2; (2) clogging of dissolved organic fraction; and (3) clogging of broken matrix aggregate (Lei & Zhu 2013; Du et al. 2014; Lancheros et al. 2017). Several studies, including Lancheros et al. (2017), Matos et al. (2017b) and Matos et al.
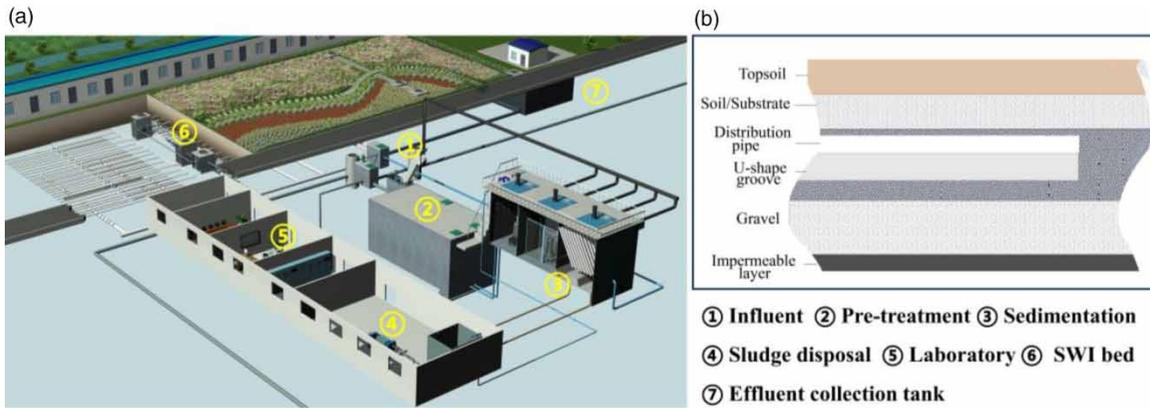
Figure 1 | Schematic diagram of SWI (a. Wastewater treatment process; b. Profile of the bed).

Table 1 | The understanding of development of clogging in the SWI beds

| Stage	Period	Representative views and references
I	1960–1980	• As long as the influent load is well controlled, nitrogen and phosphorus can be fully utilized through soil respiration (Lan *et al.* 2015). • The physio-chemical properties of the soil will not be significantly affected (Garcia-Fernandez *et al.* 2016). • The system can operate stably for a long time (Meireles *et al.* 2016).
II	1980–2000	• The porous characteristics and vertical structure of the infiltration bed are the keys to maintain the flow condition (Siegrist 1987; Ye *et al.* 2015; Hua *et al.* 2017). • Clogging of porous media is mainly resulted from the suspended solids and high hydraulic loads (Panán *et al.* 2016; Ye *et al.* 2018).
III	2000–2010	• The micro-environmental zoning in the matrix creates different types of microbial populations and restricts them to maintain metabolic and physiological activity within a given layer (Ding *et al.* 2018). • The sewage is infiltrated driven by capillary force and gravity (Dua *et al.* 2018). • Biofilm growth and extracellular polymer aggregation are the main features of biological clogging (Xia *et al.* 2020).
IV	2010 to present	• Clogging may have multiple inducing factors other than the physical and biological clogging (Coulon *et al.* 2015; Reid *et al.* 2015). • The adaptability of the system is quantitatively related to the operation conditions (Wu *et al.* 2015; Li *et al.* 2018). • Without clogging, SWI is a good natural bio-reactor (Perujo *et al.* 2018; Zhou *et al.* 2018).
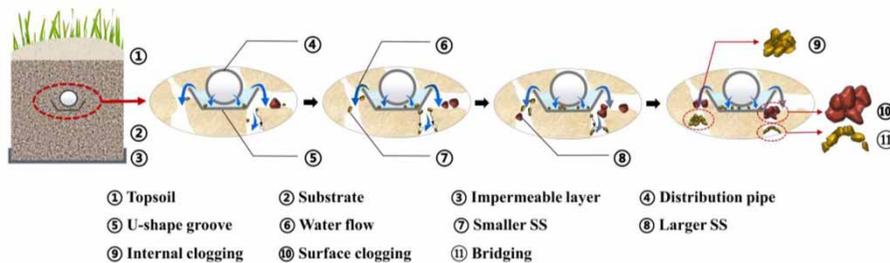
Figure 2 | Diagram of physical clogging caused by the suspended solids.

(2019) concluded that the higher the SS load applied, the faster the clogging phenomenon. From the perspective of particle size, physical clogging caused by suspended solids is divided into (1) surface clogging, (2) internal clogging, and (3) bridging. Surface clogging means that SS with a larger particle size cannot enter the pores of the matrix, collides with the matrix, and is isolated from the surface (Borris et al. 2016). Internal clogging means that the SS with a smaller particle size moves and are trapped within the smaller pores. The migration and accumulation of smaller SS narrow the pores and reduces the soil permeability coefficient. Bridging is mainly driven by high flow velocities, occurring when several particles smaller than the pore size arrive simultaneously and together block the pore. There are many factors influencing the process of SS clogging. Once the size of the SS particles is much larger than the pores, surface clogging will occur quickly. Otherwise, with the migration and accumulation of smaller-sized particles, internal clogging and bridging may gradually dominant (Alem et al. 2015; Xu et al. 2016; Boano et al. 2018; Du et al. 2018; Ferrer-Polonio et al. 2018).

Some researchers, however, hold an opposite view. Research by Zhou et al. showed that even when the influent SS reached 80 mg/L, no blockage occurred (Zhou et al. 2018). In their experiment, suspended solids were simply stacked together without microbial activity, leaving tiny gaps between the particles that maintained the permeability of wastewater. Conversely, it was observed that even if the pore dimensions were much larger than those of the suspended solids, clogging still occurred (Miranda et al. 2017).

The results obtained by Miranda et al. (2017) indicated that not only suspended solids, but also dissolved ones, contributed to physical clogging, as wastewater is always a complex mixture of different types of organic matter (Hübner et al. 2013; Matos et al. 2019). Clogging is possibly a complex phenomenon affected by different types of

solids, as suggested by Kadlec & Wallace (2009). Nguyen (2000) attributed the greater decrease in permeability to the accumulation of active organic matter, which accounted for about 30% of the total organic matter. Subsequently, Vymazal (2018) observed that of the clog-forming matters, over 63% was composed of humic, humic acid and fulvic acid fractions. While Tatoulis and Meng attributed this phenomenon to the low soil aggregate stability in the matrix layer, the particles swell and disintegrate with water to become fine clay particles, forming a dense impermeable layer that leads to physical clogging. Consequently, fragmentation of the aggregate structure may be one of the causes of clogging (Meng et al. 2017; Tatoulis et al. 2017).

Biological clogging

The biofilm clogging mechanism includes the cumulative effects of cells, extracellular polymers, and sedimentation mediated by microorganisms. Compared with SS, dissolved and hydrolyzed organics contribute indirectly to clogging. As concluded by Zhao et al. (2009), bio-clogging contributes to a more long-term effect, while SS will result in a faster clogging of the small pores. In addition, biofilm formation may lead to an increased SS retention time in the pores.

Based on biological growth and changes in hydraulic parameters, clogging caused by biological action can be divided into four stages, as shown in Figure 3 (McKinley & Siegrist 2010; Kanmani et al. 2014; Mostafa & van Geel 2015; Shi et al. 2017; Saffari et al. 2019): In the first stage, the intake of oxygen and other supplies are sufficient, which provides rich nutrients for the growth and reproduction of microorganisms, and aerobic microorganisms accumulate quickly (Barreto et al. 2015); In the second stage, the number of aerobic microorganisms in the matrix layer gradually decreases. With the consumption of
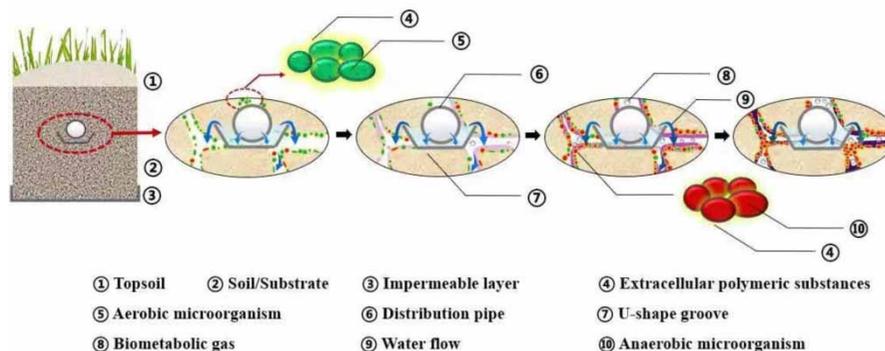

Figure 3 | Diagram of bio-clogging process in SWI beds.

nutrients and oxygen, anaerobic microorganisms grow rapidly and biological clogging occurs in partial zones (Aiello *et al.* 2016). In the third stage, biological cells continue to accumulate, and colonies and microbial metabolites (such as polysaccharides, lipids, and proteins) combine to form biofilms that block the pores of the matrix. As a result, the porosity decreases significantly, and the permeability coefficient decreases rapidly (Baptestini *et al.* 2017; Carballeira *et al.* 2017); In the fourth stage, the phenomenon of biofilm clogging is significant (Carballeira *et al.* 2017; Matos *et al.* 2017a).

Bio-clogging will be enhanced if the influent is of high nutrient loading (Sivasankar & Kumar 2019). The effect of temperature on bio-clogging still remains controversial. Most scholars believe that, as the temperature increases, the enzymatic activity and the degradation of organic matter will increase, which will lead to more serous biological clogging (Zhao *et al.* 2009; Rubol *et al.* 2014; Huang *et al.* 2017; Perujo *et al.* 2018). However, researchers believe that, unlike SS clogging, the impact of bio-clogging on the malfunction will be highlighted after long-term operation, and can be alleviated by in-situ remediation methods such as alternating operation (Carballeira *et al.* 2017; Ding *et al.* 2018; Dua *et al.* 2018). Xia *et al.* (2020) found that the volume of microorganisms in the aeration zone was less than 2‰ of the matrix pores, so biofilm development and extracellular polymer should not be the leading causes of clogging.

Mekala & Nambi (2016) studied the bio-clogging of porous media and its effect on the transportation of ammonia nitrogen and nitrate. They found that biofilm growth reached equilibrium conditions in about 12 days, and the permeability coefficient dropped to 1/5 of the original value. Consequently, the residence time of the pollutants increased, hindering the transportation of ammonium nitrogen and nitrate.

Chemical precipitation

Slag has a larger specific surface area and more active sites, which can significantly improve the removal efficiency of phosphorus. Therefore, a certain amount of slag is usually mixed with soil as the SWI matrix. However, slag usually contains oxides such as MgO, CaO and FeO. During long-term contact with sewage, precipitations such as $CaCO_3$ and $MgCO_3$ will be formed, which will cause clogging of the SWI matrix (Lan *et al.* 2015; Panán *et al.* 2016; Liu *et al.* 2018a, 2018b; Zhou *et al.* 2018; Chu *et al.* 2019). The

precipitates accumulate in the matrix pores and contribute considerably to pore obstruction.

Taking $CaCO_3$ as an example, since H_2CO_3 is prone to secondary hydrolysis (Zhou *et al.* 2018), the hydrolysis product CO_3^{2-} reacts with Ca^{2+} to produce $CaCO_3$ precipitation, as shown in Equations (1)–(3). The solubility of CO_2 is affected by ambient temperature and pressure. Low temperature and high pressure will increase the concentration of CO_2 in the water, which is not conducive to the hydrolysis of H_2CO_3, and the reduction of CO_3^{2-} concentration is beneficial to the precipitation of $CaCO_3$. High temperature and low pressure will promote the formation of $CaCO_3$ precipitation, which is beneficial to clogging (Liu *et al.* 2018a, 2018b; Zhou *et al.* 2018). When the pH is 7–9, OH^- is proportional to the formation of precipitates. In contrast, a too high or too low pH is beneficial to the dissolution of $CaCO_3$ precipitation. Therefore, although the addition of substrates such as slag can improve the phosphorus removal due to the formation of precipitates, it can contribute to rapid pore obstruction and form a retention nucleus of other solids, speeding up the clogging process.

In addition, iron hydroxides and oxyhydroxides can also cause chemical precipitation (Chu *et al.* 2019). Iron often presents in the reduced state (Fe^{2+}). With an increase in pH, Fe^{2+} can be converted to relatively insoluble Fe^{3+} or $FeOOH$ (Garcia-Fernandez *et al.* 2016; Xu *et al.* 2016; Du *et al.* 2018), as shown in Equations (4) and (5):

$$H_2CO_3 \Leftrightarrow H^+ + HCO_3^- \tag{1}$$

$$HCO_3^- \Leftrightarrow H^+ + CO_3^{2-} \tag{2}$$

$$CO_3^{2-} + Ca^{2+} \Leftrightarrow CaCO_3 \tag{3}$$

$$4Fe^{2+} + O_2 + 10H_2O = 4Fe(OH)_3 \downarrow + 8H^+ \tag{4}$$

$$4Fe^{2+} + 6H_2O + O_2 \rightarrow 4FeOOH \downarrow + 8H^+ \tag{5}$$

Gas accumulation

In order to fully reveal the clogging genesis of the SWI systems, in the past five years researchers have comprehensively explored the multi-interface process of clogging, and put forward new views. An interesting point to be mentioned is the result obtained in the work of Du *et al.* (2016), in which it was verified that temperature affected the degree of clogging in the percolation system. The higher the temperature, the lower the risk of clogging. The mechanism can be explained as follows: the surface tension

of water in the fine pores decreases as the temperature rises, accelerating the flow rate, which is helpful for stripping loose metabolic gases on the inner walls of the pores, and unclogging the pores that are blocked due to the retention of biological metabolic gases (Du et al. 2016; Zhao et al. 2017). This conclusion is quite different from the classical theory, that is clogging of particulate matter and biofilm is not the only and dominant cause of the clogging, and the metabolic gas produced by the biological processes is another important factor. This view is consistent with the research conclusion Pagán obtained earlier when he studied the clogging mechanism of the percolation layer. Physical clogging is only a short-term process, biofilm clogging is a non-dominant process, and the retention of biological metabolic gas may cause serious clogging (Panán et al. 2016; Matos et al. 2017b).

The narrowly connected channels between soil pores are called 'pore throats'. Once the air bubbles are trapped in the center of the 'pore throat', it will limit the water flux and increase the pathway of the water flow, thereby reducing the soil permeability and causing gas blockage (Petitjean et al. 2016; Matos et al. 2019; Wang et al. 2019; Li et al. 2020). The process may be as follows (Berlin et al. 2015; Ye et al. 2015; Mekala & Nambi 2016): First, some bubbles are less mobile under the action of buoyancy and water flow, and are adsorbed on the surface of substrate or suspended in the narrow space of pores. If the bubble diameter is smaller than the 'pore throat', the bubble volume can be described by Henry's law and ideal gas law. Then, the bubbles gradually grow and accumulate, hindering the direction of water flow and the movement of the bubbles. When the bubble diameter is close to or equal to the 'pore throat', gas clogging occurs. Under normal circumstances, the gas pressure is usually equivalent to the load pressure. But when the gas increases significantly, and in a relatively closed environment deep in the matrix layer, the gas pressure is greater than the load pressure, that is, an 'over-pressure zone' is formed. 'Overpressure zone' will further capture other gases, exacerbating gas clogging.

According to the theory of porous media seepage mechanics (McKinley & Siegrist 2010; Lopez-Peña et al. 2019), SWI is a typical fluid-solid coupling system. The capillary channels of the matrix are extremely developed. The tiny bubbles attached to the inner walls of the capillary channels will easily clog the void holes. The adhesion of air bubbles is greater than the shear force of the fluid in the percolation zone, so the holes clogging is basically irreversible. Under stable operation modes, microbial metabolism produces large amounts of gases, such as CO_2, CH_4 and N_2O, which may be attached or wrapped by extracellular polymers. If it cannot be released in time, the water flow will be hindered. As a result, the permeability coefficient decreased, so that the so-called 'air solidification' phenomenon occurs, causing the matrix layer to clog.

INFLUENCING FACTORS ASSOCIATED WITH CLOGGING

Characteristics of SS

SS with larger particle size can easily cause surface clogging, while a smaller SS can result in internal clogging. Du et al. (2018) used the ratio of effective medium pore size (D_p)/ median particle size (d_{50}) as the indicator of SS clogging type. When D_p/d_{50} (termed as D) is <5.5, surface clogging easily occurs, while internal clogging easily occurs when D > 180. The study of Lei & Zhu (2013) suggested that, when $D_p = 408\,\mu m$, even at the same position of the matrix layer, the greater the d_{50}, the lower the probability of SS clogging. That is, the amount of SS deposition of $d_{50} = 12.96\,\mu m$ is greater than that of $d_{50} = 22.81\,\mu m$, while the trend of $D_p = 659\,\mu m$ is totally opposite, which shows that the particle size distribution greatly affects the SS clogging status. When d_{50} is $12\,\mu m$, the amount of SS deposited inside the matrix is much larger than those on the surface. But when the d_{50} increased to $23\,\mu m$, the amount of SS deposited on the surface is larger than that inside the matrix. Alem et al. (2015) found that most of the particles with $d_{50} > 24\,\mu m$ should be removed before entering the porous medium. The study by Samsó et al. (2016) showed that the migration of particles with a particle size of less than $6\,\mu m$ is the main reason for the reduced permeability.

Generally speaking, the higher the SS concentration, the faster the clogging occurs. According to the theory of suspended solids accumulation, insoluble particles with $d_{50} > 50\,\mu m$ are the inducing factors of physical clogging. When SS concentration reaches $20\,mg/L$, clogging occurs more quickly and concentrates on the upper layer. The research by Matos et al. (2019) shows that for secondary effluent, particle concentration > $10\,mg/L$ will cause serious clogging. The experiment of Ferrer-Polonio et al. (2018) showed that under the conditions of SS 50, 100 and $200\,mg/L$, the permeability coefficients decreased to 38, 20 and 10% of their initial values, respectively. According to Du et al. (2018), when the SS concentration is less than $500\,mg/L$, the physical clogging rate is proportional to the SS concentration. But there exists a limit threshold of SS concentration for

physical clogging. For example, when the SS concentration is 1,000 mg/L, the physical clogging rate is less than that of 500 mg/L. Wang *et al.* (2020) used surface water and rainwater to recharge the aqueous medium, the physical clogging process of the aqueous medium was studied. The results suggested that the SS should be controlled within 25 mg/L. Garcia-Fernandez *et al.* (2016) studied the permeability of cohesive soil and gravel media using secondary sewage as the source of recharge. When the SS concentration was less than 10 mg/L, the medium permeability was conductive to the infiltration of sewage. Meireles *et al.* (2016) believed that only when the SS was less than 2 mg/L can physical clogging be effectively avoided.

Loading rate and operation mode

In severe bio-clogging scenarios, overland flow may be found, reducing overall treatment performance. Some studies (Kadlec & Wallace 2009) recommend chemical oxygen demand (COD) load < 25 g/m^2·d to avoid clogging in routine operation of SWI beds. The hydraulic loading rate affects the time needed for diffusive fluxes infiltrating through the matrix bed. The greater the hydraulic load, the higher the initial infiltrate rate and the more serious clogging. Alem *et al.* (2015) studied the effect of infiltration rate on the physical clogging of porous media. When the infiltration rate was low, large particulate matter is easy to deposit and form surface clogging; the higher the infiltration rate, the stronger the particle mobility within the bed and the easy formation of internal clogging. The results of Xu *et al.* (2016) also showed that the permeability coefficient decreased with an increase in the hydraulic load. When obvious clogging occurred, the average permeability coefficient decreased by 50–70% from the initial value. The study by Du *et al.* (2014) on the retention behavior of colloidal particles in saturated porous media showed that as the seepage velocity increases, clogging resulted from the colloidal particles would be alleviated. The same author attributed this phenomenon to the effect of hydraulic shear. But the results were contrary to the conclusion obtained by Nguyen (2000). According to them, the biofilm developed a gelatinous structure of extracellular polymers which was resistant to shear. The reasons for the controversy may be as follows. (1) The effect of hydraulic shear on the pore clogging caused by particulate matter is different from biofilm. (2) The appropriate load helps to destruct the colloidal structure of the biofilm, thereby alleviating the biological clogging due to the accumulation of extracellular polymers. (3) The influence of hydraulic load on physical clogging also needs to be combined with water quality for comprehensive analysis, such as SS concentration and particle size.

In addition to hydraulic load, intermittent operation mode affected the beginning of biological clogging. Intermittent operation can improve the reoxygenation of the matrix layer, thereby restoring aerobic conditions and accelerate the mineralization of clogging substances. Moreover, there would be the possibility that the 'trapped' gases in the pores, such as CH$_4$, CO$_2$ and H$_2$S, could be 'untrapped' and encourage the permeability of water (Miranda *et al.* 2016; Zhou *et al.* 2018; Li *et al.* 2020).

Matrix

The matrix configuration, particle size and porosity have an important effect on clogging caused by cell accumulation and extracellular polymer accumulation. Lan *et al.* (2015) found that when the bacterial cell volume (BCV) was lower than 0.4×10^6 CFU/g, the permeability coefficient was not greatly affected, but would reduce to the 1/100 of the original value when the BCV was higher than 1.3×10^6 CFU/g. Corroborating the same conclusions, Xia *et al.* (2016) found that within the first 144 hours, BCV increased from 6.19 logCFU/g to 8.91 logCFU/g, while the permeating coefficient decreased by 75.3%, indicating that the early biological clogging may be caused by the accumulation of bacterial cells; subsequently, although BCV continued to increase, the permeability coefficient declined less, indicating that the later biological clogging may be caused by other factors.

The composition of extracellular polymers is similar to that of microorganisms, and consists of polysaccharides, proteins, nucleic acids, and so on (Xu *et al.* 2017). Due to the high hydrophilicity, the extracellular polymer has a water content as high as 99%, which can affect the permeability coefficient by increasing the fluid viscosity or reducing the pore volume. Ye *et al.* (2018) believed that the decrease in permeability coefficient was largely related to the increase in polysaccharides. In comparison, Hua *et al.* (2017) suggested that the increase in polysaccharides will increase the permeability coefficient. Therefore, it was suggested to take the matrix configuration into consideration when considered biological clogging. In addition, the accumulation of microorganism-mediated precipitation, such as FeS, ZnS, and FeCO$_3$ produced by sulfur bacteria or iron bacteria cannot be ignored (Wang *et al.* 2020).

Gas

Compared with the saturated zone, the dissolved air in the unsaturated zone is easier to separate from the water into the pores of the bed, thereby hindering the water flow. Usually, a tracer experiment is used to study the migration and transportation of the air carried by the water. Adding distributive tracer (oxygen) and non-dispensable tracer (chloride or bromide) into the SWI beds, the distributed tracer will enter the gas phase from the liquid phase, and the non-distributed tracer will remain in the liquid phase, so the transport speed of the distributed tracer is lower than that of the non-distributed tracer, and the time required to reach the same position is longer, this delay effect is usually expressed by the hysteresis factor R. The study by Ye *et al.* (2015) revealed that the range of R is 1–8. They verified that the higher R, the more pores in the porous medium would be occupied by gas. A special gas-phase distribution tracer experiment is called 'push–pull'. In this experiment, a distribution type tracer and a non-distribution type tracer are injected into a porous medium (termed as 'push'). Tracer samples are then collected (termed as 'pull') (Reid *et al.* 2015), and the 'push–pull' experiment describes the process of the air carried by the influent blocks the medium pores. Perujo *et al.* (2019) conducted the 'push–pull' experiment and calculated the porous space occupied by the gas, and the results recommended that the gas carried by water occupied 7% to 26% of the pore space.

The dissolved organic matters contribute to pore obstruction via their microbial degradation, with the generation of gases. Once the gases are trapped between the solids, they promote a reduction in the porosity. In this context, the contribution of biological metabolic gas to the blockage cannot be underestimated. Authors such as Pan *et al.* (2016), Li *et al.* (2018), Zhang *et al.* (2018), Li *et al.* (2019), Wang *et al.* (2019) and Li *et al.* (2020) utilized static chambers, stratified gas sampling, stable isotope tracing and other methods to discover the contribution of gases on clogging. These studies acquainted us with the varying contributions of different gases. Moreover, Li *et al.* (2018) suggested that with the extension of the running time and the increase of loading rate, the middle and lower layers of SWI bed are the key zones prone to gas clogging.

NEW METHOD FOR IDENTIFICATION OF CLOGGING

To minimize the clogging in SWI beds, it is important to identify the degree of obstruction in the porous medium.

Unfortunately, since the SWI beds are constructed underground and there are complex factors affecting the clogging, there is still no consensus on which method could best describe the degree of clogging. If no effective identification method is adopted, once the surface flow is found, it means that the bed is already in a critical clogging condition, reducing the opportunities of remediation. So to detect early clogging, Berlin *et al.* (2015) and Zhou *et al.* (2018) suggested to examine the concentration ratio of ammonia nitrogen/nitrate. The decrease in the ratio indicates to some extent that the transportation of sewage is hindered under the effect of clogging.

Permeability coefficient

Based on the porous media seepage equation, the sewage infiltration process is generalized into a one-dimensional flow motion form:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial H}{\partial x}\right) = \mu \frac{\partial H}{\partial t} \tag{6}$$

in which, μ is the water storage rate; and K_x is the permeability coefficient in the X direction. Due to the different degree of clogging in different positions, the theoretical value of the equivalent permeability coefficient can be analyzed to compare the measured values to reflect the degree of clogging. The equivalent permeability coefficient of each zone is expressed in Equation (7) (Liu *et al.* 2018a, 2018b; Chu *et al.* 2019; Wang *et al.* 2020):

$$K_e = \sum_{i=1}^{n} M_i / \sum_{i=1}^{n} \frac{M_i}{K_i} \tag{7}$$

in which, M_i is the matrix thickness of the i-th layer, m; K_i is the infiltration coefficient of the i-th layer, m/s. The relationship between porous permeability and porosity can be expressed by the Kozeny–Carmen equation, as shown in Equation (8) (Liu *et al.* 2018a, 2018b; Chu *et al.* 2019):

$$K_i = K_0 \frac{n^3}{(1-n)^2} \frac{(1-n_0)^2}{n_0^3} \tag{8}$$

in which, K_0 is the initial permeability coefficient, m/s; n is the porosity of the matrix, %; n_0 is the initial porosity of the matrix, %.

Tracer experiment

The change of water flow caused by porous clogging can be obtained by the tracer experiment. In the experiment, the penetration curve is obtained by filling the influent with a distributive tracer and a non-distributable tracer (Wang *et al.* 2019). Compared with the non-distributive tracer, the transport process of the distributive tracer has a delay phenomenon, which can be expressed by the hysteresis factor *R*. The CXTFIT software can be used to simulate the tracer penetration curve to obtain the *R*, and then calculate the gas content in the pores, that is the amount of gas that will block the medium pores, termed as 'pore throat'. The hysteresis factor *R* can be calculated using the following equation (Perujo *et al.* 2019):

$$R = 1 + H' \frac{V_g}{V_w} \tag{9}$$

in which, *H'* is the Henry's law constant; V_g is the gas volume in pore space; V_W is the liquid volume in pore space. Using the *R* obtained in CXTFIT and the dimensionless Henry's law constant of oxygen, the proportion of gas occupied in the pore space (θ_g) can be calculated using Equation (10):

$$\theta_g = \frac{\dfrac{V_g}{V_w}}{1 + \dfrac{V_g}{V_w}} \tag{10}$$

In 2019, Wang *et al.* (2019) used DO and KBr's migration curve model to simulate the process of SWI clogging caused by the air carried by water. The results showed that the immobile water occupancy had a great influence on solute transport, and the air quality carried by the water had no significant effect on gas clogging. In addition, about 2% to 20% of the pore space in the middle of the SWI bed was occupied by gas, indicating that the air carried by the water mainly affected the permeability of the middle zone, where gas clogging was most likely to occur. In addition to the air carried by water, the metabolic gas generated during the biological treatment process was also likely to block the capillaries. Wang *et al.* (2019) and Li *et al.* (2020) used 99% abundance of potassium nitrate ($K^{15}NO_3$) instead of unmarked KNO_3 to prepare wastewater and sampled at different profiles of the soil bed to analyze CH_4, N_2O, CO_2 and N_2.

Numerical simulation

The mathematical model can predict the zone, time and simulate the process of porous clogging. According to the clogging genesis, numerical models can be divided into three categories, one is based on the model of physical interception, one is based on model of biofilm growth, and the last one is a model containing multiple processes such as chemical precipitation and gas blockage (Berlin *et al.* 2015; Liu *et al.* 2018a, 2018b; Chu *et al.* 2019). In the first model, the relationship between medium porosity and SS concentration can be expressed by Equation (11) (Liu *et al.* 2018a, 2018b):

$$n = n_0 - \gamma c_s \tag{11}$$

in which, γ is the clogging pore volume caused by per unit mass SS, m^3/kg; c_s is the mass of SS deposited per unit volume, kg/m^3. Due to the continuous accumulation of SS, the porosity gradually decreases to zero, and the time clogging occurs can be obtained according to Equation (12) (Berlin *et al.* 2015; Liu *et al.* 2018a, 2018b; Chu *et al.* 2019):

$$t = a \frac{\rho_{ss}}{qC_i} \tag{12}$$

in which, *t* is the time when clogging occurs, d; *a* is the empirical coefficient; ρ is the volume density of SS, g/m^3; *q* is the hydraulic load, m/d; C_i is the SS concentration in wastewater, g/m^3. The second model considers the effect of biofilm accumulation. Under stable conditions, the biological decomposition of organics provides sufficient substrate for the synthesis of new cells of microorganisms, accompanied by the decline in old cells. Therefore, the amount of new substances can be expressed by Equation (13) (McKinley & Siegrist 2010; Ye *et al.* 2018):

$$\Delta S = aL_r - bS_a \tag{13}$$

in which, ΔS refers to the quality of newly grown microorganisms, M/t; L_r refers to the nutrients used, M/t; S_a refers to the original microbial quality, M; *a* refers to the composite coefficient; *b* refers to the attenuation coefficient of the microorganism itself. If the growth and attenuation amount of microorganism are equal during stable operation, i.e. $\Delta S = 0$, then, the pore volume occupied by

microorganisms at different depths is (Chu *et al.* 2019):

$$\alpha = \frac{a}{b} \cdot \frac{1}{\rho_a} \cdot v \cdot K_m \cdot C_0 e^{-K_m x} \tag{14}$$

in which, α refers to the pore volume occupied by microorganisms, m^3; ρ_a refers to microbial density, M/L; v refers to infiltration rate, L/t; K_m is the first order reaction rate constant; C_0 is the concentration of nutrients in the wastewater, M/L^3; x is the infiltration depth, m. Since the wastewater continuously supplies the nutrients needed for the growth of microorganisms, the newly formed microbial biomass in the pores is greater than the amount of attenuation, so that the pores are continuously occupied by biofilms, resulting in a decrease in permeability. Chu *et al.* (2019) established a mathematical model of soil biological clogging via theoretical analysis of the micropore structure of porous media:

$$\frac{K}{K_0} = \left\{ 1 - \left[\left(\frac{\alpha e}{1-e} + 1 \right)^{1/3} - 1 \right] \left[\left(\frac{\tau}{1-e} \right)^{1/3} - 1 \right] \right\}^3 \tag{15}$$

in which, K, K_0 are the permeability coefficients at a certain moment and the initial moment, respectively; e is the porosity of the matrix, %; τ is the shape factor of the matrix particles (6 for spherical particles and 7.7 for angular particles). The third type of model comprehensively considers other clogging processes such as chemical precipitation and gas clogging, so it is more complicated and needs to be completed with the help of a C language program. Chu *et al.* (2019) used the PHREEQC model to simulate the clogging process of hydrological migration, and completed the equilibrium calculation of reversible reactions, such as bubble formation and fragmentation, surface complexation and ion exchange during the solute migration process. According to the simulation results, insignificant effect was found for chemical precipitation on the decrease in permeability. Although this will temporarily reduce the penetration rate, no long-term effect was reported.

With the improvement in SWI technology and application research, it has been confirmed that researchers continually established representative porous clogging identification methods, and the influencing factors considered are continuously improved (Samsó & García 2014; Coulon *et al.* 2015; Pei *et al.* 2018). Table 2 shows the advantages and disadvantages of various new methods for identifying clogging and their applications.

CLOGGING PREVENTION AND REMEDIATION

The zone in which clogging occurs is generally referred to as a 'clogging zone' or 'biozone'. The occurrence of clogging depends mostly on medium properties, bed conditions, wastewater composition and loading rate. The main task of clogging prevention and remediation is to ensure uniform

Table 2 | Method for identification of clogging

Method	Advantage	Disadvantage
Permeability coefficient measurement	• Can be well controlled and easily executed in the laboratory (Siegrist 1987; Ganot *et al.* 2017).	• The low cohesive medium prevents the withdrawal of undisturbed samples (Siegrist 1987; Matos *et al.* 2019). • No comparability between different configurations and operation conditions (Ganot *et al.* 2017; Sobotkova *et al.* 2018).
Tracer experiment	• Reveals the water flow conditions and is suitable for different configurations (Hübner *et al.* 2013).	• The complete decay time and its toxicity on microorganisms are yet to be revealed (Lancheros *et al.* 2017; Matos *et al.* 2019; Li *et al.* 2020).
Numerical simulation	• The influencing factors considered are continuously improved (Samsó & García 2014; Coulon *et al.* 2015; Pei *et al.* 2018).	• Few have been successfully applied in large-scale clogging predictions (Ganot *et al.* 2017; Pucher & Langergraber 2019). • The accuracy is restricted by complex factors (Coulon *et al.* 2015).
Measurement of electrical resistivity	• Easy to operate in the laboratory and online (Liu *et al.* 2018a, 2018b).	• Requires sophisticated equipment and has less indications for obstruction caused by organic compounds (Zhao *et al.* 2009).

wastewater distribution, stable and high removal of pollutants. Therefore, several types of techniques/strategies can be used to mitigate the problem and increase the service lifespan of SWI beds without changing the medium used, which is costly (Table 3).

Optimize the medium and pre-treatment

Medium with larger particle size is one of the guarantees to evenly distribute the water flow and prevent clogging. Although the surface of the medium with smaller particle size can provide a larger specific surface area and more adsorption sites, it is easy to cause biological clogging; while the medium with a larger particle size can reduce the clogging caused by biological growth to a certain extent (Miranda *et al.* 2016; Saffari *et al.* 2019). Additionally, multi-layer water distribution can not only provide sufficient carbon source for denitrification, but reduce biological clogging owing to the higher load and larger shear rate (Miranda *et al.* 2017). Physical clogging is usually irreversible and once this occurs, the medium will have to be replaced or reused after washing. In both options there are still needs for the disposal of clogging material. In this case, pre-treatment should be strengthened for SS removal as much as possible to reduce the risk of physical clogging. The 'Urban Sewage Land Treatment Technical Guide' in China requires that only wastewater with SS concentrations less than 20 mg/L is allowed to be treated by SWI beds (Li *et al.* 2011). The pre-treatment process includes filtration, flocculation–precipitation, adsorption, etc. With the continuous improvement of the effluent quality requirements, efficient pre-treatment processes have been gradually developed, such as biological contact oxidation, oxidation ponds, ozone treatment, etc (Zucker *et al.* 2015).

Obviously, the strategy of optimizing pre-treatment and medium has a certain effect on the relief of initial clogging, such as physical clogging caused by suspended solids. But it has little positive effect on alleviating the clogging of dissolved solids and gases. Therefore, in recent years, in-situ remediation methods such as alternating dry and wet operation have provided a new development direction for effectively unclogging the beds.

Operate alternatively

Alternating operation means that the SWI bed will properly 'rest' (empty) after continuous operation for a period of time. Such operation cannot only effectively relieve the accumulation of organic solids, but also facilitate the release of bubbles adsorbed in the pores of the medium (Baptestini

et al. 2016). During the 'rest' period, various nutrients cannot be continually replenished, and the microorganism turns to the endogenous respiration period. At the same time, as the oxygen mass transfer efficiency increases, biomass decreases, porosity and permeability are restored and improved. In recent years, scholars have carried out a lot of beneficial explorations on the optimization of intermittent conditions. Considering the removal effect for pollutants, hydraulic capacity and the production of greenhouse gases, it is recommended to control the dry-wet ratio at 1:1–3:1 (Zhang *et al.* 2018; Li *et al.* 2019).

The intermittent operation method is relatively simple and easy to apply, and is suitable for controlling and alleviating the clogging problem mainly caused by the accumulation of biodegradable organic compounds. However, the operation cannot meet the continuous sewage treatment needs, and at least two beds are needed, which invisibly increases the capital construction investment and needs large land occupancy.

Add chemical reagents

Many chemicals, such as hydrogen peroxide (H_2O_2), hydrochloric acid (HCl) and sodium hypochlorite (NaClO) have a strong redox effect, and can restore the medium permeability by oxidizing extracellular polymers or dissolving and dispersing the clogging (Kanmani *et al.* 2014). NaClO can effectively dissolve the protein and polysaccharide components, while HCl can release the gas wrapped by biological clogging. In addition, by adding an appropriate amount of phenol to the wastewater, it is also possible to oxidize the non-biodegradable components in the biofilm and alleviate biological clogging (Wang *et al.* 2019).

However, to a large extent, SWI technology relies on microorganisms to efficiently degrade pollutants. Chemical reagents will destroy the structure of functional microbial flora, resulting in pH changes, which is not conducive to the growth and reproduction of microorganisms, and may even worsen the quality of effluent. Consequently, it is not yet recommended for unclogging the beds still in service.

Aerate

To effectively increase the level of dissolved oxygen in the bed, two measurements are suggested. (1) The wastewater is aerated before the SWI process, promoting the decomposition and utilization of organic matter, and ease the bioclogging in the pores. (2) Aerate in saturated zones, so that oxygen is injected to provide rapid biodegradation of the organic matters. According to reports, if the dissolved

Table 3 │ The clogging control technology/strategy

Aim	Measurement		Effect, advantage and disadvantage	Country	References
Clogging prevention	Pre-treat the wastewater	Biological contact oxidation	• >90% SS and >33% COD were removed. • Ensuring long-term stable operation of the SWI system. • The demonstration project has been successfully operated for 11 consecutive years and no clogging has been found. • High pollutant removal rates but more energy consumption.	China	Li *et al.* (2019)
		Oxidation and lime treatment	• >82% of the SS in the sewage was removed, ensuring that SAT was running normally. • High SS removal but the pH of wastewater will be increased.	Israel	Wang *et al.* (2020)
		Biofiltration and ozonation	• Dissolution of manganese oxides and the presence of Mn^{2+} lead to clogging. • The combination process decreased manganese oxide dissolution, and improved DOC removal. • More energy consumption and complicated equipment required.	Israel	Zucker *et al.* (2015)
Unclogging technology/ strategy	Optimize the medium	Peat and sand	• The pore structure of the peat allowed the biomass to distribute itself over a greater depth and delayed the formation of a biomat and eventual clogging of the filter medium. • Increase the construction cost.	Canada	Mostafa & van Geel (2015)
		Sand grain	• Mixed and stratified mode with two different sizes (0.3 mm and 0.6 mm) of sand grains were used for column filling. • Clogging occurred in the mixed sand microbial column when compared with the stratified sand microbial column. • Stratified mode increases the complexity of system construction.	India	Kanmani *et al.* (2014)
		Bioaugmentation	• Bioaugmentation significantly increased the relative abundance of clostridia, which have good nitrate-reducing activity. • The embedding strategy significantly decreased the indigenous soil microbial diversity ($p <$ 0.05) and altered the bacterial community structure.	China	Liu *et al.* (2018a, 2018b)
		Sand, quarry dust and gravel	• Sand substrate was observed to perform better in organic reduction compared to quarry dust and gravel, resulting in a lower risk of clogging. • Sand substrate will result in a lower retention time of the wastewater.	Kenya	Mbubu *et al.* (2019)
	Operate alternatively		• Increasing the wetting–drying ratio is helpful in reducing the risk of gas clogging. • More land requirement.	China	Zhang *et al.* (2018); Li *et al.* (2019)

(*continued*)

Table 3 | continued

Aim	Measurement	Effect, advantage and disadvantage	Country	References
		• Under aerobic conditions, 35% of the accumulated solid was biodegradable at rates of 4.4–12.0 g COD/m·d. • More land requirement.	Spain	Carballeira *et al.* (2017)
	Add oxidant	• The infiltration rate and porosity increased with increased dosage of NaOH, HCl, NaClO and detergent. • NaClO had the most obvious effects on reducing clogging and the effective porosity recovered to 69% of the original condition. • Disturb the microbial community structure.	China	Hua *et al.* (2010)
		• After treating wetland clogging substances with 30% concentration of H_2O_2, the volatile organic components were reduced by 50%. • Increase the operation cost.	India	Sivasankar & Kumar (2019)
	Aerate	• The dissolved oxygen environment in vertical-flow constructed wetlands was improved. • Under the action of airflow, the biofilm is not easy to settle. • The removal rate of ammonia nitrogen can be as high as 89.6% while alleviating the clogging of biofilm. • Increase the operation cost.	China	Li *et al.* (2014)
		• Intermittent aeration achieved high removal of COD, TP, NH_4^+-N and TN. • Increase the operation cost.	China	Pan *et al.* (2015)
		• Positive correlation was found between aeration and removal efficiency of accumulated solids. • Increase the operation cost.	Italy	Labella *et al.* (2015)
Evaluate the clogging behavior	Numerical simulation	• Using the equilibrium model and physical non-equilibrium model in CXTFIT, the main location and mechanism of gas clogging in SWI were initially revealed. • Longer time required for numerical balance.	China	Wang *et al.* (2019)
		• The two-dimensional model HYDRUS was used. • The rate of decline of hydraulic conductivity is likely to depend on the particle size distribution of water. • Few reports on its application in large-scale clogging predictions.	USA	Sobotkova *et al.* (2018)

oxygen concentration in the SWI beds locates between 0 and 1.0 mg/L, the aerobic decomposition will be inhibited, and extracellular polymers tend to accumulate. Aeration can effectively increase the dissolved oxygen concentration, reduce biological clogging, and improve the effluent quality (Labella *et al.* 2015).

However, some studies, such as Wang *et al.* (2019) and Li *et al.* (2020), revealed that under different aeration treatments (microaeration and strong aeration), 2% to 20% of the pores in the central zone will be occupied by the gas, weakening the permeability of water. What is more, oxygen injection in clogging zones, as described in measurement (2), may accelerate the formation of recalcitrant byproducts and iron precipitates (Zhao *et al.* 2009; Labella *et al.* 2015). Sophisticated aeration equipment is also needed. As a result, this strategy is still under development.

Apply numerical simulation

Clogging simulations are reported to use different tools ranging from black box models to process-based models. The CXTFIT software was developed by the USDA Saline Soil Laboratory. Based on the convection–diffusion processes, it is used to simulate the equilibrium or non-equilibrium transportation of tracers. Existing studies (Wang *et al.* 2019) optimized the equilibrium model and physical non-equilibrium model in CXTFIT and revealed the main position and genesis of gas clogging. Their results indicated that with the extension of running time, the lower zone is more prone to gas clogging. To evaluate time-dependent clogging, Pei *et al.* in 2018 developed a model based on the principle of unit cell analysis. In this study, clogging is evaluated quantitatively and the porosity of the medium is determined through continuous scanning. The results revealed that although the clogging phenomenon was obvious in the upper layer, it diminished significantly with bed depth.

Due to the complexity of clogging, only a few of the models have been successfully applied to practical clogging prediction. With the continuous update and progress of computer software, the results of numerical simulation will be continuously used to guide on-site monitoring, and more accurate prediction results are expected to be obtained (Samsó & García 2014).

CONCLUSIONS AND FUTURE PERSPECTIVES

(1) As discussed throughout the review, there is still much to be understood about the phenomenon of clogging, which is caused by many elements such as physical, chemical and biological factors. It is a complex phenomenon from micro to macro, from localized effect to overall effect, from single factor to multiple process coupling. Therefore, to diagnose the cause of clogging, comprehensive analysis of the wastewater quality, bed configurations, and solid constituents accumulated in the pores should be given priority, so that accurate measures could be taken.

(2) Combining numerical simulation with on-site monitoring methods for clogging prediction and early warning, it is possible to predict the low permeability and potential zones. Based on the results, the monitoring scheme is reasonably and effectively formulated and sensors are arranged.

(3) Physical clogging is generally difficult to recover. Once it occurs, it needs to be solved by replacing the medium or subjecting it to washing. Therefore, it is necessary to select it as inert as possible, which is less subject to wear and therefore the inorganic solids that contribute to clogging of the pores are less released. Second, operational strategies, such as alternately running the beds are effective measures to prevent biological clogging.

(4) Because SWI is a simple and natural technology, the techniques that are easy to implement and that with less interference to operations should be prioritized. In this case, the practice of adding chemical oxidants should be used with caution.

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COMPLIANCE OF INTEREST

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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