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Effect of solid waste landfill leachate contaminants on hydraulic conductivity of landfill liners

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ABSTRACT

Landfilling is one of the most widely used methods to reduce the impact on the environment and human health by ensuring the management of solid wastes. For the process in question to be called landfill, the landfill leachate must be controlled and liner impermeability conditions must be provided. For this reason, compacted clay liners (CCL) and geosynthetic clay liners (GCL) with very low hydraulic conductivity are often used as hydraulic barriers in landfills to prevent the risk of leachate mixing with groundwater. However, as a result of various interactions between leachate-clay liners, changes occur in the hydraulic conductivity of the liners. In this review, the change (increase/decrease) in the hydraulic conductivity of the landfill liners caused by the contaminants in the leachate composition and the mechanisms responsible for this change were examined. In addition, deficiencies in the literature on this subject were identified and directions for future studies were presented.

Key words: clay liner, hydraulic conductivity, landfill, leachate

HIGHLIGHTS

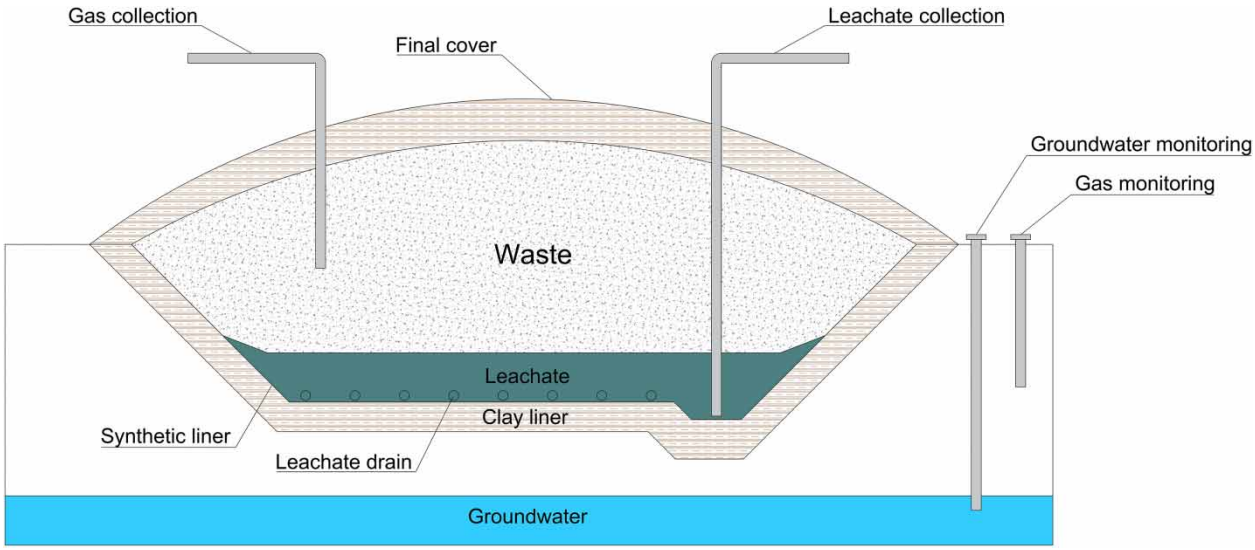
- The change in hydraulic conductivity as a result of the interaction of clay soil and leachate is presented.
- The change in the hydraulic conductivity of clay by organic matters was discussed.
- The changes in the hydraulic conductivity of the clay by inorganic salt solutions and heavy metals were discussed.
- The effective factors in reducing the hydraulic conductivity of the soil by suspended solids and microorganisms are presented.

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GRAPHICAL ABSTRACT



1. INTRODUCTION

Recently, the amount of municipal solid waste (MSW) has increased in many countries due to the increasing population, increasing standard of living, and urbanization (Chen 2018). The landfill is the most common method used for the final disposal of MSWs, as it is the most economical, simplest, and appropriate method available (Adhikari *et al.* 2014; Vaverková *et al.* 2020). It is known that 95% of the total MSW collected worldwide is disposed of through landfills (Tamru & Chakma 2016; Luo *et al.* 2020).

The hydraulic conductivity of the soil in landfills is one of the most important engineering parameters required in infiltration and stability calculations (Sivapullaiah *et al.* 2000). Hydraulic conductivity (k) describes the capacity of a porous medium to transmit a given liquid and is a function of both the medium and the liquid. The intrinsic permeability (K) expresses the flow capacity in terms of the properties of the porous medium. The relationship between K and k is given in Equation (1).

$$\mathrm{k} = \frac{K\rho \mathrm{g}}{\mu} \tag{1}$$

where ρ is the density of permeate, g is the acceleration of gravity and μ is the dynamic viscosity of permeant.

The hydraulic conductivity of MSW varies considerably depending on the composition of the waste in the landfill, compaction, and soil-contaminant interaction (Reddy *et al.* 2009). Compacted clay liners (CCL) and geosynthetic clay liners (GCL) are frequently used as hydraulic barriers in landfills due to their low hydraulic conductivity (Uma Shankar & Muthukumar 2017; Visentin *et al.* 2019). One of the factors that indicate the compatibility of the clay barrier to the contaminant is the resistance to the increase in hydraulic conductivity caused by the contaminant (Li & Li 2001). CCLs have advantages such as good damping capacity and cheapness, as well as disadvantages such as high swelling and shrinkage (Uma Shankar & Muthukumar 2017). The thickness and hydraulic conductivity of CCLs are typically between 0.3–1.5 m and 1×10^{-10} and 1×10^{-9} m/s, respectively (Giroud *et al.* 1998).

The hydraulic conductivity of sandy soils ($10^{-5} < \mathrm{k_{sand}} < 10^{-3}$) is at least 1,000 times higher than clay soils (Akyıldız 2011). According to the United States Environmental Protection Agency (US EPA), the minimum thickness of compacted liners should be 60 cm and the hydraulic conductivity of compacted liners should not be more than 1×10^{-7} cm/s. GCLs are widely used in landfills due to their low hydraulic conductivity against water ($\mathrm{k_w} < 10^{-10}$), resistance to weather conditions such as freezing and drying, ease of installation, and relatively low cost (Shackelford *et al.* 2000; Bouazza 2002). GCLs are divided into three parts according to their configuration: (1) a clay layer bonded with geotextile to its lower and upper surfaces; (2) a layer of clay placed between two geotextiles sewn together; (3) Clay layer adhered to a geomembrane. GCLs are

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generally composed of sodium bentonite or calcium bentonite sandwiched between two geosynthetic materials (Ruhl & Daniel 1997). GCLs are 5–10 mm thick and their hydraulic conductivity typically ranges from 5×10^{-12} to 5×10^{-11} m/s (Giroud *et al.* 1998).

The hydraulic conductivity of GCLs is 10–100 times lower compared to CCLs. It is bentonite that has the main impact on hydraulic conductivity in GCLs (Shackelford *et al.* 2000; Uma Shankar & Muthukumar 2017; Visentin *et al.* 2019). The microstructure of sodium bentonites is more uniformly distributed compared to calcium bentonite and sodium bentonites have more water-binding capacity. Therefore, the permeability of calcium bentonites is about one order higher than sodium bentonites (Egloffstein 2001).

The hydraulic conductivity of CCLs and GCLs in landfills is vital in environmental control applications as it controls the transport of high polluting leachate (Sivapullaiah *et al.* 2000; Khalid *et al.* 2020). Soil structure, particle size, specific surface area of the particle, pore size and ratio, as well as the properties of the liquid interacting with the soil are among the factors affecting the movement of contaminants (Stpniewski *et al.* 2011). This review provides an overview of the change in hydraulic conductivity of liners used in the landfill by contaminants in leachate. In addition, the factors affecting the change in the hydraulic conductivity of the liners by each contaminant in the leachate are also discussed.

2. IMPERMEABILITY METHODS APPLIED IN LANDFILL AREAS

Several different barrier systems can be used to prevent groundwater contamination by ensuring waterproofing in landfill areas. The main function of hydraulic barriers is to create a barrier between the waste and the environment. Therefore, it is necessary to limit the impermeability of the hydraulic barrier to a value equal to or lower than the maximum acceptable value. The aim here is to prevent the contamination of groundwater by preventing the passage of leachate from landfills to groundwater. CCL, GCL, and GM are generally used as hydraulic barriers in landfill areas. These liners can be used alone or in combination with each other, depending on the potential threat posed by the waste in landfills (US EPA 2004; Ojoawo & Adegbola 2014). To ensure impermeability, a single or double liner can be used in storage areas. While single liners consist of CCL, GCL or GM; double liners are formed by combining two single liners, two composite liners, or a single and composite liner (Ojoawo & Adegbola 2014).

The use of composite liners exhibits lower permeability performance than using a liner alone. All conditions being equal, composite barrier systems such as CCL/GM, GCL/GM, CCL/GCL/GM are known to allow less infiltration than the use of CCL, GCL, or GM barriers alone (US EPA 2004). Top liners form the primary barrier to impermeability, while lower liners act as a backup to the top liners, providing an additional barrier system for impermeability.

In industrialized countries, it is common to use a composite liner or double liners, mostly composed of GM on the CCL, in landfills. In such landfills, liner combinations of CCL/GM, CCL/GCL, CCL/GCL/GM can be used in order from lower liner to the upper liner (Barroso *et al.* 2006). In hazardous waste landfill areas, on the other hand, double liners are used to keep the leakage from the waste to a minimum and to protect the groundwater from pollutants (Kavazanjian *et al.* 2006; Ojoawo & Adegbola 2014).

The choice of liner type in liner combinations to be used in landfill areas is also an important factor affecting permeability. Field monitoring and theoretical calculations have shown that GCL/GM composite liners leak one to two times less than CCL/GM composite liners (Rowe 2011). Lower permeability performances can be achieved with GCL/GM liners because the substrate of GCL is smoother compared to CCL and the bentonite present in GCL closes the small gaps between GCL and GM (Rowe 2011). Abd-Ehamid *et al.* reported that as a result of the numerical model applied to the clay and geomembrane, the pollutant dispersions decreased along with the decreasing hydraulic conductivity of the materials. The pollutant dispersal reduction for clay and geomembrane was found to be 43% and 91.4%, respectively, by Abd-Elhamid *et al.* (2019). Ojoawo & Adegbola (2014) developed models for four different GMs, smooth HDPE (high density polyethylene), textured HDPE, smooth LDPE (low density polyethylene) and textured LDPE, using their main properties such as hydraulic conductivity, porosity and thickness. Ojoawa and Adegbola ranked the liner effectiveness of the four different GMs they examined as smooth HDPE > smooth LDPE > textured HDPE > textured LDPE and suggested the use of smooth HDPE liners for containment of leachate in landfills (Ojoawo & Adegbola 2014).

In recent years, the most focused issue on reducing the hydraulic conductivity of soils by researchers is the reduction of hydraulic conductivity through the contribution of different materials to soil samples. Ranaivomanana & Razakamanantsoa (2018) found that the hydraulic conductivity of the silty sand and clay soil sample treated with cement was 1–2 orders of

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magnitude lower than the untreated samples, due to the reduction of macroporosity (Ranaivomanana & Razakamanantsoa 2018). Amiralian *et al.* (2012) reported that after stabilizing the soil with lime (1–3%), fly ash (5–15%), and lime-fly ash, the hydraulic conductivity of the soil decreased 7 times, 65 times and 180 times, respectively. In the study by Amiralian *et al.*, hydraulic conductivity decreased with increasing lime and fly ash concentration, and the effect of fly ash on reducing hydraulic conductivity was found to be higher than the effect of lime (Amiralian *et al.* 2012). Metelková *et al.* (2011) showed that the hydraulic conductivity of soil samples mixed with 1 and 8% lime decreased with time (Metelková *et al.* 2011). Ng & Coo (2015) showed that the hydraulic conductivity of the clay (1.1×10^{-9} m/s) decreased by adding gamma-aluminum oxide (γ-Al_2O_3) and nano-copper oxide (CuO) into the clay. The addition of 6% γ-Al_2O_3 and nano CuO to the clay caused the pores of the clay to be clogged by nanomaterials, resulting in a decrease in hydraulic conductivity to 6.6×10^{-10} m/s and 4.4×10^{-10} m/s, respectively (Ng & Coo 2015). Taha & Alsharef (2018) reported that with the addition of 0.2% carbon nanotube (CNT) and carbon nanofiber (CNF) to sandy clay soil, the hydraulic conductivity decreased from 2.16×10^{-9} m/s to 9.46×10^{-10} and 7.44×10^{-10} m/s, respectively (Taha & Alsharef 2018). Kananizadeh *et al.* (2011) reported that with the addition of 3% nanoclay into the clay with a hydraulic conductivity of 3×10^{-9} cm/s, the hydraulic conductivity of the clay decreased to 9.4×10^{-11} cm/s (Kananizadeh *et al.* 2011). Bahmani *et al.* (2014), in their study on the hydraulic conductivity of cement-treated residual soil loaded with 15 and 80 nm silica (SiO_2) nanoparticles, reported that the hydraulic conductivity decreased with the addition of 0.4% nanosilica. In addition, Bahmani *et al.* showed that silica particles with a size of 15 nm perform better on reducing hydraulic conductivity than silica particles with a size of 80 nm due to the high particle packing density (Bahmani *et al.* 2014). Taipodia *et al.* (2011) reported that the hydraulic conductivity of the clay (2.41×10^{-5}) decreased to 1.25×10^{-5} cm/s as a result of the addition of nano CaO to the clay, and this result was related to the filling of soil voids with nanoparticles (Taipodia *et al.* 2011). Taha & Taha (2016) reported that the hydraulic conductivity decreased in general as a result of the addition of nano-alumina and nano copper to the soil samples containing 20% bentonite, and nano-alumina performed better than nano copper in terms of reducing the hydraulic conductivity (Taha & Taha 2016).

3. LEACHATE CONTAMINANTS AND THE EFFECT OF CONTAMINANTS ON HYDRAULIC CONDUCTIVITY

Leachate is an important pollution problem caused by the water in the waste itself, the leakage of precipitation (especially rain), physical, chemical, and biological reactions in the landfills (Scott *et al.* 2005; Adhikari *et al.* 2014).

The chemical composition of the leachate varies depending on both the type, composition, age, moisture content, decomposition rate of the waste in the landfill, as well as the height, age, storage technology, and climatic conditions of the landfill (Chu *et al.* 1994; Scott *et al.* 2005; Zhang *et al.* 2013; Stefanakis *et al.* 2014). Leachate, whose composition is highly variable and heterogeneous, generally contains high concentrations of dissolved organic matter and inorganic ions (Lema *et al.* 1988). Contaminants in leachate can be classified into five groups; dissolved organic substances, inorganic macro components, heavy metals, microorganisms, and xenobiotic organic compounds (Kjeldsen *et al.* 2002; Zhang *et al.* 2013; Luo *et al.* 2020). Interactions between clay liners and leachates are solute diffusion, cation exchange, anion exclusion, redox reactions, and dissolution/precipitation (De Soto *et al.* 2014). There may also be differences in hydraulic permeability performance due to the decomposition of the clay liner itself or the shrinkage or cracking of the clay (Spooner & Giusti 1999).

The hydraulic conductivity of different soils through which leachate is passed varies both according to the structure and properties of the soil and according to the properties of the leachate (Han *et al.* 2009; Xu *et al.* 2011; Ozcoban *et al.* 2013; Aldaeef & Rayhani 2014; Bradshaw & Benson 2014). Han *et al.* (2009) determined the hydraulic conductivity of GCL permeated with distilled water, old and young leachate as 1.68×10^{-9}, 3.50×10^{-7}, and 5.35×10^{-9} cm/s, respectively (Han *et al.* 2009). Ozcoban *et al.* (2013) reported that the hydraulic conductivity of compressed clay varies between 5.2×10^{-8} and 6.45×10^{-8} m/s when it penetrates with hydraulic distilled water, but the hydraulic conductivity of the compressed clay penetrating with leachate water decreases (Ozcoban *et al.* 2013).

3.1. Acids and bases: the effect of pH

The pH value of leachate is generally in the range of 4.5–9 (Aziz *et al.* 2010). The most aggressive leachates are those with $pH < 3$ and $pH > 11$ (Spooner & Giusti 1999). The pH of the leachate can have a great influence on the structure and permeability of the clay. Acid type, acid concentration, soil type, reaction time, and temperature are important factors in acid-soil interaction (Daniel & Shackelford 1968; Ishiguro & Nakajima 2000; Zhang *et al.* 2010; Liu *et al.* 2015; Lin *et al.* 2017). Liu

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et al. (2015) reported that the hydraulic conductivity of GCLs increased with increasing sulfuric acid (H_2SO_4) concentration (Liu *et al.* 2015). Ishiguro & Nakajima (2000) found that dilute nitric acid (HNO_3) significantly increased the repulsion forces between allophonic andisol soil particles containing pH-dependent charge and induced soil dispersion, and reported a decrease in hydraulic conductivity (Ishiguro & Nakajima 2000).

Strongly acidic and strongly basic liquids can dissolve clay minerals (Daniel & Shackelford 1968; Uppot & Stephenson 1989; Allen 2005; Sunil *et al.* 2006; Karaoğlu 2010; Eltarabily *et al.* 2015; Emmanuel *et al.* 2020). Strong acids can break down carbonates, iron oxides, and alumina-octahedral clay layers. High pH basic solutions (pH > 12) mostly dissolve the silica layer, but they also cause the alumina octahedral layers of clay minerals to dissolve, albeit to a lesser extent (Allen 2005).

The removal of dissolved substances from the soil medium can cause an increase in hydraulic conductivity, while the precipitation of these substances can cause clogging of the porous medium, contributing to a decrease in hydraulic conductivity (Anderson *et al.* 1985; Uppot & Stephenson 1989; Spooner & Giusti 1999). Initially, the reduction in hydraulic conductivity is due to the neutralization of the acid by the dissolved soil, causing the solids to precipitate. The subsequent increase in hydraulic conductivity is due to the acid entering the soil and re-dissolving the precipitates (Daniel & Shackelford 1968; Anderson *et al.* 1985). As an example, Lin *et al.* showed that citric acid greatly reduces the pH of the soil, causing the soil matrix to break down. A decrease in permeability has occurred due to the accumulation of the formed colloids in the micropores of the soil (Lin *et al.* 2017).

As a result of the reaction of carbonates in the clay with acidic substances, carbon dioxide gas may be formed and the solid product of the reaction may pass into the solution (Uppot & Stephenson 1989). Due to the increase in mass loss with the dissolution of clay minerals, channels are formed in the soil and the effective pore space increases. Thus, an increase in hydraulic conductivity occurs. Uppot & Stephenson (1989) stated that as a result of the reaction of calcium carbonate in the structure of magnesium montmorillonite with acetic acid, the mass loss occurred and a 3-fold increase was obtained in the permeability of magnesium montmorillonite (Uppot & Stephenson 1989). On the other hand, there was no change in permeability in kaolinite, which does not contain calcium carbonate, since dissolution did not occur (Uppot & Stephenson 1989).

Some researchers reported an increase in hydraulic conductivity with increasing pH (Sunil *et al.* 2006; Eltarabily *et al.* 2015; Faraghati *et al.* 2019). Sunil *et al.* (2006) related the increase in hydraulic conductivity caused by strong alkaline solutions to the deterioration of soil structure as a result of soil-solution contact (Sunil *et al.* 2006). Similarly, in the study by Eltarabily *et al.* (2015), the effective pore space and hydraulic conductivity of clay soils increased due to clay-alkali (diammonium phosphate) contamination (Eltarabily *et al.* 2015). Faraghati *et al.* (2019) showed that the hydraulic conductivity of kaolinite gradually decreased until pH 7 and then increased (Faraghati *et al.* 2019). Thammathiwat & Chim-oye (2008) investigated the effect of permeable liquids prepared by adding sufficient concentrated HCl or NaOH to 0.1 M $CaCl_2$ on bentonite and reported that permeability coefficients increase with increasing pH in acidic conditions, whereas permeability coefficients decrease with increasing pH in basic conditions (Thammathiwat & Chim-oye 2008). Studies on the effect of pH on hydraulic conductivity are summarized in Table 1.

3.2. Salt solutions

The concentration and solubility of inorganic substances in the leachate are affected by the pH and the contents of the waste in the landfill. In landfills, the concentration of inorganic compounds increases due to the predominance of low pH

Table 1 | Effect of pH on hydraulic conductivity

pH	Liner	Hydraulic conductivity (cm/s)	Change in hydraulic conductivity	Reference
4 7 10	Kaolinite	$\sim 1.62 \times 10^{-7}$ 1.42×10^{-7} 1.8×10^{-7}	With increasing pH, the hydraulic conductivity first decreased and then increased.	Faraghati *et al.* (2019)
2 6 12	GCL	2.33×10^{-10} 2.94×10^{-9} 8.96×10^{-11}	With increasing pH, the hydraulic conductivity first increased and then decreased.	Thammathiwat & Chim-oye (2008)

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conditions in the acetic phase. With the transition to the methanogenic phase, a decrease in concentration occurs due to the increase in pH (Ehrig & Stegmann 2018). Increases in concentration and cation valence cause agglomeration of small particles due to a decrease in the thickness of the diffuse double layer (DDL) increasing hydraulic conductivity (Rahman 2000).

The DDL model is a conceptual model developed by Helmholtz-Smoluchowski (1879–1914) and improved by Gouy-Chapman (1910–1913) (Mortezaei & Karimpour Fard 2017). The DDL model is widely used to describe interactions between clay and liquid. The factors affecting the thickness (t) of the DDL layer can be explained by the following equation based on the Gouy-Chapman theory (Daniel & Shackelford 1968; Mortezaei & Karimpour Fard 2017).

$$t = \sqrt{\frac{\varepsilon K_{b\,T}}{8\pi n_e e^2 v^2}} \tag{2}$$

where ε is dielectric constant, K_b is Boltzmann constant, T is temperature, n_e is electrolyte concentration, e is elementary change and v is ionic valance.

The increase in DDL thickness causes the narrowing of the flow channels, resulting in a decrease in the hydraulic conductivity of the soil. According to Equation (2), DDL thickness decreases with decreasing dielectric constant, increasing ion valence, and increasing electrolyte concentration. The dielectric constant of solutions consisting mainly of water is relatively constant. Therefore, according to Equation (2), it is the electrolyte concentration and cation valence that have the main effect on the double layer thickness in solutions containing mainly water.

The high cation concentration and/or the replacement of interlayer cations by divalent or trivalent cations in the exchangeable regions of the clay affect the double layer thickness. It is very difficult for the cations, which are in the closest distance to the clay particles or firmly attached to the particle surface, to be replaced by other cations by any interaction due to the high electrical attraction force. The cations are dispersed in the next layer, where the electrical attraction is less compared to the clay surface. Cations dispersed in clay soils begin to replace other cations in the pore fluid. When the displacement is complete, the water around the particle is suppressed, the layer thickness becomes narrower, the soil becomes more porous, and finally the hydraulic conductivity increases (Spooner & Giusti 1999; Oren & Demirkiran 2015).

Researchers mainly addressed two issues when examining the effect of salt solutions on the hydraulic conductivity of CCLs and GCLs. In the studies, the effect of ion concentration on hydraulic conductivity (Shackelford *et al.* 2000; Jo *et al.* 2004; Yilmaz *et al.* 2008; Mishra *et al.* 2009; Nayak *et al.* 2010; Oren & Demirkiran 2015; Setz *et al.* 2017; Wang *et al.* 2019) and the effect of increases in cation valence on hydraulic conductivity (Jo *et al.* 2004; Mishra *et al.* 2009; Shariatmadari *et al.* 2011; Xue *et al.* 2012; Chen *et al.* 2019) were investigated. In Table 2, studies in the literature on the effect of salt solutions on hydraulic conductivity are summarized.

When the salt solutions come into contact with the clay soil, the structure of the clay particles changes and the clay particles can agglomerate and flocculate. Yilmaz *et al.* (2008) reported that the hydraulic conductivity of clays increased due to the decrease in the thickness of the diffuse layer and flocculation of the clay particles with the increasing concentration of NaCl, NH_4Cl, KCl, $CaCl_2$, and $FeCl_3$ inorganic salt solutions (Yilmaz *et al.* 2008). Emmanuel *et al.* (2020) also stated that the increase in hydraulic conductivity as a result of leachate-clay contact is due to the increase in the effective void ratio of the soil as a result of the clay particles becoming flocculated due to high salinity (Emmanuel *et al.* 2020). In another study on the effect of ion concentration on hydraulic conductivity, Setz *et al.* (2017) showed that the effect of ionic strength of NH_4^+ solutions on the increase in the hydraulic conductivity of Na-bentonite GCLs becomes significant from 150 mM concentration (Setz *et al.* 2017). Hydraulic conductivity values of GCLs are found to be less than 6×10^{-11} m/s up to ionic strength up to 100 mM, while for solutions with ionic strength $\geq$500 mM to NH_4^+ they range from 1.6×10^{-6} to 5.2×10^{-6} m/s found (Setz *et al.* 2017). Similar results showing that hydraulic conductivity increases with increasing ion concentration have also been revealed by other researchers (Shackelford *et al.* 2000; Jo *et al.* 2004; Mishra *et al.* 2009; Nayak *et al.* 2010; Oren & Demirkiran 2015).

Monovalent cations such as Na^+ and K^+ have less effect on the increase in hydraulic conductivity than polyvalent cations such as Ca^{+2} and Mg^{+2}. Jo *et al.* (2004) showed that solutions with divalent cations ($CaCl_2$) cause both greater and faster changes in the hydraulic conductivity of Na-bentonite GCLs compared to those with monovalent cations (KCl) (Jo *et al.* 2004). Mishra *et al.* (2009) reported that the hydraulic conductivity for 0–0.1 N NaCl and $CaCl_2$ in basalt soil-bentonite mixture (100:20) increased 3.3 and 21 times, respectively (Mishra *et al.* 2009). It was revealed in the study by Shariatmadari *et al.*

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Table 2 | Effect of salt solutions on hydraulic conductivity

Contaminants	Liner	Hydraulic conductivity (cm/s)	Change in hydraulic conductivity	Reference
0.01–0.1 M $ZnCl_2$	GCL	Increase from 10^{-9} to 10^{-5}	As the concentration increased, hydraulic conductivity increased.	Shackelford *et al.* (2000)
Distilled water Tap water	GCL	7.1×10^{-10} 1×10^{-9}	Cations in tap water increased the hydraulic conductivity.	Oren & Demirkiran (2015)
$\leq$100 mM NH_4^+ $\geq$500 mM NH_4^+	Na-bentonite GCL	$<6 \times 10^{-11}$ 1.6×10^{-6}–5.2×10^{-6}(m/s)	As the concentration increased, hydraulic conductivity increased.	Setz *et al.* (2017)
0–0.1 N NaCl 0–0.1 N $CaCl_2$	Basalt soil- bentonite clay (100:20)	Increase from 3.6×10^{-9} to 1.2×10^{-8} Increase from 3.6×10^{-9} to 7.6×10^{-8}	3.3 times increase 21 times increase	Mishra *et al.* (2009)
20 mM $CaCl_2$ 40 mM $CaCl_2$	Na-bentonite GCL	2.66×10^{-9} 6.76×10^{-8}	As the concentration increased, hydraulic conductivity increased.	Jo *et al.* (2004)
0–4,000 mg/L Na^+		Increase from $\sim 1.25 \times 10^{-9}$ to 2×10^{-9}	As the concentration increased, hydraulic conductivity increased.	Wang *et al.* (2019)
0.01–1 M NaCl, NH_4Cl, KCl, $CaCl_2$, and $FeCl_3$	Clay (high plasticity)	–	For all solutions, hydraulic conductivity increased as the concentration increased.	Yilmaz *et al.* (2008)
0% 0.5 N NaCl 5% 0.5 N NaCl10% 0.5 N NaCl 20% 0.5 N NaCl	Lateritic soil	3.2×10^{-5} 4×10^{-5} 5.1×10^{-5} 5.8×10^{-5}	As the concentration increased, hydraulic conductivity increased.	Nayak *et al.* (2010)
Typical coal combustion product leachate Leachate with high polyvalent cation	GCL containing bentonite– polymer composites	1.1×10^{-10} 2.2×10^{-8}	Leachate with more polyvalent cation increased the hydraulic conductivity more.	Chen *et al.* (2019)
200 mM $CaCl_2$, $MgCl_2$, KCl and NaCl	GCL	–	284 times, 262 times, 19.5 times and 19 times increase, respectively.	Xue *et al.* (2012)
$CaCl_2$, $MgCl_2$ and NaCl	Clay-bentonite	–	$CaCl_2$ and $MgCl_2$ increased the hydraulic conductivity 25 and 7% more than NaCl, respectively.	Shariatmadari *et al.* (2011)

(2011) that the average increase in the hydraulic permeability of the clay-bentonite mixture caused by $CaCl_2$ and $MgCl_2$ salt solutions was approximately 25 and 7% higher, respectively than the increase caused by NaCl (Shariatmadari *et al.* 2011). Xue *et al.* (2012) showed that the hydraulic conductivity of GCLs exposed to $CaCl_2$, $MgCl_2$, KCl, and NaCl solutions increased due to the thinning of the double layer on the GCL mineral particle surface with increasing salt concentration (Xue *et al.* 2012). In experiments performed at 200 mM concentrations, the hydraulic conductivity of GCL (3.25×10^{-9} cm/s) increased 284-fold, 262-fold, 19.5-fold, and 19-fold for $CaCl_2$, $MgCl_2$, KCl, and NaCl solutions, respectively (Xue *et al.* 2012). Chen *et al.* (2019) found that leachate with a higher polyvalent cation concentration causes a greater increase in hydraulic conductivity of GCL than leachate with a lower polyvalent cation concentration (Chen *et al.* 2019).

3.3. Organic contaminants

In addition to inorganic components, solid waste landfill leachates also contain organic compounds that cause pollution of the environment and groundwater. While volatile fatty acids (VFAs) constitute 80% of the organic components in young

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leachates, it forms humic and fulvic-like fractions in old leachates (Kulikowska & Klimiuk 2008; Naveen *et al.* 2015). While COD is >10.000 mg/L in young landfill leachate, COD is <3,000 mg/L in leachate from landfills older than 10 years (Kulikowska & Klimiuk 2008; Xue *et al.* 2012; Gu *et al.* 2019). While the BOD_5/COD ratio is 0.5–0.7 in young leachates, this ratio is close to 0.1 in old leachates (Naveen *et al.* 2015). In some of the world's largest landfills (New Zealand, Hong Kong, Malaysia, Indonesia, Korea, United Kingdom, South Africa) COD values are generally between 2,000 and 8,000 mg/L, while BOD5 values are generally below 1,000 mg/L (Robinson 2005). The presence of many organic compounds such as alcohols, phenols, aldehydes, ketones, carboxylic acids, chlorinated benzenes, phenols, dioxins and furans, aromatic and polyaromatic hydrocarbons have been detected in leachates around the world (Jambers Scandelai *et al.* 2017).

Most of the organic contaminants in landfills are not prone to adsorbing by soil particles and are difficult to decompose by microorganisms and chemical processes (little/no oxygen and sunlight), making them extremely mobile. Therefore, the spread of organic materials into the groundwater is more (Scott *et al.* 2005; Sreedharan & Sivapullaiah 2011). For this, the hydraulic performance of the barrier systems must be good.

Another important point is that although volatile organic compounds (VOC) are found in lower concentrations (μg/L) in leachate compared to inorganic compounds, their presence in leachate is important because they are more toxic. In addition, VOCs have high transmission rates and the ability to diffuse through the geomembrane layer. Geomembranes are less resistant to the diffusion of organic contaminants than to the diffusion of inorganic contaminants.

The passage of inorganic contaminants through the soils of the storage area occurs through advection and diffusion mechanisms after the openings in the geomembrane. Passages of inorganic contaminants occur through advection and diffusion mechanisms, following the openings in the geomembrane. There are two ways for the passage of volatile organic compounds. The first of these is the advection and diffusion of volatile organics through the openings in the geomembrane layer, just as in the passage of inorganic contaminants. Another way is the passage of volatile organics through the geomembrane by diffusion, even if there is no opening in the geomembrane layer.

Many researchers have reported that most organic chemicals will cause an increase in the hydraulic conductivity of clay soil (Moon *et al.* 2007; Amadi 2013; Mosavat & Nalbantoglu 2013; Mortezaei & Karimpour Fard 2017; Wang *et al.* 2019).

For the hydraulic conductivity of clay soils not to be affected by organic liquid, the solution should consist of at least 50% water and there should be no phase separation. In other words, since organic liquids that can be mixed with water are diluted with water, the effect of organic liquids on clay soils is reduced. When organic liquid is less dense than water, it floats above the water and affects the properties of the soil at the point of contact with the clay soil (Daniel & Shackelford 1968; Anderson *et al.* 1985). Mosavat & Nalbantoglu (2013) reported that permeability increased from approximately 2.25×10^{-8} to 4.5×10^{-8} with increasing ethylene glycol concentration from 20% to 100% (pure) (Mosavat & Nalbantoglu 2013).

Among the reasons why organic liquids affect soil permeability are that their dielectric constants and polarities are lower than water, they are less adsorbed on the surface of soil particles and they change the texture of the soil.

There are studies in the literature suggesting that organic liquids increase soil permeability due to their low dielectric constants (Kinsky *et al.* 1971; Fernandez & Quigley 1985; Mosavat & Nalbantoglu 2013; Mortezaei & Karimpour Fard 2017).

Since the dielectric constant of organic chemicals is lower than the dielectric constant of water, the thickness of the diffuse double layer surrounding the clay particles decreases. With the shrinkage of the diffusion bilayer, the soil particles get closer to each other, in other words, flocculation occurs. As a result, both macroporous aggregates occur and cracks occur between aggregates (Eltarabily *et al.* 2015; Mortezaei & Karimpour Fard 2017). Generally, the dielectric constant must be less than 30–50 for a change in the hydraulic conductivity of the soil to occur (Daniel & Shackelford 1968).

Kinsky *et al.* (1971) stated that the dielectric constant of the pore fluid is one of the main factors affecting the permeability and that the permeability increases as the dielectric constant decreases (Kinsky *et al.* 1971). Fernandez & Quigley (1985) found that as the dielectric constant decreased from 80 (water) to 2 (benzene), the hydraulic conductivity of soil increased from 5×10^{-9} to 1×10^{-4} cm/s (Fernandez & Quigley 1985). Mortezaei & Karimpour Fard (2017) found that organic liquids (methanol, car oil, and gasoline) cause shrinkage of DDL surrounding clay soil particles and agglomeration of soil particles. It has been reported that methanol with a dielectric constant of 32.6 can increase the permeability of the soil up to 5 times, while car oil and gasoline with a lower dielectric constant (2.3 and 2.28, respectively) can increase it up to 120 and 2,500 times, respectively. It has been observed that viscosity is an important factor in the difference between the change in hydraulic conductivity of car oil and gasoline, which have very close dielectric constants (Mortezaei & Karimpour Fard 2017). Mosavat & Nalbantoglu (2013) showed that organics with low dielectric constants (37.7 and 2.40 for ethylene glycol and toluene, respectively) cause flocculation and aggregation of the soil structure, increasing permeability (Mosavat & Nalbantoglu 2013).

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As a different result from the above-described studies in which organic contaminants increased the hydraulic conductivity of the soil, according to the findings of Petrov *et al.* (1997), although 25% ethanol/water and 50% ethanol/water solutions had lower dielectric constants than water, they reduced the hydraulic conductivity of GCL (Petrov *et al.* 1997). The permeability of GCL increased as a result of contact with 75% ethanol/water and 100% ethanol. Petrov *et al.* (1997) associated this with viscosity as the controlling factor for hydraulic conductivity at ethanol ratios of less than 50%, while double-layer effects were the controlling factor for ethanol ratios higher than 50%. (Petrov *et al.* 1997). Green *et al.* (1981) obtained a result that contradicted the results of other researchers (Fernandez & Quigley 1985; Mosavat & Nalbantoglu 2013; Mortezaei & Karimpour Fard 2017) and reported that the permeability of the soil increased as the dielectric constant of organic solvents increased (Green *et al.* 1981). Green *et al.* (1981) explained this situation by the fact that liquids with high dielectric constants are generally hydrophilic and can move through the ground more easily (Green *et al.* 1981).

Polarity is one of the reasons why organic liquids change in clay soil. The plastic properties of the clay are affected by the polarity of the pore fluid. Various intermolecular attraction forces allow the pore liquid to be adsorbed on the soil surface in clay soils with small pores and high surface area. The water (polar) layer adsorbed on the surface of the soil particles reduces the size of the pore channels. In smaller pores, the ability of the liquid to move in the soil decreases (Budhu *et al.* 1991). Most organic liquids have a lower polarity than water. Some researchers suggest that organic liquids with a lower polarity than water will move through pores more easily because they bind less strongly to soil particles (Anderson *et al.* 1985; Amadi 2013; Mortezaei & Karimpour Fard 2017). Therefore, these researchers argue that the increase in permeability caused by non-polar fluids is higher than the increase brought by polar fluids. Brown and Anderson *et al.* (1985) reported that as a result of the reaction between organic liquid (non-polar heptane and xylene) and clay, the permeability is approximately 100 times higher than the initial one, with the change in soil structure (Anderson *et al.* 1985). Amadi (2013) reported that even when the concentration of acetone/water and ethanol/water rises to 75%, the hydraulic conductivity is quite close to the base value of 1×10^{-7}, due to the inability of chemicals to reach the double spreading layer of the three different lateritic soils, and the hydraulic conductivity does not decrease much. When 100% acetone and ethanol were used, an increase of about half, one, and two times occurred in the hydraulic conductivity of soil samples against water. The increase in hydraulic conductivity has been attributed to the more polar water hydration of DDL cations in compacted soils and the rejection of less polar acetone and ethanol (Amadi 2013). Mortezaei & Karimpour Fard (2017) revealed that the soil permeability for methanol, which is a relatively polar fluid, has the lowest permeability after water, and the permeability is the highest for gasoline as a non-polar fluid (Mortezaei & Karimpour Fard 2017). On the contrary, Sentenac *et al.* (2012) reported a study that clay has high hydraulic conductivity for highly polar liquids (water and ethanol) (Sentenac *et al.* 2012).

Large spaces in flow channels are one of the reasons for the increase in hydraulic conductivity. Clay minerals can agglomerate with the clay-organic fluid interaction, forming a soil matrix with large pore spaces. Thus, the soil structure undergoes a change that allows the liquid to flow more easily. According to Anandarajah (2004), with the passage of organic materials, the void ratio between the clumps may increase along the clay soil, and cracks may occur in the soil structure (Anandarajah 2004). Table 3 shows the results of studies in the literature on the effect of organic contaminants on the hydraulic conductivity of landfill liners.

3.4. Suspended solids

The voids of porous media may decrease depending on the presence of biological (biomass increase), chemical (mineral precipitation), and physical factors. The decrease in porosity and pore size in porous media leads to a decrease in hydraulic conductivity (Vinten *et al.* 1983; Vangulck & Rowe 2004; Banihashem & Karrabi 2020). Suspended solids in the leachate accumulate in the soil pores, causing physical clogging of the soil and a decrease in hydraulic conductivity. Metzger *et al.* (1983) reported that unfiltered wastewater (containing suspended solids) causes about 50% reduction in soil hydraulic conductivity, while filtered wastewater causes 20% reduction in hydraulic conductivity (Metzger *et al.* 1983). The results showed that the main reason responsible for the decrease in the hydraulic conductivity of the soil is due to physical clogging by suspended solids (Metzger *et al.* 1983). Viviani & Iovino (2004) also showed that in two different soil samples, the suspended solids in wastewater have a reducing effect on the hydraulic conductivity, and the hydraulic conductivity of the soil gradually decreases as the suspended solids concentration increases (Viviani & Iovino 2004).

The size of the suspended solid affects both the hydraulic conductivity and the location at which clogging occurs in the porous medium. The smaller the size of the blocking particle, the greater the likelihood that the blockage will occur far from the surface. Or vice versa, large particle sizes increase the likelihood of clogging near the surface (Du *et al.* 2018). Sepaskhah & Sokoot (2010) investigated the effect of wastewater with $\geq$40 mg/L total suspended solid on hydraulic conductivity in different soil

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Table 3 | Effect of organic materials on hydraulic conductivity

Contaminants	Liner	Hydraulic conductivity (cm/s)	Change in hydraulic conductivity	Reference
Old leachate Young leachate	GCL	3.50×10^{-7} 5.35×10^{-9}	Hydraulic conductivity decreased as DOC concentration increased.	Han *et al.* (2009)
Water Methanol Car oil Gasoline	Clay	3.5×10^{-9} 1.45×10^{-8} 4.22×10^{-7} 8.8×10^{-6}	Hydraulic conductivity increased as the dielectric constants of organic solvents decreased.	Mortezaei & Karimpour Fard (2017)
0–60,000 mg/L COD	Clay	~Increase from 1.5×10^{-9} to 7×10^{-9}	Hydraulic conductivity increased as the COD concentration increased.	Wang *et al.* (2019)
Distilled water Toluene Ethylene glycol		3×10^{-8} 4×10^{-8} 4.5×10^{-8}	Hydraulic conductivity increased as the dielectric constants of organic liquids decreased.	Mosavat & Nalbantoglu (2013)
20% ethylene glycol 100% ethylene glycol		~2.25×10^{-8} 4.5×10^{-8}	Hydraulic conductivity increased as the ethylene glycol concentration increased.	Mosavat & Nalbantoglu (2013)
Water Gasoline	Kaolin Bentonite Kaolin Bentonite	2.16×10^{-8} 2.35×10^{-9} 4.61×10^{-5} 8.41×10^{-5}	When the permeable liquid was converted from water to gasoline, the hydraulic conductivity of the clay minerals increased by 3–4 orders of magnitude.	Moon *et al.* (2007)
Water 100% acetone and 100% ethanol	Lateritic soil Lateritic soil Lateritic soil Lateritic soil Lateritic soil	6.29×10^{-8} 1.44×10^{-8} 8.55×10^{-9} (m/s) – – –	– The hydraulic conductivity increased by half, one and two times compared to the values obtained with water.	Amadi (2013)
25% ethanol 50% ethanol 75% ethanol 100% ethanol		7.3×10^{-10} 6.0×10^{-10} 4.1×10^{-9} 2.0×10^{-7}	Hydraulic conductivity decreased to less than 50% ethanol and then increased.	Petrov *et al.* (1997)
Water Ethanol Isopropanol Butanol Ethanediol	Kaolinite	~1.3×10^{-9} 7×10^{-10} 4×10^{-10} 3×10^{-10} 2×10^{10} (m/s)	A high hydraulic conductivity is obtained for high polarity liquids (water and ethanol); A low hydraulic conductivity was obtained for ethanediol with the highest viscosity.	Sentenac *et al.* (2007)
Water Gasoline	Silty clay-HDTMA bentonite (90:10)	1.57×10^{-8} 9.20×10^{-10}	Due to the organophilicity of HDTMA, the hydraulic conductivity of the liner for gasoline is about 1.5 orders of magnitude lower than the hydraulic conductivity of the liner to water.	Javadi *et al.* (2017)

textures and found that the main effect occurred at the surface (more than 50% reduction at 0–50 mm). In the deeper parts of the soil (100–300 mm), the hydraulic conductivity of the soil layer was not significantly affected by the total suspended solids. For four different wastewaters with suspended solids concentration of 40 mg/L–235 mg/L, the reduction in hydraulic conductivity of clay loam at 100–300 mm was quite low (11, 13, 6, and 0%, respectively) (Sepaskhah & Sokoot 2010). Table 4 summarizes the results of studies on the effect of suspended solids on hydraulic conductivity of landfill liners.

3.5. Microorganisms

It has been proven by many researchers that microbial activity causes a decrease in the hydraulic conductivity of the soil (Faybishenko 1995; Seki *et al.* 1996, 1998; Dennis & Turner 1998; Kirk *et al.* 2012; Kerry Rowe & Yu 2013; Soon *et al.*

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Table 4 | Effect of suspended solids on hydraulic conductivity

Suspended solids (mg/L)	Liner	Change in hydraulic conductivity	Reference
50 (No filtration) 7 (After filtration)	Sandy loam Sand Sandy loam Sand	53% decrease 65% decrease 20% decrease 22% decrease	Metzger *et al.* (1983)
57–68 92–372	Loam soil Clay soil	%20 decrease There was a reduction of up to 80% in hydraulic conductivity.	Viviani & Iovino (2004)
40–235	Clay loam Sandy loam Loam	In wastewater applications with ≥40 mg/L suspended solids, the hydraulic conductivity decreased by more than 50% at 0–50 mm.	Sepaskhah & Sokoot (2010)

2014; Tang *et al.* 2018; Osinubi *et al.* 2020). The resulting biofilms and colonies cover the surface of the mineral particles and grow in the pore spaces of the soil, clogging the pores and playing a role in the reduction of the hydraulic conductivity of the soil (Brovelli *et al.* 2009; Francisca & Glatstein 2010). The factors that directly affect the decrease in the hydraulic conductivity of the soil caused by microbial activity can be explained by the colony, extracellular polymeric substances (EPS), and gas formation.

Microorganisms in the leachate can cling to the surfaces of soil particles and form a biofilm in the porous environment. Biofilms are communities of microorganisms embedded in a polymer matrix, attaching to surfaces and growing (Tang *et al.* 2018). Bacteria first colonize using the nutrients available in the medium and then produce EPS. (Seki et al. 1998; Vangulck & Rowe 2004) The physical properties of biofilms vary depending on the types of bacteria forming the biofilm and the EPS composition (Dennis & Turner 1998).

The nutrient load found in leachate causes the growth of bacteria and/or yeast colonies that cause partial or permanent clogging of soil pores. The addition of growth substrates such as carbon increases the activity of microorganisms (Magesan *et al.* 2000). Frankenberger *et al.* (1979) reported that the addition of glucose + KNO_3 caused the greatest decrease in hydraulic conductivity among glucose, KNO_3, and glucose-KNO_3 in two different soil samples (Frankenberger *et al.* 1979). Frankenberger *et al.* (1979) attributed this phenomenon to the fact that glucose + KNO_3 is a source of both carbon (C) and nitrogen (N), which further stimulates the production of bacterial metabolic products (Frankenberger *et al.* 1979). Seki (1996) stated that the decrease in the hydraulic conductivity of the soil with glucose over time is due to the effect of biological clogging and gas occlusion (Seki *et al.* 1996). Similarly, Seki *et al.* (1998) showed that the permeability of the soil decreased with glucose, and with the addition of sodium azide, which is a strong biocide, the gas volume ratio of the sample decreased and the hydraulic conductivity increased at the same time (Seki *et al.* 1998). The results in the literature show that soil voids are blocked and hydraulic conductivity decreases with the presence of substances such as C, N, which promote microbial growth.

EPSs, like bacterial cells, have a similar effect in reducing soil porosity. It is known that biofilm thicknesses in the range of 15–150 μm cause significant reductions in the porosity and permeability of the medium (Or *et al.* 2007). Ragusa *et al.* (1994) found that a 16-fold increase in the amount of polysaccharides in the soil caused a 4.8-fold decrease in hydraulic conductivity (Ragusa *et al.* 1994). Tang *et al.* (2018) reported that the effective porosity of clay/sand mixed soils is reduced due to the production of large amounts of extracellular polymeric material by E. coli, the bacteria most commonly found (Bodzek *et al.* 2006; Grisey *et al.* 2010) in leachate (Tang *et al.* 2018). The results showed that the permeability decreased by 81%–95% due to the decrease in effective porosity (Tang *et al.* 2018).

Dennis *et al.* (1998) reported that *Beijerinckia indica*, a biofilm-producing bacterium, caused a reduction of 3 orders of magnitude (from 10^{-5} cm/s to 10^{-8} cm/s) in the final hydraulic conductivity of the soil (Dennis & Turner 1998). Kirk (2012) has shown that biomass remains substantially undegraded in the medium even after acidification and that the medium can continue to reduce hydraulic conductivity even if significant death occurs (Kirk *et al.* 2012). Kanmani *et al.* (2014) reported that biofilm formation with detectable thickness was observed due to hasty growth in the medium within 2–3 days in a microbially inoculated sand-filled colon (Kanmani *et al.* 2014). While there was a 68% decrease in hydraulic conductivity in the first 6

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days due to the uniform biofilm thickness throughout the sand-filled column, a decrease of up to 98.88% occurred in hydraulic conductivity at the end of the 45th day (Kanmani *et al.* 2014). A similar study of the physical clogging of soil pores by microorganisms was also carried out by Soon *et al.* (2014) reported a 25% reduction in hydraulic conductivity because *B. megaterium* caused a decrease in soil porosity (Soon *et al.* 2014).

Another factor that has a direct effect on the reduction of the hydraulic conductivity of the soil by microorganisms is the gases produced by the microorganisms. Gases produced by bacteria, such as methane, clog conductive spaces due to bubbles, resulting in reduced permeability (Sanchez de Lozada *et al.* 1994; Seki *et al.* 1996, 1998). Seki *et al.* (1996) showed that the decrease in the hydraulic conductivity of the soil is caused by the microbially synthesized products accumulating in the soil pores and the methane gas produced by the bacteria clogging the pore spaces (Seki *et al.* 1996). Table 5 contains the results of the literature studies on the effects of microorganisms and some substances that promote the growth or reduction of microorganisms on the hydraulic conductivity of the liners.

3.6. Heavy metals

Clay type, metal type, temperature and pH are the factors affecting the interaction between metal and clay. The effect of heavy metal solutions on the clay structure can be explained by Equation (2) given in Section 3.2. The double layer thickness of the clay particles is inversely proportional to the concentration and valence. Double layer thickness for clay particles decreases with increasing heavy metal solution concentration. For clay particles larger t values mean repulsive forces dominate, while lower t values mean attractive forces dominate. Since a dispersed particle structure is formed in the conditions where repulsive forces are dominant, the passage of the liquid becomes difficult and lower hydraulic conductivity values are obtained. On the contrary, in conditions where attractive forces dominate, flocculation of clay particles occurs. As the pore spaces around the flocculated structures increase, the hydraulic conductivity also increases. Therefore, heavy metals often cause a flocculated structure in clay soils (Li & Li 2001).

The effect of heavy metal concentration on various barrier liners used in landfills has been studied by some researchers (Metzger *et al.* 1983; Li & Li 2001; Dutta & Mishra 2016; Ajitha & Sheela Evangeline 2019; Wang *et al.* 2019; Zheng *et al.* 2019; Ban *et al.* 2021; Yu *et al.* 2021). Unlike other researchers, Ajitha *et al.* (2019) found that the hydraulic conductivity of the thonnakkal clay-bentonite mixture decreased with increasing heavy metal (Pb^{+2}) concentration (Ajitha & Sheela Evangeline 2019). Li & Li (2001) examined the effect of heavy metals on the hydraulic conductivity of sand/bentonite mixed soils at a weight ratio of 100:8 (Li & Li 2001). It has been reported that the Pb adsorption capacity of bentonite is higher than that of Cu and Cd, and as a result, three different metal ions have different effects on the flocculation of bentonite mixtures. However, in experiments with Pb, Cu, Pb/Cu, and Pb/Cu/Cd mixtures, the hydraulic conductivity of the soils was found to be quite close to each other. Li and Li associated this with the fact that the soil was mainly composed of sand (Li & Li 2001). Dutta & Mishra (2016) reported that with the increase of heavy metal concentration in the soil pore fluid, the amount of unadsorbed concentration on the surface of the clay particles increased, the repulsive forces between the particles decreased and the clay particles approached each other (Dutta & Mishra 2016). Zheng *et al.* (2019) stated that the hydraulic conductivity increases as a result of heavy metal ions mixing into the soil and the soil particles forming a larger permeability channel (Zheng *et al.* 2019). In Table 6, studies in the literature on the effect of heavy metals on the hydraulic conductivity of liners are summarized.

4. DİRECTİONS FOR FUTURE STUDİES

The composition of the leachate generated in solid waste landfills is very complex, and the contaminant concentration of the leachate is highly variable depending on many factors. Therefore, it is quite difficult to determine the effect of each contaminant on the hydraulic conductivity of the clay liner in real leachate. Many researchers have prepared synthetic solutions at certain concentrations by selecting a single contaminant parameter to determine the effect of contaminants in leachate on the hydraulic conductivity of clay liners, and research has been carried out. Investigation of the effect of each contaminant such as ions, organic matter, suspended solids, microorganisms, and heavy metals on the hydraulic conductivity of the clay liner is very important and valuable to determine the factor responsible for the change in the hydraulic conductivity of the contaminant. However, even if the concentration of a contaminant whose effect on hydraulic conductivity is known is high in real leachate, a different result than expected may be encountered in the change in hydraulic conductivity due to the presence of other contaminants in the environment and interactions between contaminants. It is difficult to prepare synthetic water with a contaminant composition similar to real leachate in laboratories. However, in future research, synthetic waters containing

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Table 5 | Effect of microorganisms and substances that promote the growth or reduction of microorganisms on hydraulic conductivity

Additive	Liner	Hydraulic conductivity (cm/s)	Change in hydraulic conductivity	Reference
Beijerinckia indica	Silty sand	Decrease from 10^{-5} to 10^{-8}	There was a decrease of about 3 orders of magnitude compared to baseline.	Dennis & Turner (1998)
Glucose (50 μg/cm^3) Sodium azide (50 μg/cm^3)	Andisol	Decrease from 2×10^{-3} to 3×10^{-6} Increase from 3×10^{-6} to 5×10^{-4}	At the end of the 120 day, the hydraulic conductivity decreased. Hydraulic conductivity increased within 8 days.	Seki *et al.* (1998)
E. coli	Clay-sand (2:8), (4:6) (8:2)	–	There was a 10-fold, 81 and 95% reduction compared to the baseline value.	Tang *et al.* (2018)
Glucose (50 ppm)	Andisol	Decrease from 10^{-4} to 10^{-6}	After 118 days the hydraulic conductivity decreased by two orders of magnitude from baseline.	Seki *et al.* (1996)
Glucose KNO_3 Glucose + KNO_3 Glucose KNO_3 Glucose + KNO_3	Loam Silty loam	0.08 (cm/h) 0.14 (cm/h) 0.01 (cm/h) 0.14 (cm/h) 0.28 (cm/h) 0.03 (cm/h)	The greatest decrease in hydraulic conductivity occurred with the addition of glucose + KNO_3.	Frankenberger *et al.* (1979)
Polysaccharide (from 0.26 to 4.28 mg/g)	Fine sandy loam	Decrease from $\sim 3.7 \times 10^{-7}$ to 1.4×10^{-7} (m/sn)	As the concentration increased, the hydraulic conductivity decreased.	Ragusa *et al.* (1994)
Bacterial strains isolated from landfill leachate	Sand	2.31×10^{-4} (45th day)	Hydraulic conductivity decreased up to 98.88% at the 45th day due to biofilm formation.	Kanmani *et al.* (2014)
Methanosarcina barkeri	Sand	–	Hydraulic conductivity decreased by 3 and 25%, respectively, at two permeameters filled with sand.	Sanchez de Lozada *et al.* (1994)

several polluting parameters should be prepared and the effect on the clay liners should be examined. Thus, in the presence of more than one contaminant parameter, which is a great lack of research in the literature, results can be obtained about which contaminant parameter has a more dominant effect on the hydraulic conductivity of the clay liner compared to the others.

As another issue, studies should be focused on examining the interaction between the characterization results of clay liners used in landfills and each contaminant. Thus, it will be possible to select and design a longer-lasting, more efficient, and more economical clay liner against the strong contaminant composition of the leachate.

As a result, there is a need to investigate the following questions regarding the effect of leachate on the hydraulic conductivity of clay liners used in landfills and to fill the gap in the literature:

(1) Which contaminant component makes the most dominant contribution to the change in hydraulic conductivity in real leachate where all the contaminant components are together or in synthetic water where more than one contaminant component coexists?
(2) To what extent is the effect of a contaminant component on hydraulic conductivity in synthetic waters prepared in different combinations containing several contaminant components, affected by the presence of other polluting component(s) in the environment?
(3) What is the effect time of synthetic water consisting of several contaminants on the hydraulic conductivity?
(4) According to the type of contaminant, what is the most important factor (such as dielectric constant, polarity, viscosity) of the contaminant that affects the change in hydraulic conductivity?
(5) What effect do the same contaminants with the same concentration have on the hydraulic conductivity of liners with different compositions and structures?

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Table 6 | Effect of heavy metals on hydraulic conductivity

Contaminants	Liner	Hydraulic conductivity (cm/s)	Change in hydraulic conductivity	Reference
Pb Cu Pb + Cu Pb + Cu + Cd	Sand/ bentonite (100:8)	4.7×10^{-9} 4.8×10^{-9} 4.3×10^{-9} 2.4×10^{-9} (m/s)	The hydraulic conductivity was found to be close to each other because the soil samples were mainly composed of sand.	Li & Li (2001)
0–4 mg/L Pb^{+2}	Clay	~Increase from 1.25×10^{-9} to 2.2×10^{-9}	As the concentration increased, hydraulic conductivity also increased.	Wang *et al.* (2019)
0–40 mg/L Pb^{+2}	Clay-bentonite (95:5)	Decrease from 2×10^{-5} to 7.8×10^{-7}	As the concentration increased, hydraulic conductivity decreased.	Ajitha & Sheela Evangeline (2019)
0–10 mM Pb^{+2}	GCL	Increase from 10^{-9} to 10^{-7}	As the concentration increased, hydraulic conductivity also increased.	Yu *et al.* (2021)
0 mg/kg Pb^{+2} or Zn^{+2} 1,000 mg/kg Pb^{+2} 1,000 mg/kg Zn^{+2}	Weak expansive soil	2.2×10^{-8} 5×10^{-8} 4.8×10^{-8} (m/s)	As the concentration increased, hydraulic conductivity also increased.	Zheng *et al.* (2019)
0–10 g/L Cu^{+2}	Red Clay	3.54×10^{-6} 42.25×10^{-6}	As the concentration increased, hydraulic conductivity also increased.	Ban *et al.* (2021)
0–100 ppm Cu^{+2} 0–1,000 ppm Cu^{+2} 0–100 ppm Pb^{+2} 0–1,000 ppm Pb^{+2} 0–100 ppm Zn^{+2} 0–1,000 ppm Zn^{+2}	Bentonite	1.7 times increase 2.6 times increase 1 time increase 1.2 times increase 1.4 times increase 2.2 times increase	As the concentration increased, hydraulic conductivity also increased.	Dutta & Mishra (2016)

(6) Can the deterioration in the soil structure, which is responsible for the change in hydraulic conductivity as a result of the contaminant-clay soil interaction, be improved by adding different materials to the soil, and can the soil structure be made more resistant to the contaminant effect?

5. CONCLUSIONS

There are many studies on the effect of leachate contaminants on the hydraulic conductivity of landfill liners. Substances such as acids, bases, salt solutions, organic contaminants, suspended solids, microorganisms, and heavy metals in the leachate affect the hydraulic conductivity of the landfill liners. The effect of acids and bases on hydraulic conductivity generally occurs through the dissolution of clays. Increasing the concentration of salt solutions and increasing the valency of the cations reduces the DDL thickness of the clay particles, creating an effect that increases the hydraulic conductivity. Since organic contaminants generally have lower dielectric constants and lower polarity than water, they are less adsorbed on the soil surface and cause a change in the structure of the soil, thus increasing the hydraulic conductivity in general. Suspended solids, microorganisms, gases produced by microorganisms, and EPS produced by microorganisms cause decrease in hydraulic conductivity as a result of soil clogging. Since heavy metals cause clay liners to form a more flocculated structure, they generally increase the hydraulic conductivity depending on the heavy metal concentration. Although significant progress has been achieved so far in the effect of each contaminant in the leachate on the hydraulic conductivity of the liners used in

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the landfill, studies and effort are needed to determine the effect of real leachate and/or synthetic leachate on the hydraulic conductivity of the landfill liners.

DATA AVAILABILITY STATEMENT

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

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