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1 **The Case for Examining Fluid Flow in Municipal**
2 **Solid Waste at the Pore-Scale – A Review**

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ABBREVIATIONS

MSW, Municipal solid waste; REV, Representative elementary volume; FLAC, Fast lagrangian analysis of continua; ERT, Electrical resistivity tomography; CFD, Computational fluid dynamics; NH, Neglects heterogeneity; IC, Ignores coupled phenomena; AD, Advection-dispersion; DP, Dual-porosity

16 **Graphical abstract**

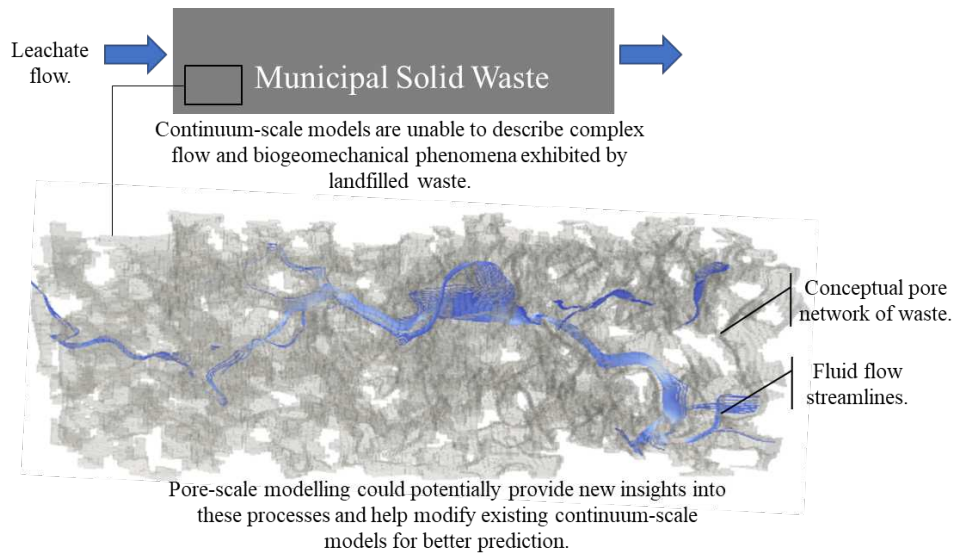
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23 **ABSTRACT**

24 In this paper, we discuss recent efforts from the last 20 years to describe transport in municipal
25 solid waste (MSW). We first discuss emerging themes in the field to draw the reader's attention to
26 a series of significant challenges. We then examine contributions regarding the modelling of
27 leachate flow to study transport via mechanistic and stochastic approaches, at a variety of scales.
28 Since MSW is a multiphase, biogeochemically active porous medium, and with the aim of
29 providing a picture of transport phenomena in a wider context, we then discuss a selection of
30 studies on leachate flow incorporating some of the complex landfill processes (e.g. biodegradation,
31 settlement). It is clear from the literature survey that our understanding of transport phenomena
32 exhibited by landfilled waste is far from complete. Attempts to model transport have largely
33 consisted of applying representative elementary-scale models (the smallest volume which can be
34 considered representative of the entire waste mass). Due to our limited understanding of fluid flow
35 through landfilled waste, and the influence of simultaneously occurring biogeomechanical
36 processes within the waste mass, elementary-scale models have been unable to fully describe the
37 flow behaviour of MSW. Pore-scale modelling and experimental studies have proven to be a
38 promising approach to study fluid flow through complex porous media. Here, we suggest that pore-
39 scale modelling and experimental work may provide valuable insights into transport phenomena
40 exhibited by MSW, which could then be used to revise elementary-scale models for improved
41 representation of field-scale problems.

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45 **KEYWORDS**

46 municipal solid waste; modelling leachate transport; landfill; waste heterogeneity; preferential
47 flow.

48 **1. INTRODUCTION**

49 Global municipal solid waste (MSW) generation is expected to increase at least threefold by the
50 end of the century (Hoornweg and Bhada-tata, 2012; Hoornweg et al., 2013). Due to high
51 production rates and landfilling being the most common method of waste disposal worldwide, a
52 significant proportion of this waste is expected to go to landfill. Likewise, in parts of the world
53 where disposal has moved away from landfilling, closed facilities will remain. As such, landfilling,
54 at least for the foreseeable future will be of relevance to the waste sector. The leachate produced
55 due to infiltration of net precipitation, typically contains dissolved heavy metals, recalcitrant
56 organics and inorganics that could contaminate groundwater and surface water if allowed to escape
57 from the landfill (Kjeldsen et al., 2002). As such, the fate of this waste water within the landfill
58 mass and in the geoenvironment is of interest to environmental engineers and scientists (Remmas
59 et al., 2017). In bioreactor landfills, the leachate may be recirculated through the waste mass to
60 enhance degradation and methane recovery with the prospect of early stabilization of the landfill
61 (Barlaz and Reinhart, 2004; Reinhart et al., 2002). Moreover, flushing technologies using water
62 and/or other biotechnological agents have also been studied to accelerate landfill stabilisation and
63 decrease its potential to contaminate the surrounding geoenvironment (Bolyard, 2016; Bolyard and
64 Reinhart, 2016; Hettiaratchi et al., 2014; Hettiaratchi et al., 2015; Jayasinghe et al., 2014; Rashid
65 et al., 2017). The aforementioned approaches may pave the way towards sustainable landfilling

66 (Jayasinghe, 2013; Jayasinghe et al., 2011, 2014; Jayasinghe et al., 2013; Rashid et al., 2017).
67 However, for field-scale application and prediction, an understanding of the transport phenomena
68 at play within the waste matrix, which will ultimately determine the effectiveness of flushing or
69 recirculation techniques with the possibility of relatively early stabilisation of the landfill, is
70 required.

71 MSW is a complex, biogeochemically active, heterogeneous porous medium (Barlaz et al.,
72 1990). Due to its spatially and temporally varying nature (both within individual landfills and
73 across the worldwide inventory), it is challenging to develop transport models with a realistic
74 prospect of widespread applicability to MSW. However, it is important to note that models, no
75 matter how complex, will always be a simplification of reality, and that the need and accuracy of
76 models is often operationally defined. Early studies on flow were focused primarily on predicting
77 the overall volume of leachate produced from an MSW sample under laboratory conditions
78 (Ahmed et al., 1992; Demetracopoulos et al., 1986a; Demetracopoulos et al., 1986b; El-Fadel et
79 al., 1997; Khanbilvardi et al., 1995; Korfiatis et al., 1984; Noble and Arnold, 1991; Zeiss, 1992).
80 The most common approach to model the flow of leachate has consisted of applying the Richards
81 equation to calculate the evolution of the leachate velocity in space-time while also incorporating
82 the convection-dispersion equation to provide solute concentrations (Bendz and Singh, 1999;
83 Demetracopoulos et al., 1986a; Demetracopoulos et al., 1986b; El-Fadel et al., 1997; Han et al.,
84 2011; Haydar and Khire, 2005; Haydar and Khire, 2007; Khire and Kaushik, 2012; Khire and
85 Mukherjee, 2007; Khire and Saravanathiiban, 2010; Korfiatis et al., 1984; Noble and Arnold,
86 1991). Extensive use of these mechanistic representative elementary volume (REV) (often defined
87 as the smallest volume which can be considered representative of the entire waste mass) based
88 models has been carried out to understand the flow behaviour of MSW (Rosqvist and Destouni,

89 2000; Rosqvist et al., 2005) with some studies focusing on conceptual models of the pore structure
90 of MSW at the elementary scale (Han et al., 2011; Woodman et al., 2014, 2015; Woodman et al.,
91 2013). However, to date, our understanding of the flow of leachate, biogas and the impact of other
92 simultaneously occurring biogeochemical processes on flow and transport is incomplete,
93 especially at the pore-scale. This is particularly important to note since it is these pore-scale
94 processes, with the possibility of field-scale processes dominating particular facets at particular
95 times, that ultimately govern the overall behaviour in reactive porous media (Blunt, 2001; Blunt
96 et al., 2013; Menke et al., 2017; Xiong, 2015; Xiong et al., 2016). It is likely that processes average
97 over a wide range of different scales, which would explain the success of the widely used empirical
98 landfill gas models. The real challenge lies in the integration of modelling processes at all the
99 scales and understanding how averaging works. It is clear that one of the most difficult aspects to
100 model is the inherent heterogeneity of the waste mass, and the impact of different waste
101 components (e.g. their shapes, sizes and varying biodegradation rates) and numerous coupled
102 processes on the flow regime. In this paper, heterogeneity is referred to as the variability in the
103 properties of MSW, while preferential flow is defined as the phenomenon where the leachate takes
104 the path of least resistance through the waste mass and channels through the larger pores (Beaven
105 et al., 2011; Dixon and Langer, 2006; Dixon et al., 2008a; Dixon et al., 2011; Dixon et al., 2008b;
106 Kjeldsen and Beaven, 2011; Powrie and Beaven, 1999; Woodman, 2007).

107 The objective of this paper is to provide a case for examining fluid flow in municipal solid waste
108 at the pore-scale. Following from El-Fadel et al. (1997), we pay particular attention to the
109 development of the field within the last 20 years. Whilst attempting to make a case for moving
110 past the REV this paper is not intended to provide an exhaustive overview of the field. Instead, we
111 reflect on a focussed collection of recent key contributions with the aim of painting an accurate

112 picture of the state of the art, highlighting the limitations of and gaps in our knowledge to identify
113 emerging themes in the field and provide suggestions for future work. We first discuss emerging
114 themes in the field to draw the reader's attention to a series of significant challenges. We then
115 examine contributions regarding the modelling of leachate flow and chemical transport via
116 mechanistic and stochastic approaches, at a variety of scales. This is followed by consideration of
117 contributions regarding leachate flow and chemical transport incorporating some of the complex
118 landfill processes (e.g. biodegradation). We conclude with future needs and recommendations to
119 improve our understanding of transport phenomena within MSW. Our recommendations are
120 focused around obtaining pore-scale insights (Figure 1) into these processes with the ultimate aim
121 of better field-scale prediction. We provide the literature search methodology as part of supporting
122 information for this article.

123 **2. EMERGING THEMES IN THE FIELD & MOTIVATION**

124 As shown in Table 1, in the last 20 years, work in the field has developed from consideration of
125 homogeneous 1D models primarily focused on the liquid phase to representation of complex 3D
126 transport processes (e.g. solute transport, biodegradation, settlement), and the interaction of these
127 phenomena with the waste structure. However, from the literature discussed hereafter, it is evident
128 that our understanding of the transport phenomena at play in MSW is far from complete.

129 As discussed in the following sections, elementary-scale models (e.g. the Richards equation)
130 have been applied extensively in the last 20 years to study flow in MSW. While researchers have
131 tried to consider the physical and biogeochemical processes taking place in the waste mass, current
132 modelling approaches simplify these processes in comparison to the high level of complexity
133 found in a typical MSW landfill system, likely adding to the discrepancies between experimental

134 data and models; all the while there is growing evidence that these complex processes play a
135 significant role in transport through MSW. Of course, models are always a simplification of reality,
136 and even coupling of relatively simple processes produces models that can be difficult to validate
137 against typical, easily available datasets. However, validation exercises are vital to identify the
138 range of validity of a particular model and its weaknesses. For instance a relatively recent model
139 comparison exercise, which is explored in detail later, found inconsistencies between available
140 models and their ability to predict experimental data from a well-constrained lab-scale MSW
141 landfill (Beaven, 2008; Beaven et al., 2008), suggesting that perhaps our understanding of
142 underlying coupled processes within the waste matrix needs improvement before reliable short-
143 term and long-term predictions can be made. It is also important to note that models are made for
144 a specific objective and in many cases the models are performing at an acceptable level to achieve
145 that objective. An example of this is the use of landfill gas models in practice (for example GasSim
146 (Golder Associates, 2012) is a widely used model in the UK) (Clewes et al., 2008). Such models
147 are extreme simplifications of reality (e.g. based on zero or first-order decay functions) but match
148 the measured trends well and are used to make operational decisions, even though our
149 understanding of the underlying processes in the waste body is still quite poor. The same applies
150 to the stoichiometric equations used in recent geochemical speciation modelling work for landfills
151 (van der Sloot et al., 2017; van der Sloot et al., 2007). While this may be the case for models with
152 a certain objective, when it comes to flow/transport models incorporating biogeomechanical
153 phenomena to describe the landfill system and predict its behaviour, they are difficult to validate
154 due to lack of complete data sets, and/or they become highly parameterized requiring empirical
155 data to infer model parameters, and even then, the high number of degrees of freedom make it
156 difficult to parameterize the models. Within this body of work, we have also found that there is a

157 significant lack of full validation of a number of flow and transport models which attempt to
158 incorporate biogeomechanical processes, against real experimental or field data. Where model
159 comparison exercises have occurred, discrepancies between modelled and experimental data are
160 suggestive of our lack of understanding of the MSW system. As such, it is difficult to say at this
161 moment in time whether these complex models are applicable to real-life scenarios for the
162 operational needs of the waste industry.

163 Recent studies (Woodman, 2007; Woodman et al., 2017; Woodman et al., 2014, 2015;
164 Woodman et al., 2013), contrary to previous work (Bendz et al., 1998; Bengtsson et al., 1994;
165 Oman and Rosqvist, 1999; Rosqvist and Bendz, 1999; Rosqvist and Destouni, 2000; Rosqvist et
166 al., 2005), have discovered that some tracers (e.g. lithium, deuterium) exhibit anomalous transport
167 in MSW, with tracers previously thought to be geochemically inert (Oman and Rosqvist, 1999;
168 Reinhart, 1989; Rosqvist and Destouni, 2000) in their passage through the pores of MSW being
169 found to exhibit non-conservative transport (Woodman et al., 2014, 2015). Current mechanistic
170 REV-based approaches have not been able to predict this behaviour; thus, we do not fully know
171 what happens to these tracers as they travel through the pore space. Upon studying the impact of
172 mechanical compression of the waste matrix on diffusion of different tracers with varying
173 diffusivities, researchers have also found that while compression decreases the hydraulic
174 conductivity block diffusion times do not vary significantly, contrary to predictions by continuum-
175 scale models (e.g. Richards' equation), suggesting that our understanding of diffusive transport
176 through MSW may not be entirely representative of real-life behaviour (Woodman et al., 2014).
177 From anomalous tracer transport, to conceptual models of the structure of MSW, it is clear that
178 our understanding of the role of MSW structure and its fluid-structure interaction with leachate as
179 it travels through the pore space is incomplete and requires further development.

180 It is also clear that the structure of the waste plays a significant role in the transport of leachate.
181 Generally, attempts to describe the structure as a homogeneous matrix have been unsuccessful,
182 with leachate exhibiting preferential channelling. Typically, in attempts to describe preferential
183 channelling, the waste structure has been split into two domains representing slow- and fast-
184 moving water. It is possible that these dual-porosity/permeability models are an oversimplification
185 of the complex flow behaviour exhibited by MSW, where the flow regimes are instead more likely
186 to be a continuous spectrum rather than just two categories of flow. However, it is important to
187 acknowledge that the simplifications within these models are a direct consequence of the intended
188 purpose of modelling. If the purpose is understanding, then simplification allows a focus on the
189 interaction of the main governing principles, if the purpose is prediction then the focus is
190 interpolation and extrapolation. However, it is important to note here that it is likely that this
191 preferential channelling, at least in part, is a direct consequence of the structure of MSW and the
192 fluid-structure interaction exhibited by the system as the leachate flows through the pore network.

193 To further understanding of these phenomena, conceptual models of the waste structure have
194 been proposed, where the waste mass is assumed to contain low and high permeability objects in
195 layers. Here, preferential pathways occur through the large gaps between these objects, and
196 advection dominates, whereas within these layers, diffusion dominates and occurs mainly in the
197 horizontal direction within the more permeable layers (Bendz et al., 1998; Woodman et al., 2014).
198 However, such proposed conceptual models of the structure of MSW are likely to be, at best,
199 difficult to validate via continuum modelling approaches that are prevalent in the literature. As
200 such, when considering transport of leachate in landfills, it may be necessary to adopt more
201 complex models offered by REV approaches to add an extra layer of detail and consider the
202 composition and hydraulic properties of MSW components and the resulting pore network. As

203 discussed below, it is likely that different waste components exhibit different permeability
204 characteristics and may cause local variation of flow properties within the waste matrix (Muaaz-
205 Us-Salam et al., 2017), and it might be important to take these into account, especially due to the
206 ever-evolving pore-structure of MSW due to biodegradation, mechanical creep etc. (Fei, 2016; Fei
207 and Zekkos, 2012; Fei and Zekkos, 2013; Fei and Zekkos, 2016; Fei et al., 2013; Fei et al., 2014a;
208 Fei et al., 2014b, 2015, 2016).

209 **3. MODELLING OF LEACHATE FLOW & SOLUTE TRANSPORT**

210 In this section we consider the development of mechanistic and stochastic modelling approaches
211 to represent leachate flow in MSW and seek to critically assess how well these models have been
212 able to capture experimentally observed behaviour. Whilst a considerable number of studies have
213 been reported e.g. (Abbaspour, 2005; Abbaspour et al., 2004; Al-Thani et al., 2004; Brun and
214 Engesgaard, 2002; El-Fadel, 1999; Haydar and Khire, 2005; Islam et al., 2001; Olaosun, 2001;
215 Oman and Rosqvist, 1999; Powrie and Beaven, 1999; Rosqvist and Bendz, 1999; Ünlü and Rowe,
216 2004), we discuss a selected few representative contributions in detail to highlight the significant
217 issues.

218 **3.1. Mechanistic techniques:** Earlier studies on flow were focused on simple REV-based
219 approaches, predominantly involving models treating MSW as a homogeneous porous medium
220 based on Darcy's law incorporating advection-dispersion phenomena to represent solute transport
221 (Ahmed et al., 1992; Bleiker et al., 1995; Chen and Chynoweth, 1995; Deeley et al., 1985;
222 Demetracopoulos et al., 1986b; El-Fadel et al., 1997; Khanbilvardi et al., 1995; Pohland, 1980;
223 Reinhart, 1995; Reinhart, 1996; Sykes and Farquhar, 1983; Sykes et al., 1982). For instance, the
224 theory of unsaturated flow through homogeneous and isotropic porous media has been applied to

225 study flow through MSW by Korfiatis et al., 1984. Their model used a vertical 1D equation for
226 downward flow through an unsaturated porous medium, considering the variation of moisture
227 content with time, hydraulic conductivity with depth and a source-sink term. Overall, the
228 agreement between the modelled and experimental data was poor. To our knowledge, this was one
229 of the first recorded studies to demonstrate the existence of preferential flow and spatial variance
230 of hydraulic properties of municipal solid waste. Much of this earlier work highlighted the
231 unsuitability of assuming MSW to be a homogeneous, porous medium and the importance of
232 including the heterogeneous nature of waste in the modelling framework.

233 In recent years, researchers have also used commercial codes and simulation software (e.g.
234 HYDRUS, MODFLOW-SURFACT, COMSOL Multiphysics etc.) to model transport in MSW
235 (Audebert et al., 2016a; Audebert et al., 2016b; Beaven et al., 2011; Fellner and Brunner, 2010;
236 Haydar and Khire, 2005; Haydar and Khire, 2007; Khire and Kaushik, 2012; Khire and Mukherjee,
237 2007; Khire and Saravanathiiban, 2010; Kjeldsen and Beaven, 2011; Olivier et al., 2009; Saquing
238 et al., 2012; Slimani et al., 2016; Tinet et al., 2011a; Tinet et al., 2011b). Amongst commercial
239 codes, HYDRUS has been a recurrent choice for modelling flow through MSW (Fellner and
240 Brunner, 2010; Haydar and Khire, 2005; Haydar and Khire, 2007; Khire and Kaushik, 2012; Khire
241 and Mukherjee, 2007; Reddy et al., 2013). HYDRUS is based on a modified form of the Richards
242 equation solved for saturated-unsaturated flow, and the advection-dispersion equation for solute
243 and heat transport. The Richards equation may also be modified to include dual-
244 porosity/permeability effects (Simunek and van Genuchten, 2008; Šimůnek et al., 2011). For
245 instance, transport of phenol as a model contaminant in a laboratory-scale reactor containing
246 simulated MSW has been studied and its transport modelled via HYRUS-1D (Saquing et al., 2012;
247 Simunek et al., 2003; Simunek and van Genuchten, 2008). Solute transport in the liquid phase was

248 described by the advection-dispersion equation. When the combined effects of sorption and
249 biodegradation on phenol transport were studied, the model was in very poor agreement with the
250 data, yielding an inversely derived biodegradation rate that was two orders of magnitude higher
251 than the independently measured rate, suggesting that transport through the MSW medium is
252 complex and the fluid-structure interaction exhibited through the medium is of relevance for
253 hydrological prediction.

254 In recent years, as demonstrated below, the scale of interest for modelling leachate transport has
255 shifted from bench scale towards pilot- and field-scales, partly due to developments in
256 computational capacity but also because engineers, waste managers and regulatory authorities are
257 ultimately interested in the field-scale. For instance, researchers have adopted a kinetic wave
258 model, first proposed by Beven and Germann (1981) for describing water flows in soils with
259 macropores, to determine the channel flow in landfills (Bendz et al., 1998). A source/sink term
260 was used to account for flow from and into the channel from the matrix (Beven and Germann,
261 1981). Upon moisture intrusion into the landfill due to precipitation or leachate recirculation, water
262 would filtrate from the channel into the matrix domain, whereas during dry periods it would be
263 released to the channel domain. They tested their approach against a pilot-scale MSW sample and
264 found that the model could describe the arrival of the wetting front and the drainage front during
265 unsteady flow, whereas it was not able to describe the observed dispersion through the MSW
266 sample. Their work highlighted the unsuitability of assuming the flux laws through MSW to be
267 strictly convective in nature, and the importance of considering the spatial variability of this porous
268 medium for hydrological modelling.

269 A very popular mechanistic approach to modelling of flow has been to apply different
270 formulations of the Richards equation, dividing the domain into two homogeneous and isotropic

271 overlapping continua (e.g. mobile and immobile regions of liquid) in an attempt to capture the
272 complex pore space of MSW (Beaven et al., 2011; Di Bella et al., 2012; Di Bella et al., 2015;
273 Fellner and Brunner, 2010; Han et al., 2011; Kjeldsen and Beaven, 2011; McDougall, 2011;
274 Slimani et al., 2016; Statom et al., 2006; Tinet et al., 2011b). For instance, vertical flow in MSW
275 samples at the pilot-scale has been investigated by Woodman et al., (2015) interestingly in their
276 study lithium did not behave conservatively as a tracer. The positively skewed tracer breakthrough
277 curves exhibited tailing, as observed in previous studies (Bendz et al., 1998; Oman and Rosqvist,
278 1999; Rosqvist and Bendz, 1999; Rosqvist and Destouni, 2000; Rosqvist et al., 2005). They
279 compared advection-dispersion, dual-porosity and hybrid advection-dispersion/dual-porosity
280 models. In the advection-dispersion approach, different processes responsible for non-uniform
281 flow are essentially lumped together into the dispersivity parameter. The dual-porosity model
282 consistently offered a better fit. The hybrid advection-dispersion/dual-porosity model only
283 performed well when either advection-dispersion or dual-porosity behaviour dominated. This
284 research shed light on the previously mentioned anomalous transport within MSW, in terms of
285 REV domain-based modelling approaches, indicating that multi-porosity mechanisms may be
286 significant, and considering the variety of components present in MSW (wood, paper, card, food
287 waste etc.), this is entirely plausible (Athanasopoulos, 2008; Beaven et al., 2011; Dixon et al.,
288 2011; Dixon et al., 2008b; Gotze et al., 2016; Grellier, 2007; Hossain, 2002; Koganti, 2015;
289 Matasovic et al., 2008; Reddy et al., 2011; Reddy et al., 2009; Zekkos, 2005; Zekkos et al., 2010;
290 Zekkos et al., 2008). For instance, researchers have studied the hydraulic properties of different
291 MSW components (e.g. paper and wood (Ghane et al., 2014; Ghane et al., 2016; Han et al., 2011;
292 Subroy et al., 2014)) where both these components' hydraulic properties could be described by
293 dual-permeability Richards equations, but their intrinsic permeability varied by 1-2 orders of

294 magnitude, suggesting that if they were both present in a waste matrix, due to their varying
295 hydraulic characteristics, it may not be possible to model the dual-porosity characteristics of the
296 entire waste body by assigning them a single set of properties.

297 It is important to note that any model be it analytical or numerical is an approximation of real
298 behaviour. Whilst analytical models cannot really handle heterogeneity, and therefore have
299 lumped parameters, numerical models do allow us to include heterogeneity however, the number
300 of parameters required make it very difficult to parameterize the models. All assumptions, the
301 manner in which the models are implemented (reaction pathways/solution algorithms/numerical
302 schemes) and how the boundary conditions are integrated into the model also have a significant
303 impact on the model outcome. This could help explain why models based on the same governing
304 equations, initial and boundary conditions can yield varying predictions (Beaven, 2008; Beaven et
305 al., 2008).

306 The increasingly popular dual-porosity approach was recently tested against field-scale data by
307 Woodman et al., (2017). Solute transport and horizontal fluid flow between well pairs in a
308 saturated MSW landfill via the use of lithium and bromide tracers along with a fluorescent dye
309 was investigated. Poor fits were obtained with the advection-dispersion model, while the dual-
310 porosity model considered offered a better fit to the breakthrough curves. However, simply
311 because dual-porosity models tend to fit the data better than others (likely due to the extra degrees
312 of freedom in the equations) is not sufficient to conclude that this is absolutely and the only manner
313 in which fluid flows through MSW, it is more of an indication that REV-based dual-porosity
314 approaches are relatively better at describing the behaviour than other simpler REV-based
315 approaches. This research also added to the growing body of evidence regarding the anomalous
316 behaviour of lithium as a tracer in MSW (Woodman et al., 2014, 2015; Woodman et al., 2013).

317 More importantly, this anomalous behaviour highlights the significance of the fluid-structure
318 interaction of the MSW with the mobile liquid, tracers and transport phenomena in general. Fitting
319 parameters in a model to match data is an approach that is adequate if interpolation and limited
320 extrapolation is the objective of model. Nevertheless, models developed to increase our
321 mechanistic understanding should be based on independently determined material parameters.
322 However, this is only practical for relatively small simple waste samples and upscaling to full-
323 scale landfills will require some form of fitting (determination of parameters of a probability
324 distribution), thereby moving the model away from its mechanistic basis.

325 Similar to the above, the Richards equation has also been applied to model leachate pumping
326 and injection data at the field-scale by Slimani et al. (2016). They tested the Richards equation
327 under homogeneous conditions, as well as stratified conditions by decreasing the permeability with
328 depth in order to represent ‘real-life’ conditions, drawing support from the conceptual model of
329 the layered structure of MSW first presented by Bendz and Singh (1999). They found the
330 homogeneous assumption to be inappropriate to describe the flow behaviour, and that
331 consideration of stratification yielded better fits to the data. It should be noted that REV-based
332 modelling approaches, where the domain is essentially homogenized, albeit segmented in some
333 approaches, as discussed above, may not be entirely suitable to carry out a deeper investigation
334 into the role of the structure of MSW, or that of its different components and their dual-/multi-
335 porosity characteristics. This is because the transport processes at play take place inside the pores
336 of this porous medium and it is likely that it is their multi-scale behaviour that governs transport
337 at the field-scale. In another study, researchers developed a dual-porosity flow model to study the
338 flow of leachate to vertical wells (Ke et al., 2018). As is typical for this type of model, the waste
339 mass was divided into matrix and fracture domains, whereby flow could occur horizontally and

340 vertically towards the vertical well with the possibility of mass exchange between the two
341 continua. Sensitivity analysis indicated that the hydraulic properties of the fracture domain
342 influence leachate drawdown more so than those of the matrix domain. Interestingly, the degree
343 of anisotropy (horizontal hydraulic conductivity \div vertical hydraulic conductivity) was found to
344 have a negative impact on leachate drawdown as it gets sequentially harder for leachate to flow
345 vertically. Furthermore, the authors also tested their model against field-scale drawdown test data.
346 Whereby upon fitting the data to the proposed model to obtain parameters such as hydraulic
347 conductivities of the fracture and matrix continua, the authors were able to obtain a reasonably
348 good fit. Their study shed light on the need for field-scale data which is required to inform current
349 elementary-scale models, without which the predictive capabilities of current elementary-scale
350 models are very limited.

351 Researchers have also applied electrical resistivity tomography (ERT) subsurface modelling to
352 understand the flow in two landfill cells and subsequently model the flow of leachate within them
353 (Audebert et al., 2016a; Audebert et al., 2016b). Despite the inherent heterogeneity of landfilled
354 waste, similarities between the leachate injection experiments were reported. They proposed a
355 hydrodynamic model (based on the dual permeability model in HYDRUS-2D) with one parameter
356 set to predict leachate flow for the waste deposit cells. Similar to recent studies, they found the
357 dual continuum approach better described the flow of leachate in comparison with the single-
358 continuum assumption (Han et al., 2011; Woodman, 2007; Woodman et al., 2017; Woodman et
359 al., 2014, 2015; Woodman et al., 2013).

360 **3.2. Stochastic and probabilistic modelling:** Instead of mechanistic approaches, some
361 researchers albeit comparatively few in number, have adopted stochastic and/or probabilistic
362 modelling approaches (McCreanor and Reinhart, 1999, 2000; Reinhart et al., 2002; Rosqvist and

363 Destouni, 2000; Rosqvist et al., 2005; Zacharof and Butler, 2004a, b). For instance, the U.S.
364 Geological Survey's saturated-unsaturated transport model (SUTRA) has been applied to model
365 flow in MSW in homogeneous anisotropic and heterogeneous waste masses (McCreanor and
366 Reinhart, 1999, 2000) using a stochastic approach to model the heterogeneous nature of MSW.
367 They used normal, exponentially increasing and exponentially decreasing probability density
368 functions to model the frequency-hydraulic conductivity relationships for anisotropy and
369 heterogeneity. The flow in the model itself was described by a general form of Darcy's law (Voss,
370 1984). They compared results for the homogeneous, isotropic case, due to low computation times,
371 against field data for cumulative leachate volumes generated and found errors ranging from 27 to
372 160%, indicating the unsuitability of modelling the waste mass isotropically. They discussed that
373 the discrepancies were likely due to preferential flow. Overall, their study was one of the first to
374 highlight the possibility of applying stochastic approaches to tackle the problem of waste
375 heterogeneity. Similarly, a probabilistic Lagrangian modelling approach was adopted to interpret
376 tracer breakthrough curves by (Rosqvist and Destouni, 2000; Rosqvist et al., 2005). To account
377 for preferential flow, they divided the domain into mobile and immobile water (Hopmans et al.,
378 2002; Kohne et al., 2009; Simunek et al., 2003; Simunek and van Genuchten, 2008; Vereecken et
379 al., 2016). Likewise, another approach divided the waste into regions of fast and slow flow paths,
380 where the solute advection variability between these fast and slow flow paths was described by a
381 bimodal probability density function (BIM). The tracer breakthrough curves had a long tail, and
382 the early peaks were indicative of rapid solute transport in preferential flow paths, while the
383 prolonged tails were possibly due to transport in the slow regions. Overall, the experimental work
384 indicated the existence of nonuniform transport. Interestingly, the authors claimed that the MIM
385 model was able to fit to the data adequately, however, the dispersivity values were unreasonably

386 high suggesting that the spreading of the breakthrough curves could not be explained by local
387 dispersion alone. The BIM model achieved good agreement with the tracer tests. Interestingly, the
388 model interpreted that 90% of total water flow occurred through 47% of the water content of the
389 waste sample, suggesting that preferential flow dominated the flow regime. This study showed
390 that the landfill system cannot be described by models based on homogeneous isotropic media and
391 indicated that two-domain models are better at describing transport through MSW. Interestingly,
392 recent work (Caicedo-Concha, 2016; Caicedo-Concha et al., 2011; Caicedo, 2013; de Vries et al.,
393 2017; Kohne et al., 2009; Simunek et al., 2003; Simunek and van Genuchten, 2008; Vereecken et
394 al., 2016) has suggested that different MSW fractions affect flow in different ways and as such,
395 the validity of assigning the same immobile region characteristics to the entire waste matrix is
396 debatable. Of course, the suitability of adopting such assumption depends significantly on the
397 objectives of the model, as accuracy is operationally defined and not an absolute term.

398 **4. MODELLING OF LEACHATE & GAS TRANSPORT INCORPORATING** 399 **DEGRADATION & DEFORMATION**

400 Here, we consider the development of modelling approaches to represent leachate flow in MSW
401 coupled with biogeomechanical processes occurring within the waste mass. Within this body of
402 work, we demonstrate that there is a significant lack of validation against real experimental or field
403 data. Where validation has occurred, the differences between modelled and experimental data
404 suggest a lack in our understanding of the MSW system as a whole. For instance, as noted earlier
405 a recent model comparison exercise was conducted where modellers were provided with set-up
406 and operational data for two experimental lab-scale landfills and invited to submit predictions for
407 variables such as waste settlement, gas generation, changes in leachate chemistry etc. (Beaven,

408 2008; Beaven et al., 2008; Clewes et al., 2008; Ivanova et al., 2008; Lobo et al., 2008; McDougall,
409 2008; Reichel and Haarstrick, 2008; White, 2008; White and Beaven, 2013). The majority of the
410 models underpredicted the cumulative biogas production, with one of the models overpredicting
411 the yield (for one of the experiments, by almost twofold). Most of the models predicted the trends
412 in data such as settlement and volatile fatty acid concentrations with varying degrees of accuracy.
413 Detailed descriptions of some of these models and their underlying frameworks are discussed later.

414 To describe two-phase flow (gas, liquid) in landfills, REV-based models obeying Darcy's law
415 overall, and in some instances explicitly modelled via variants of the Richards equation, with van
416 Genuchten functions to describe relative permeabilities of leachate and gas, have been applied
417 widely (Feng and Zhang, 2013; Feng et al., 2017; Feng et al., 2015; Feng and Zheng, 2014; Feng
418 et al., 2016; Kindlein et al., 2006; Sanchez et al., 2006; Sanchez et al., 2007, 2010; White and
419 Beaven, 2013; White et al., 2011; White et al., 2014). As a typical example, Reddy et al. (2014)
420 applied the finite-difference based Fast Lagrangian Analysis of Continua (FLAC) model to
421 simulate two-phase flow in bioreactor landfills. They assumed leachate and biogas to be
422 immiscible fluids whose flow was governed by leachate saturation and capillary pressure (pressure
423 difference between pore water and pore gas). The flow of these two fluids was described via
424 Darcy's law, and the relative permeabilities were related to the saturation of the waste via van
425 Genuchten functions (van Genuchten, 1980). Upon validation against data obtained from the
426 literature (-laboratory & field-scale) & similar single-phase modelling work, the authors claimed
427 that FLAC was on par with currently available/used models.

428 **4.1. Implicit and explicit modelling of biogeomechanics.** Likewise, variants of the two-phase
429 approach have been coupled with models of other biogeomechanical processes in landfills in
430 attempts to describe the whole system. For instance, a 2D multiphase flow and transport model

431 incorporating degradation was presented by Kindlein et al., 2006. They modelled the landfill
432 system as a homogeneous domain arguing that the landfill heterogeneity at the field-scale can be
433 neglected, which, as previously discussed, may not be a suitable assumption. The hydraulic model
434 for multiphase flow was based on the work of Bear and Helmig by applying Darcy's law for fluid
435 flow incorporating diffusion and dispersion (Bear, 1972; Helmig, 1997). The relative permeability
436 of waste and gas was based on the Brooks and Corey functions (Brooks and Corey, 1964). Monod
437 kinetics was employed to model biodegradation and the evolution of organic compounds with
438 time. Biodegradation was coupled with multiphase flow implicitly by including sinks and sources
439 in the multiphase equations for leachate and biogas. Although they did not validate their model
440 against field-scale or laboratory-scale data, their model suggested that leachate tends to move
441 preferentially around regions of waste exhibiting gas production. Overall, their study showed the
442 possibility of modelling flow of leachate and gas exclusively, while considering biodegradation as
443 sources and sinks instead of explicitly modelling individual degradation stages. However, their
444 study lacked the inclusion of the inherent heterogeneity of the waste, which might have impacted
445 their results.

446 In many instances, many of the two-phase flow models in the literature have not been fully tested
447 against experimental or field-data, and where reported, the agreement between these types of
448 models and measured data has been poor. For instance, a hydro-bio-mechanical model to represent
449 the behaviour of landfilled waste has been developed (Datta et al., 2017; Kazimoglu et al., 2006;
450 McDougall, 2007; McDougall, 2011). The hydraulic model was based on the 2D formulation of
451 Richards' equation, and the van Genuchten parameters were used to express the relationship
452 between suction and moisture content in order to solve unsaturated flow scenarios. The
453 biodegradation model was based on modelling individual anaerobic degradation reactions

454 explicitly (hydrolysis, acetogenesis, methanogenesis). However, the biodegradation model
455 assumed a perfectly-mixed two-stage anaerobic digester, while all the degradable waste was
456 classified as cellulose in the modelling of these reactions. Recently, Datta et al. applied this model
457 to a laboratory-scale experiment studying coupled processes in MSW (Datta et al., 2017). The
458 overall predicted methane generation volume was more than double the experimental value,
459 suggesting that approximating all the degradable content of MSW as cellulose for modelling
460 purposes is likely an unsuitable assumption, particularly due to the presence of hemicellulose and
461 the more recalcitrant, lignin components of the biodegradable matter within MSW. Similarly,
462 researchers have developed a 3D two-phase flow model for leachate and gas flow in landfills (Feng
463 et al., 2018; Feng et al., 2017). As with Kindlein et al. (2006) they modelled the leachate and gas
464 flow via Darcy's law, with source-sink terms for gas and leachate resulting from biodegradation
465 from the landfill, ignoring intermediate degradation products (Feng and Zhang, 2013; Feng et al.,
466 2017; Feng and Zheng, 2014; Feng et al., 2016; Kindlein et al., 2006). The relative permeabilities
467 were modelled by adopting the van Genuchten and Mualem model and assuming that gas and
468 leachate are immiscible, the porosity of the waste remains constant and isothermal conditions
469 prevail (Mualem 1976; van Genuchten 1980). Comparison against field data for spatial variation
470 of pore water pressure showed poor fits, and the authors discussed the possibility of heterogeneity
471 of the waste hydraulic properties causing disagreements between measured and predicted data.
472 This study highlighted the importance of considering the flow of leachate and gas as coupled
473 phenomena, and the unpredictability that arises in modelling these phenomena when the waste
474 structure and its heterogeneity are not considered, as is typical of REV-based modelling strategies.

475 In addition to modelling two-phase flow with biogeomechanical processes, some researchers
476 have opted for a compromise between modelling biodegradation explicitly, reaction-by-reaction

477 (McDougall, 2007; Kindlein et al., 2007) and simply including it as a source-sink term by
478 modelling bulk biogas generation as a first-order process. For instance, a 2D coupled hydro-bio-
479 mechanical model was recently developed (Reddy et al., 2017a; Reddy et al., 2017b). The two-
480 phase hydraulic model was based on Richards' equation, where the biogas and leachate were
481 considered immiscible and the relative permeabilities of the leachate and gas were modelled via
482 the van Genuchten model. A Mohr-Coulomb based plane-strain plasticity model was adopted to
483 model the settlement of the waste. USEPA's LandGEM model was used to model first-order
484 biodegradation of the waste mass (USEPA, 2005). It should be pointed out that whilst this model
485 has not been verified against field data as of yet, the authors have performed parametric case
486 studies to identify the importance of certain parameters to inform bioreactor landfill design. Their
487 modelling framework does not consider heterogeneity of the hydraulic, biochemical and
488 geotechnical properties of the waste mass, which would likely impact their model's predictions at
489 the field-scale. Their framework also assumes a first order bulk gas generation and degradation
490 behaviour from the waste mass. Recent evidence has shown that different MSW components
491 which are biodegradable exhibit variable degradation behaviour and that lignin-rich components
492 of MSW generally do not undergo biodegradation in the landfill environment (Jayasinghe et al.,
493 2014; Krause et al., 2017; Krause et al., 2016; Muaaz-U-Salam et al., 2017; Wang, 2015; Wang
494 and Barlaz, 2016; Wang et al., 2015; Wang et al., 2011; Wang et al., 2013; Warwick et al., 2018;
495 Ximenes et al., 2015; Ximenes et al., 2008). Overall, their studies have provided valuable insights
496 into the importance of coupled processes in designing bioreactor landfills for leachate recirculation
497 and early stabilization of the waste mass.

498 **4.2. Consideration of heterogeneity.** In addition to coupling biogeochemical processes with
499 the aforementioned two-phase REV-based approaches, some researchers have also attempted to

500 capture the heterogeneity of the waste mass (McCreanor and Reinhart, 1999, 2000; Sanchez et al.,
501 2006; Sanchez et al., 2007, 2010; Zacharof and Butler, 2004a, b). For example, flow has been
502 modelled stochastically through MSW incorporating waste heterogeneity and biogas production
503 (McCreanor and Reinhart, 1999, 2000; Zacharof and Butler, 2004a, b) . In the latter model,
504 biochemical pathways (hydrolysis, acetogenesis and methanogenesis) were modelled individually
505 for the various components of the organic fraction represented by carbohydrates, fats and proteins.
506 Model molecules for each of these components were chosen and growth/decay functions were
507 used to model the rates of change in the molar mass of these components during hydrolysis,
508 acetogenesis and methanogenesis. Flow was modelled stochastically to include the effects of waste
509 heterogeneity by taking the overall flow through the landfill to be time invariant. It was also
510 assumed that the flows through the waste were log-normally distributed against the average
511 vertical water velocities. The statistical velocity model was then used to calculate the travel times
512 of the leachate particles by using the random function given by the ratio of the distance travelled
513 to the average velocity experienced. Since time was the key variable in the hydrological and
514 biochemical modules, it was used as the basis to produce the integrated model with the overall aim
515 of predicting leachate and biogas compositions. However, similar to other field-scale models
516 discussed in this section, testing against actual field data was not reported. It should also be noted
517 that whilst stochastic modelling may be suitable to fit experimental data and gain some insight into
518 the flow regime of the porous medium, unlike mechanistic approaches, it is not an ideal way to
519 gain in-depth understanding of the physics and biogeochemistry of these phenomena. In another
520 attempt to consider the impact of the inherent heterogeneity of MSW on flow and biogeochemical
521 phenomena, a 3D model for biodegradation, and flow of landfill gas and leachate has been
522 developed (Sanchez et al., 2006; Sanchez et al., 2007, 2010). They modelled individual aerobic

523 and anaerobic degradation reactions by employing Suk et al. and Lee et al.'s models for the
524 dissolved carbon, its conversion to organic acids and the rate of growth of microorganisms.(Lee et
525 al., 2001; Suk et al., 2000) They then employed El-Fadel et al.'s strategy to model the bulk
526 biodegradation of the waste by including relative biodegradability of certain fractions (El-Fadel et
527 al., 1996; El-Fadel, 1996). The biodegradation module linked with the standard convection-
528 diffusion-reaction equation to model the concentration of landfill gas. Their hydraulic model was
529 based on Richard's equations, while the relative permeabilities of gas and leachate were modelled
530 via van Genuchten functions. They considered heterogeneity of the waste mass by introducing
531 spatial variation of permeabilities and porosities in 3D by employing the sequential Gaussian
532 simulation technique. Although they did not test their model against actual field data, they
533 simulated a variety of scenarios for homogeneous and heterogeneous landfills. In summary, their
534 study demonstrated the impact of waste heterogeneity on flow of leachate and gas, and the
535 significance of including two-phase flow to realistic modelling of landfill processes, since the
536 inter-phase interactions impact the gauge pressure within the waste mass and influence the stability
537 of landfills. (Table 1 here)

538 **5. FUTURE NEEDS & RECOMMENDATIONS**

539 In light of the state of the art reviewed above, we identify the following challenges and on this
540 basis, provide recommendations for future research needs and potential multidisciplinary
541 approaches to address them.

542 (1) **The 'black box' of waste** – As perhaps suggested by other researchers, we recommend that
543 gaining a better understanding of the aforementioned challenges requires penetrating the
544 'black box' of waste. To achieve this an extra layer of detail is required in our current

545 continuum-scale understanding of transport. For instance, geophysics and petroleum
546 engineering literature is rich with contributions successfully exploring transport in
547 permeable geological media at the pore-scale (Bijeljic et al., 2011; Blunt, 2017; Blunt et al.,
548 2013; Mostaghimi, 2012; Mostaghimi et al., 2010; Mostaghimi et al., 2012; Mostaghimi et
549 al., 2016; White and Beaven, 2008). Currently, a popular approach to modelling transport
550 at the pore-scale involves using micro-CT X-ray scanning techniques to provide image data
551 which are compiled to produce a digital 3D representation of pore-structure which is then
552 used to define the modelling domain for flow simulations via various methods (e.g. Lattice-
553 Boltzmann, Navier-Stokes, [Figure 1](#)) (Abdelhay et al., 2016; Al-Gharbi and Blunt, 2005;
554 Al-Kharusi and Blunt, 2007; Al-Khulaifi et al., 2017; Bijeljic et al., 2013; Bird et al., 2014;
555 Boon, 2017; Davit et al., 2013; de Vries et al., 2017; Graveleau et al., 2017; Guibert et al.,
556 2016; Larachi et al., 2014; Liu et al., 2017; Menke et al., 2016; Menke et al., 2017; Pereira
557 Nunes et al., 2015, 2016; Piller et al., 2014; Quintard, 2015; Raeini et al., 2013; Raeini et
558 al., 2012; Roman et al., 2016; Seetha et al., 2017; Soulaine et al., 2011; Soulaine et al.,
559 2016). We suggest that studying flow and transport at the pore-scale in MSW would help
560 us understand the complex mechanisms involved and generate vital information which can
561 then be used to inform and/or modify our existing models for better prediction. For instance,
562 micro-CT (depending on the resolution and sample size) might also be able to identify the
563 pores within different MSW components (wood, food waste etc.) and with the help of pore-
564 scale computational fluid dynamics (CFD) simulations, could shed light on the dual-
565 porosity/permeability characteristics of MSW at the component-level and their role in
566 impacting flow through the pore space.

567 (2) **Fluid-structure interaction** – The variable nature of MSW composition, and the resulting
568 fluid-structure interaction resulting from various biogeochemical processes needs to be
569 better understood, with particular attention to biodegradation, mechanical creep and other
570 processes that result in a transient system with an evolving pore space (Caicedo, 2013). In
571 order to understand the fluid-structure interactions and similar processes well, it may be
572 beneficial to study the structure at the component-scale, including the packing between
573 different components, as well as flow through individual material types, for instance, the
574 fluid-structure interactions resulting from wood might be different to those resulting from
575 food waste (Caicedo-Concha, 2016; Caicedo-Concha et al., 2011).

576 (3) **Heterogeneity** – Throughout this paper it has been evident that researchers have found the
577 multiscale heterogeneity of MSW, paired with other factors discussed above, has resulted
578 in preferential flow and added to the complexity of modelling flow through this porous
579 medium. This has been, and likely will continue to be, a significant challenge. Measuring
580 and quantifying the variability of waste components in the matrix, their arrangement and
581 the resulting multiscale heterogeneities is challenging, and has not been, to date, fully
582 investigated. However, this review has highlighted how understanding the impact of
583 heterogeneity on flow through MSW is an integral part of improving our predictions. Here
584 we offer some suggestions to study heterogeneity. As discussed above, pore-scale
585 experimental and modelling investigations of flow will likely improve our understanding of
586 transport mechanisms. Fractal theory has been widely investigated in the sciences to study
587 the inherent irregularity in nature and natural phenomena (Dekking et al., 1999; Hutchinson,
588 1981; Mandelbrot, 1982; West et al., 1997). Recently, fractals have also been applied to
589 porous media to study the properties of pore structures including multifractal analyses and

590 their ability to quantitatively describe multi-scale pore-structure heterogeneities (Bird et al.,
591 2006; Bird et al., 2000; Caplan et al., 2017; Gibson et al., 2006; Jaya et al., 2013; Liu and
592 Ostadhassan, 2017; Lopes and Betrouni, 2009; Morató et al., 2017; San José Martínez et
593 al., 2010; Wang et al., 2016a; Wang et al., 2016b; Xie et al., 2010; Xu, 2015; Xu et al.,
594 2015; Zhang et al., 2014). We suggest that this line of inquiry combined with pore-scale
595 modelling of flow might help us quantitatively relate heterogeneity of MSW to the spatial
596 distribution of its components and their individual dual permeability characteristics. It might
597 also help us quantitatively determine the changes in heterogeneity due to the evolution of
598 the pore space due to biogeochemical processes at a variety of scales to study their impact
599 on transport phenomena.

600 (4) **Data and sources of error** – Thus far, this paper has discussed modelling efforts to describe
601 fluid flow in MSW, as well as fluid flow and transport incorporating biogeomechanical
602 phenomena. In making the case for pore-scale modelling in MSW, a crucial focal point is
603 the data that is required to study flow, transport and biogeomechanical processes and
604 validate pore-scale modelling efforts. Since to the best of our knowledge such experimental
605 data is sparse, within the context of MSW, it is important to explore possible experimental
606 techniques and ideas at the pore-scale which could help in generation of data to gain a better
607 understanding of the above to study and model these processes at the pore-scale. Following
608 this, since the ultimate scale of interest is the field-scale, exploring the integration of insights
609 obtained from pore-scale experiments and models into existing elementary/field-scale
610 models could perhaps form the next step. [Figure 2](#) shows some of the processes that take
611 place in the MSW system. Studying these processes at the pore-scale could be addressed
612 with micro-model experiments combined with modern imaging techniques currently widely

613 used in digital rock physics work (Blunt et al., 2013; Xiong et al., 2016). Micromodel
614 experiments in pore-scale literature have been vital in understanding fluid properties and
615 fluid flow in permeable media. For instance, researchers have successfully used these
616 techniques for investigating the evolution of the pore space in certain rocks due to typical
617 geochemical dissolution reactions whereby the pore space is modified (Al-Khulaifi et al.,
618 2017; Blunt, 2017; Menke et al., 2016; Menke et al., 2017). However, detailed examination
619 and review of these experimental techniques and possible lines of experimental inquiry are
620 beyond the scope of this paper. (Fig. 1 here)

621 While pore-scale investigation of fluid flow and biogeochemical processes might lead to new
622 insights, as is the case with any experimental/modelling technique, sources of error and challenges
623 will arise. One of the key points addressed in this paper has been the heterogeneity of the waste.
624 This inherent heterogeneity makes representative sampling of a waste body very difficult and casts
625 doubt on extrapolating the conclusions from one particular study to another. Pore-scale studies
626 with micro-model experiments/models will likely encounter these doubts and difficulties.
627 However, the purpose of this line of work would be to further understanding of the fundamental
628 processes of the MSW system and the interaction between the different processes from Figure 2.
629 What does this mean for currently existing models? Hopefully, experimental and numerical pore-
630 scale studies as described above, when put against currently existing data at the lab and field scales
631 will help in establishing a relationship between scaling of flow/transport and
632 biogeochemical/physical processes. This relationship between the scales should then help in
633 understanding how averaging will work to upscale from the pore-scale, to the centimetre scale, up
634 to the metre scale, leading all the way up to the field scale. (Fig. 2 here)

635 In conclusion, modelling transport phenomena in MSW is challenging due to its inherent multi-
636 scale heterogeneity and ever-evolving pore space due to various biogeochemical/physical
637 processes. Continuum-scale models have not been able to sufficiently describe transport due to the
638 impact of the aforementioned processes. We suggest studying transport at the pore-scale to further
639 our understanding of transport within the pores of the waste, since it is these pore-scale processes
640 that ultimately govern transport at the field-scale. The insights obtained could then be used to
641 modify existing continuum-scale models for better prediction.

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648 (<https://www.digitalrockportal.org/projects/11>) (Muljadi et al., 2016).

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654 **Supporting Information Available.** Initial literature search strategy (Table S1), subsequent
655 pathways and sources (Table S2) have been provided as part of the supporting information for
656 this article.

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663 **Table 1.** An overview of recent transport models.

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Author(s)	Objectives	Features	Assumptions & Limitations
Bendz and Singh (1999); Bendz et al. (1998)	Modelling of unsteady water flow in landfilled MSW, later modified for solute transport.	DP under steady and transient conditions incorporating solute transport.	1D, NH, IC.
McCreanor and Reinhart (1999, 2000)	Better understanding of leachate movement mechanisms.	Stochastic modelling incorporating heterogeneity.	2D, IC.
Suk et al. (2000)	Develop a numerical model to compute leachate quality, gas composition, and gas pressure distribution over time in a landfill.	2-phase, multispecies solute transport incorporating biodegradation.	1D, NH and DP, ignores impact of biodegradation.
Rosqvist and Destouni (2000)	Study and quantify water and solute transport through preferential flow paths in biodegraded MSW by model interpretation of experimental BTCs.	DP, under steady and transient conditions.	IC, NH, unable to explain spreading of breakthrough curves.
Zacharof and Butler (2004a, b)	Mathematical modelling of the landfill environment.	Stochastic modelling incorporates biodegradation and waste heterogeneity.	Unable to simulate transient fluxes, limited testing against field data.

Rosqvist et al. (2005)	Study and quantify pollutant concentrations after long-term leaching at relatively low flow rates and residual concentrations after heavy flushing of an MSW sample.	Transfer function model able to simulate tracer BTCs.	IC, NH, overpredicting tracer concentrations.
Statom et al. (2006)	Simulate the overall trend in chloride concentration from a closed landfill cell.	DP, able to predict long-term leachate concentrations.	IC, NH, steady-state conditions only, failed to predict high chloride concentrations.
Kindlein et al. (2006)	Numerical analysis of coupled transport and reaction processes inside landfills.	2-phase transport incorporating degradation, heat and heterogeneity.	2D, neglects relative biodegradability of different components and DP.
(Garcia de Cortazar and Tejero Monzon, 2007; Garciadecortazar and Monzon, 2007)	Simulation of the hydrological and biodegradation behavior of MSW landfills.	Able to calculate daily leachate flow, organic pollution and the generation and composition of biogas in landfills.	Impact of waste mechanics neglected, limited classification of biodegradable matter.
McDougall (2007)	Integrated analysis of the hydraulic, biodegradation and mechanical behavior of MSW.	Coupled biodegradation, hydraulics, mechanics.	No DP, NH, simplifies waste to cellulose, resulting in overestimation of biogas.(Datta et al., 2017)

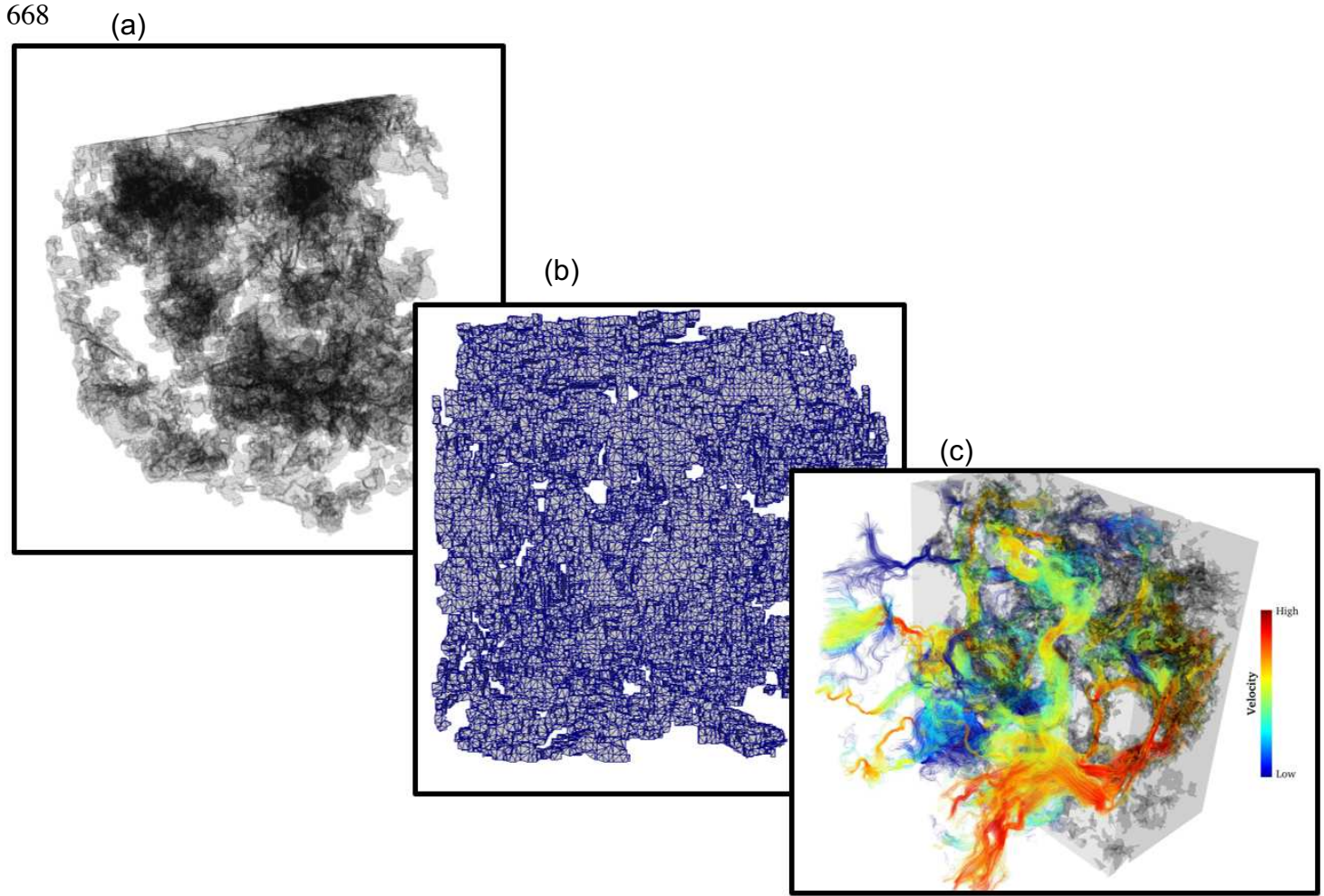
Sanchez et al. (2010)	Generation and transport of the major gaseous components of landfill gas. Study flow of both the leachate and the gases. Leachate distribution in a bioreactor landfill, evaluate the performance of drainage blankets as leachate recirculation systems.	Coupled 3D, 2-phase reactive-transport, incorporating biodegradation and heterogeneity.	Neglects DP, biodegradability and rates of degradation of different components.
Reddy et al. (2013, 2014, 2015)	Quantification of the flow and transport of leachate in pilot- and field-scale MSW.	2-phase flow.	Gas and leachate considered immiscible, IC, NH.
Woodman et al. (2013, 2014, 2015, 2017)	Describe the flow around a well during pumping and injection at the field scale.	DP, also developed a DP-AD hybrid.	IC, DP, NH, failed to predict at the laboratory-scale.
Slimani et al. (2016)	Investigate the hydrodynamic and biochemical behavior within a bioreactor landfill subjected to leachate recirculation.	Simulates response to pumping and injection, exponential relationship between hydraulic conductivity and depth used.	No DP, anomalous behaviour at the transition phases, IC.
Feng et al. (2013, 2014, 2015, 2016 2017a,c)		3D 2-phase model with biogas generation.	Gas and leachate regarded as immiscible, ignores mechanical effects of biodegradation, NH.

De Donno and Cardarelli (2017)	Evaluate the benefit of a priori information for the characterisation of landfills.	Data-driven, utilizes resistivity and chargeability to limit variation of parameters.	IC, 2D snapshots of the landfill, dependent on ERT sensor-placement, NH.
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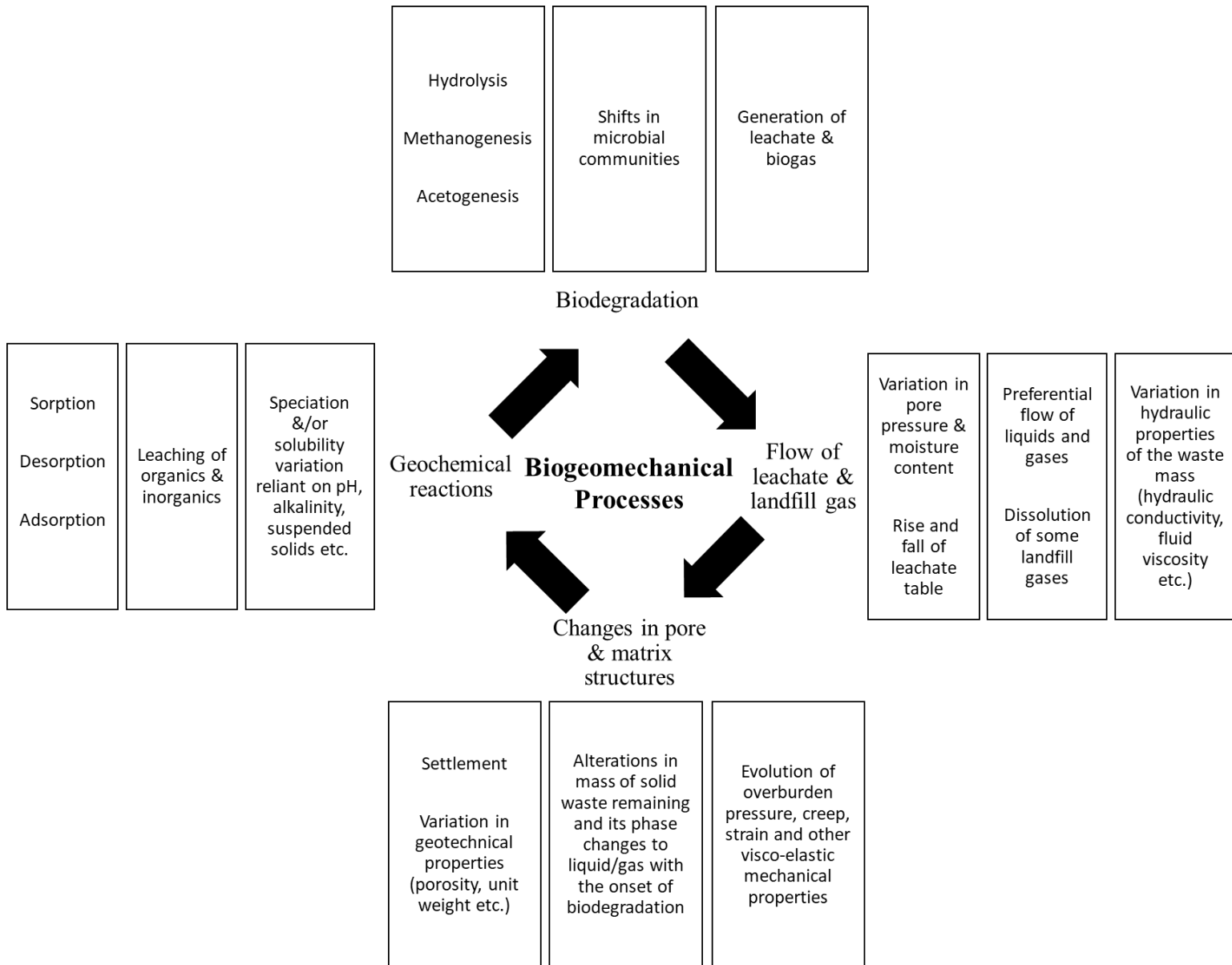
666 *Note: NH, Neglects heterogeneity; IC, Ignores coupled phenomena; AD, Advection-dispersion; DP, Dual-porosity; BTC, Breakthrough*

667 *curve*



669 **Figure 1.** Schematic of a pore-scale simulation. (a) Scanning, (b) pre-processing, (c) CFD
670 simulation.

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Figure 2. Different processes that take place in the MSW system. Conceptual model informed by the works of Datta et al., 2018, Fei et al., 2014a and McDougall, 2007.

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Supporting Information

The Case for Examining Fluid Flow in Municipal Solid Waste at the Pore-Scale – A Review

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METHODOLOGY

In the first instance, we employed a similar strategy to that of Rummel et al. (2017).¹ The ISI Web of Science and Google Scholar databases were used to search for keywords and track citations from relevant papers (Table S1). In some instances, the authors' ResearchGate profiles were also used to look for publications that may have been missed otherwise. The publications citing the

16 following references and the bibliographies therein were also explored for possible inclusion
 17 (Table S2).

18 **Table S1:** Results of ISI Web of Knowledge search queries conducted in September 2017.

Keywords	Search type and/or operator	Total results	Selected for inclusion	References
“municipal solid waste” + “transport” + “model”	TOPIC	270	20	Woodman et al. (2017) ² Audebert et al. (2016a) ³ Audebert et al. (2016b) ⁴ Woodman et al. (2015) ⁵ Woodman et al. (2014) ⁶ Woodman et al. (2013) ⁷ Saquing et al. (2012) ⁸ Han et al. (2011) ⁹ Fellner and Brunner (2010) ¹⁰ Kindlein et al. (2006) ¹¹ Statom et al., (2006) ¹² Rosqvist et al. (2005) ¹³ Haydar and Khire (2005) ¹⁴ Rosqvist and Destouni (2000) ¹⁵ McCreanor and Reinhart (2000) ¹⁶ Bendz and Singh (1999) ¹⁷ Uguccioni and Zeiss (1997) ¹⁸ ElFadel et al. (1997) ¹⁹ Di Bella et al. (2012) ²⁰ Al-Thani et al. (2004) ²¹
“landfill” + “leachate” + “modelling” + “flow”	Topic	348	9	Feng et al. (2017) ²² Slimani et al. (2017) ²³ Feng et al. (2017) ²⁴ Feng et al. (2016) ²⁴ Audebert et al. (2016a) ³ Audebert et al. (2016b) ⁴ Reddy et al. (2015) ²⁵ Feng et al. (2015) ²⁶ Tinet et al. (2011) ²⁷

19 **Table S2:** Results of citation tracking of selected references to capture similar references of
 20 interest. *
 21

Publication	Times cited	Selected for inclusion	References
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Audebert et al. (2016)	7	1	Donno and Cardarelli (2017) ⁴⁰
Bendz and Singh (1999)	17	6	Saquiring et al. (2012) ⁸ Woodman et al. (2015) ⁵ Woodman et al. (2014) ⁶ Woodman et al. (2013) ⁷ Woodman (2008) ⁴¹ Caicedo (2013) ⁴²

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Demetracopoulos et al. (1986) ³⁶	23	2	Khanbilvardi et al. (1995) ⁴⁴ Suk et al. (2000) ⁴⁵
Bendz et al. (1998) ³⁵	26	3	Sanchez et al. (2010) ⁴⁶ Zacharof and Butler (2004a) ⁴⁷ Han et al. (2011) ⁹
Zacharof and Butler (2004a) ⁴⁷	43	1	Zacharof and Butler (2004b) ⁴⁸
Zacharof and Butler (2004b) ⁴⁸	42	1	Kindlein et al. (2006) ¹¹
Kindlein et al. (2006) ¹¹	20	1	Agostini et al. (2012) ⁴⁹
Han et al. (2011) ⁹	20	1	Slimani et al. (2016) ²³
Ahmed et al. (1992) ³⁴	28	1	McDougall et al. (1996)
Khanbilvardi et al. (1995) ⁴⁴	55	1	Oman and Rosqvist (1999) ⁵⁰
Khire and Mukherjee (2007) ³⁰	68	1	Haydar and Khire (2007) ⁵¹
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