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1 Sustainable Environmental Geotechnics Practices for a Green 2 Economy

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46 **Abstract**

47 The revitalization of the global economy after the COVID-19 era presents Environmental
48 Geotechnics with the opportunity to reinforce the need for a change in paradigm toward a
49 green, circular economy and to promote aggressively the use and development of
50 sustainable technologies and management practices. This paper aims to assist in this effort
51 by concentrating on several thematic areas where sustainability solutions and future
52 improvements are sought. These include the re-entry of construction and demolition waste,
53 excavated material, industrial waste, and marine sediments into the production cycle and
54 the reuse of existing foundations. Despite the recent trend in advanced countries toward
55 recycling and waste-to-energy thermal treatment, landfills still constitute the most common
56 municipal solid waste management practice, especially in low-and-middle-income
57 countries, and technological solutions to improve their environmental footprint are
58 presented. At the same time, remediation solutions are required to address the multitude of
59 contaminated sites worldwide. Advanced developments that incorporate environmental,
60 economic, and social dimensions are expounded, together with sustainable ground
61 improvement solutions for infrastructure projects conducted in soft and weak soils. The
62 topic of thermo-active geostructures concludes this paper, where, apart from their
63 infrastructure utility, these structures have the potential to contribute as a renewable energy
64 source.

65

66 **Keywords:** Rehabilitation, reclamation & renovation; Renewable energy; Waste
67 management & disposal

68 **1. Introduction**

69 Since the beginning of 2020, the COVID-19 health crisis has been added to existing global
70 challenges threatening the well-being of humankind. The pandemic has further exposed the
71 relationship between our economic and social modes of operation and environmental
72 problems. Thus, reduction in atmospheric pollution over many cities has been observed
73 during the lockdown, environmental noise has subsided, and cleaner beaches and coastal
74 waters have resulted from the much-reduced tourism. On the other hand, the pandemic has
75 accentuated some environmental problems through the increase of waste production, the
76 significant reduction in waste recycling, and the entry of disinfectants into soils and waters
77 (Paleologos et al., 2020; Tang et al., 2020; Vaverková et al., 2020).

78 The construction industry is a well-known source of negative environmental impacts due
79 to the high consumption of natural resources and energy, and the large production of waste
80 (Farid, 2020). The environmental performance of the construction industry remains sub-
81 par, despite the fact that, principles of sustainability and circular economy can easily find
82 application in this industry. This has become even more critical since the rate of extraction
83 of natural resources has become 1.6 times higher than their capacity to regenerate.

84 Renovation, replacement, and retrofitting of aging building stock gives rise to the reuse
85 of existing building material and the development of new, more sustainable construction
86 practices (European Commission, 2020b). This is assisted by the development of “green”
87 codes and regulations regarding the design, construction, and operation of buildings
88 (LEED, 2021; DMT, 2020). It becomes especially critical for the post COVID-19 recovery,
89 which is seen by governments as an opportunity to “*transition to a greener and more*
90 *sustainable economy*”, as exemplified by the joint declaration of the European Union (EU)
91 and China on September 14, 2020 (European Commission, 2020a).

92 This paper aims to present an overview of and recommendations regarding the reuse of
93 several types of waste in geoenvironmental projects. Foundation reuse is a topic of interest,
94 especially for older cities that are congested by a large number of infrastructure elements in
95 their subsurface. Management of marine sediments has become important given the
96 expansion of ports in many countries, the need to retain the natural balance between
97 waterways and sea, to conserve coastal ecosystems, and to accommodate tourist,
98 transportation, and even desalination needs in an integrated manner. Waste and sediment
99 management practices are being implemented in several countries with significant national
100 action plans and regulations anticipated to accelerate these efforts.

101 Landfills remain the principal way to dispose solid waste across the world. The USA and
102 especially the EU have moved to transition away from landfilling to recycling and waste-
103 to-energy, but for low-and-middle-income countries (LMICs) the cost, lack of
104 technological and organizational expertise, and waste composition make landfilling a
105 desirable option to the alternative of open dumps. The challenges in the management of
106 landfills are expounded here and the use of sulphur concrete as a component of landfill
107 barrier systems is presented, as well as the emerging topic of mining landfills for the
108 recovery of useful materials.

109 It has also become amply clear that improper disposal practices and accidental spills
110 have resulted in contamination of the geoenvironment. Developers are generally hesitant to
111 convert contaminated land into beneficial use, due to liabilities issues. Many initiatives
112 have been undertaken and environmental laws/regulations have been promulgated over the
113 last thirty years to assist in the clean up of brownfields, and to utilize such lands for
114 housing and commercial needs, and for natural reclamation (USEPA, 2020a). Thus, another

115 theme of our paper is to discuss advanced developments in sustainable land remediation, as
116 well as sustainable ground improvement solutions in infrastructure projects conducted in
117 soft, weak, and unstable soils.

118 Geotechnical engineers are routinely involved in the design and construction of
119 underground structures, such as tunnels, base slabs, piles and diaphragm walls. Apart from
120 the role that these elements play as infrastructure, recent studies have shown that they may
121 also be used for the production of shallow geothermal energy. Technological improvements
122 in the design of thermo-active geostructures together with standardization in their
123 application will assist market penetration and increase the interest in developing countries.
124 Geo-structures may present an example of a situation where the synergy between a
125 project's variable functions may be sought and this constitutes the concluding theme of our
126 paper.

127

128 **2. Sustainable Waste Management**

129 **2.1 Minimizing and recycling of construction and demolition waste (C&DW)**

130 Much of the focus in environmental geotechnics has been on recycling non-hazardous
131 industrial waste and by-products of different origins and characteristics. Examples of the
132 application of such materials in geotechnical works include: 1) C&DW in road pavement
133 layers, geosynthetic reinforced structures and drainage layers; 2) steel slag in road
134 pavement layers and drainage layers; 3) waste tires in embankments, and drainage layers;
135 4) quarry waste in road pavement layers and landfill liners or cover systems; and 5) bottom
136 ash from incineration of municipal waste in road pavement layers (Roque et al., 2020).

137 Other non-hazardous industrial waste and by-products studied for use in geotechnical
138 works are coal fly ash and bottom ash, and foundry sand.

139 Prevention, reduction and reuse are top priorities in the waste management hierarchy,
140 and are critical especially for the construction industry, which utilizes large amounts of new
141 material and generates large volumes of waste. Two-fifths of the global raw stone, gravel,
142 and sand have been depleted as a result of the construction industry. In Europe, the
143 construction industry was responsible for generating about 820 Mt of C&DW in 2012,
144 about one-third of the total waste generated for the region that year (European Commission,
145 2019a), while consuming 12 to 18 Mt of new construction material (Ecorys, 2014).

146 On the positive side, several indicators suggest that sustainability considerations are
147 becoming mainstream in construction projects, with numerous companies emphasizing
148 green design and construction practices. Credit-bearing “green” systems that reward
149 projects, which adapt sustainability methods in the design, construction, and operation of
150 buildings and neighborhoods include the USA-developed LEED (Leadership in Energy and
151 Environmental Design) (LEED, 2021). Projects certified by LEED have claimed impressive
152 accomplishments, with water and energy savings, recycling of materials, extensive green
153 areas, etc. Some countries have made the use of sustainability codes mandatory for the
154 construction industry, such as the United Arab Emirates (UAE), which requires all new
155 projects constructed in Abu Dhabi after 2010 to attain a certain rating under the Estidama
156 Pearl Rating System (DMT, 2020).

157 Important benefits from reduction and reuse of C&DW include: 1) cost savings from a
158 decrease in mining activities, reduced material transport to and from construction sites,
159 along with reductions in transportation and disposal of waste in landfills; 2) lower carbon

160 dioxide emissions from resource processing and transportation; 3) increased competitive
161 advantage through differentiation; and 4) flexibility to adapt to more stringent policy
162 requirements related to C&DW generation and disposal (European Commission, 2019a,b).

163 Geotechnical works can be responsible for the movement of large volumes of earth
164 material with matching large energy consumption. Considerable quantities of excavation
165 soil and rock are generated in transport infrastructures (e.g., roads, railways, subways),
166 urban infrastructures (e.g., supply networks for electricity, gas, water, sewerage,
167 telecommunications, and drainage networks for flood prevention), and multi-floor
168 basements of large buildings. Despite the fact that excavated material often presents
169 characteristics that makes it appropriate for reuse on-site or off-site, it is often disposed in
170 landfills, or even dumped indiscriminately, along roads or streams. Benefits from reusing
171 excavated soil and rock include savings of up to 14 kg of carbon dioxide per ton of soil, as
172 well as material handling cost-savings of up to 85 % (Magnusson et al., 2015).

173 In order to encourage the reuse of excavated material, be it clean or lightly
174 contaminated, several countries have developed regulations (MTES, 2017; CL:AIRE, 2011)
175 to support best management practices (BMP). These guidelines avoid the classification of
176 excavated soil as waste, with commensurate savings owing to the avoidance of controlled
177 disposal. Most regulations only allow the geotechnical improvement of excavated soil, but
178 the French (MTES, 2017) and English-Welsh (CL:AIRE, 2011) guides also allow the
179 chemical treatment of soil if it is contaminated.

180 Foundation reuse is another topic that has become progressively important in recent
181 years because of an increased concern regarding ground congestion in urban areas, and the
182 need to maximize material reuse and minimize resource exploitation and waste production.

183 Many older cities, especially in Europe, are finding that urban reconstruction below ground
184 level has become increasingly difficult and expensive, as this space is often crowded with
185 existing infrastructure/services that include utilities, tunnels, and shallow and/or deep
186 foundations of buildings.

187 In addition to ground congestion, drivers for foundation reuse are improvements in: 1)
188 project delays; 2) foundation costs; 3) carbon dioxide emissions; 4) waste production; and
189 5) archaeological preservation. Jones et al. (2017) presented a case where the reuse of the
190 foundations of an old building, constructed in the mid-1970s, in a new nine-storey
191 residential building achieved cost savings of \$178k and reduced the completion time of the
192 project by six weeks. Tsubakihara and Yamashita (2005) calculated that the reduction in the
193 volume of newly built piles and in carbon dioxide emissions was about 40 % and 70 %,
194 respectively, through the reuse of existing cast-in-place concrete piles. These authors
195 claimed that engineering advantages with the reuse of old foundations include non-
196 disturbance of the supporting ground, and retention of the bearing capacity of adjacent piles
197 and of the structural integrity of neighbouring buildings or underground structures.

198 The main problem with foundation-reuse design is often the lack of credible information
199 about the original design and the as-built construction of existing foundations. Thus,
200 despite the benefits of reusing old foundations, currently such foundations tend only to be
201 reused if the ground beneath a building is already occupied by them or if there exist at the
202 site archaeological remains that must be preserved. Thus, in order to make foundations
203 accessible to future interventions and reuse, detailed information about their design and
204 construction must be retained in current projects.

205

206 **2.2 Sustainable management of marine sediments**

207 Despite the fact that the total amount of sediments dredged from marine basins in Europe
208 reaches 100–200 million m³/year, current European Directives do not report about the
209 handling of dredged sediments in a comprehensive and uniform manner. In most cases,
210 dredged sediments are still classified as ‘waste’ and the disposal in large fill-in basins is the
211 most used practice with associated high environmental risks.

212 In this context, stabilization/solidification (S/S) treatment of sediments with binders and
213 additives represents a promising option for managing marine sediments, which are dredged
214 periodically in harbour areas, either for port effectiveness or for on-site remediation
215 (SedNet, 2011). This solution is highly flexible since the most efficient mix of binders and
216 additives can be designed depending on both the chemo-mechanical features of the
217 sediments at each site and the required performance of the selected recycling application.
218 Treatments can be specifically customized mainly to: 1) improve the hydro-mechanical
219 properties of the sediments (Federico et al., 2016); 2) prevent the release of toxic elements
220 into the environment (Wang et al., 2018), and 3) reduce the interference of contaminants
221 with binders’ chemistry that may otherwise compromise the effectiveness of stabilization.
222 The treated sediments may be either recycled as aggregates for road construction, cemented
223 mortars, fill material, brick production, or transformed into sustainable resources useful for
224 port infrastructures (Wang et al., 2012; 2015).

225 Recent research aims to treat marine sediments by using effective and sustainable
226 additives that comply with the lowering of carbon dioxide emissions through the
227 minimization of hydraulic binders (e.g., 900 kg of carbon dioxide per ton of clinker are
228 required to produce the binders). This is the case, for example, of biochar (a by-product of

229 thermochemical industry), as an eco-friendly adsorbent for remediation of contaminated
230 sediments, or mussel shell flour (MSF) (Papadimitriou et al., 2017). MSF is a by-product of
231 the fish industry, made of calcium carbonates, which after specific treatment form a flour,
232 which can be used in partial substitution of cementitious binders for chemical and hydro-
233 mechanical stabilization of sediments (Petti et al., 2020).

234 In this context, the Politecnico di Bari, ETH Zurich and Italcementi - HeidelbergCement
235 Group are performing experimental studies for the stabilization of dredged sediments using
236 sustainable binders of lower environmental impact, in which part of the binder is replaced
237 by MSF. Table 1 reports some geotechnical properties of the natural sediments from the
238 Gulf of Taranto, in the south of Italy, both before and after treatment with either 8 %
239 Portland cement (Sed8PC), or 6 % Portland cement with 2 % MSF (Sed6PC2MSF). All the
240 values in Table 1 are corrected for the pore water salinity, as described in Sollecito et al.
241 (2019).

242 Table 1 shows that the addition of 8 % Portland cement (PC) to marine sediments (clay
243 fraction: 30.4 %) causes a significant increase in liquid limit, such as to classify the
244 amended sediments (i.e., Sed8PC) as silts of high plasticity, MH, in the Casagrande's
245 plasticity chart. It follows that the recorded increase in consistency index (CI) is essentially
246 due to the reduction in water content for the treated sediment. It is worth noting that, the
247 replacement of part of the PC with 2 % MSF additive increases the CI of the produced
248 material (i.e., Sed6PC2MF) with respect to that of the standard PC-mixture. Promising
249 results have been obtained also from mechanical tests, both in compression and shear (Petti
250 et al., 2020), comparing the mechanical response of the natural sediments with that of the
251 same sediments treated with traditional cement and cement–MSF additives.

252 The study on the marine sediments from the Gulf of Taranto has been emblematic also in
253 showing that the search for effective in-situ and ex-situ treatments could become extremely
254 challenging due to the recurrent heterogeneity and contamination that characterizes natural
255 environments close to industrial areas (Vitone et al., 2016, 2020). Preliminary results from
256 these sediments confirm that multi-scale testing is necessary to explore the reactions
257 occurring during the cementation process and their effects on the treatment performance,
258 especially when both additives and binders are used (Petti et al., 2020).

259 The framework defined for normally-consolidated natural clays and the most used
260 standards (ASTM D2487-17e1 and ASTM D4318-17e1) do not focus on soils containing
261 sources of complexity such as those typical of marine sediments: i.e., high content of
262 organic matter, high carbonate content (e.g., fossils and shells), diatoms, and pollutants.
263 Indeed, organic matter may absorb water and promote the aggregation of clay-size particles
264 to form a more open fabric, and, as such, affect the soil consistency, activity and
265 compressibility (Levesque et al., 2007). Moreover, microfossils and diatoms present in
266 marine soils may be responsible for high plasticity, activity and compressibility even within
267 samples of low clay fraction (CF), due to their capacity to trap water into the intraskeletal
268 pore space. Lastly, salts and pollutants alter the thickness of the diffusive double layer of
269 clay particles, affecting the engineering properties of fine-grained soils, depending on their
270 mineralogical composition. The presence of these contributions could have an impact on
271 the geotechnical properties of marine sediments making them exhibit unexpected
272 behavioural facets, with engineering implications also for the effectiveness of remediation
273 and recycling strategies.

274 The activity chart of these marine sediment samples show peculiar deviations from
275 predicted soil facets (Figure 1a) (Vitone et al., 2020). The chaotic distribution in the chart is
276 mainly due to some results from the most contaminated top layer (0-1.5 m below sea floor),
277 which do not show the expected increase in soil plasticity with CF. Hence, some sediment
278 samples exhibit high activity ($A > 1.25$) because they can sustain high plasticity despite
279 their low CF. Conversely, others samples are in the low activity region ($A < 0.75$), due to
280 their low plasticity and high CF.

281 Standard testing procedures on sediments often fail in depicting their altered physical-
282 chemical properties due to cross contamination, salt diffusion, organic matter degradation,
283 and fossil abundance, inducing bias in measurements and classification (Sollecito et al.,
284 2019; Vitone et al., 2020). As an example, the sieving procedure at No. 40 sieve (ASTM
285 D4318-17e1) required by the standards for the Atterberg limit determination, removes the
286 organic components and alters the sediment plasticity (Mitaritonna et al., 2013). As
287 reported in Figure 1b for the marine sediments under study, the liquid limit and the
288 plasticity index determined without sieving the sediments (Sed_UP) are higher than those
289 obtained according to the standard procedure (Sed_ASTM). It follows that the sediment can
290 be classified as CL (medium to low plasticity clay, USCS; ASTM D2487-17e1) according
291 to American Society for Testing and Materials (ASTM) and CH (high plasticity clay) if the
292 Atterberg limits are determined with unconventional procedures taking account of the
293 whole material.

294

295 **2.3 Sustainable management of municipal solid waste (MSW)**

296 **2.3.1 MSW generation, incineration, and recycling**

297 The trend in municipal solid waste (MSW) management in the USA and the EU is toward
298 recycling, reduction of landfilling, and increase of thermal treatment tied with energy
299 recovery. Thus, in the USA, recycling and composting increased from 10 % in 1980 to
300 34.5 % in 2012, while waste-to-energy treatment accounted for 11.7 % of the waste stream
301 during the same year (Paleologos et al., 2016, 2018). For the 27 member states of the EU
302 (EU-27), in 2018 recycling of the MSW had reached 47.4 % (Eurostat, 2020b), whereas
303 2016 data, which included the United Kingdom, showed an average of 20 % incineration
304 across the 28 member states of the EU (Eurostat, 2020c). Per capita, MSW generation in
305 the EU has dropped slightly from an average of 1.41 kg/day (515 kg/annum) in 2015 to
306 1.35 kg/day (492 kg/annum) in 2018 (Eurostat, 2020c). MSW generation in the USA is
307 much higher and stood at 2.05 kg/day/capita in 2017. There has been a sharp increase in
308 waste creation in the USA from the 1960s to 1990, and since then per capita production has
309 stabilized between a minimum of 2.02 kg/capita/day, in 2010, and a maximum of 2.15
310 kg/capita/day, in 2000 (USEPA, 2020b).

311 The Organization for Economic Co-operation and Development's (OECD's) data show a
312 sharp increase in solid waste generation in the three largest economies over the last twenty-
313 seven years. Thus, MSW generation, in thousand tonnes, was (OECD, 2020): in 1990,
314 227,417 in Europe, 188,939 in USA, and 67,668 in China; in 2000, 277,344 in Europe,
315 220,854 in USA, and 118,190 in China; in 2010, 279,011 in Europe, 227,749 in USA, and
316 158,048 in China; and in 2017, 282,743 in Europe, 242,935 in USA, and 215,209 in China
317 (Figure 2). This means that from 1990 to 2017, each of the three largest economies
318 increased their waste production, albeit at different rates, and from a combined 484,021
319 thousand tonnes of waste in 1990 reached 740,887 thousand tonnes of waste in 2017, which

320 represents a cumulative 53% increase. It is clear that despite technological advancements,
321 intensification of recycling efforts, and public awareness campaigns, the continuous
322 creation of new products and our lifestyle and consumption patterns has created a problem
323 that can be addressed only through a radical shift in both the economic and lifestyles
324 paradigms.

325 Landfills have been an essential part in the waste management system, although the
326 trend in most developed countries is away from landfilling and towards incineration tied
327 with energy and heat recovery. The EU's Landfill Directives specifically state that,
328 *“according to the waste management hierarchy, landfilling is the least preferable option*
329 *and should be limited to the necessary minimum”* (European Commission, 2019b). The
330 progressive move away from landfilling and towards increased recycling and waste-to-
331 energy in the EU is shown in Figure 3, where landfill use has steadily reduced during 2010-
332 2016, composing in 2016 about 23% of the total solid waste management options (Eurostat,
333 2020a). Some countries in Europe have done significantly better than this figure. For
334 example, Belgium in 2016 sent only 3.8% of waste to landfills, 17.9 % was incinerated, and
335 78.2 % of waste was recycled (Eurostat, 2020a). Denmark also sent about 4% of its MSWs
336 to landfills, incinerating about 54 % of them, with the remaining being recycled (EEA,
337 2013). Slovenia is being quoted as a success story, in that prior to entering the EU, the
338 country relied heavily on landfilling, but by 2018, it had almost reached the EU 2030
339 recycling target of 65 % for MSW.

340 For developing nations, mainly Asian and African countries, landfilling is mostly
341 adopted due to the difficulty of thermal treatment of MSW that exhibits high moisture
342 content and low calorific value in these countries. In this context, bioreactor landfill (BLF),

343 wherein the decomposition rate of the MSW is accelerated technologically by practising
344 leachate recirculation, air purging or a combination of both, and enhancing methane
345 generation as an alternative energy source, can be used.

346

347 **2.3.2 Challenges and opportunities in landfill management**

348 The key issue in landfill management is to prevent and control harmful impacts to the
349 environment over a period of many decades (Mohamed and Paleologos, 2018). During the
350 COVID-19 pandemic, waste management systems had to rapidly adjust to transport and
351 dispose safely waste potentially contaminated by SARS-CoV-2 (Vaverková et al., 2020).

352 The survival of pathogens in clay barrier systems highly depends on soil hydraulic
353 properties. Changing conditions in soil parameters, such as in hydraulic conductivity (K),
354 moisture content and ground temperature, determine the ability of the microorganisms to
355 grow. When it comes to the unsaturated soil of the barrier system, where hydraulic
356 properties are subject to significant changes (Tang et al., 2018), development of
357 microorganisms can become much more rapid than expected. Clay liners interact with
358 viruses and bacteria depending on nutrient availability, soil pH, medium temperature,
359 moisture content, and soil structure.

360 The complexity of virus interaction with host soils calls for new alternative barrier
361 material to mitigate the transport of SARS-CoV-2 virus in clay liners. One example of such
362 material may be elemental sulphur, which has found application in the construction and
363 waste management industries (El Gamal et al., 2017; Mohamed and El Gamal, 2017). The
364 use of sulphur concrete as a basic component of landfill barrier systems, in order to prevent
365 migration of leachate to groundwater is shown in Figure 4. This barrier is a multi-layered
366 composite system, where an impermeable Modified Sulphur Concrete (MSC) layer is

367 placed in between the primary and secondary leachate collection and removal systems,
368 surrounded by sand and sand-substrate layers (Mohamed and El Gamal, 2017). The liner
369 consists of a layer of MSC with a minimum thickness of 0.3 m. The MSC has a K of the
370 order of about 10^{-13} m/s, much lower than the value of $K=10^{-9}$ m/s specified by the US
371 Environmental Protection Agency (USEPA). The MSC has very low leaching rate in
372 variable-pH environments, and has good resistance to chemical and physical degradation,
373 so it retains its strength under different environmental conditions.

374 Since diffusion can be a significant contributor in the migration of contaminants carrying
375 SARS-CoV-2, the porosity of constructed barriers is important. The very low K of MSC is
376 due to the significant low pore size distribution and the extremely low pore
377 interconnectivity. Moreover, the use of micro fillers in the production of MSC results in
378 high bulk density barriers, which enhance isolation properties (Moosberg-Bustnes et al.,
379 2004). Despite the small size of viruses and bacteria (typically of a diameter of around
380 60–140 nm in the case of the SARS-CoV-2 virus), the combination of very low pore radius
381 of the MSC (ranging from 38 to 110 nm) and disconnected pores - in addition to the
382 hydrophobic properties of sulphur - restrict the fluid flow paths through the concrete bulk,
383 thereby preventing the leakage of toxic and medical hazardous components through the
384 MSC barrier system.

385 Landfill mining has emerged, lately, as a way to recover metals, construction material,
386 refuse-derived fuel, and/or plastic from landfill sites (Canopoli et al., 2018). The interest in
387 landfill mining arose from the fact that significant quantities of useful material have been
388 buried, with USA landfills alone holding over 589 million megatons of metals (USEPA,
389 2014). As an example, the amount of copper deposited in landfills is estimated to be about

390 393 million tons, comparable to the 330 million tons of copper in use in the techno sphere
391 (Krook et al., 2012).

392 In the EU the total landfilled waste is estimated to be 30 to 50 billion cubic meters
393 (Ratcliffe et al., 2012), which in the future may represent a valuable resource of metals and
394 other materials. Recovery of plastic waste and landfill-mined, soil-like fractions (LFMSF)
395 have become major driving forces for the economic viability of landfill mining due to the
396 large fraction (20 to 70 %) of these in waste (Chandana et al., 2020).

397

398 **2.4. Geoenvironmental applications plastic and rubber reuse - zero waste discharge**

399 The extensive utilization of plastic as an everyday commodity has led to its indiscriminate
400 disposal in the geoenvironment. It has been estimated that around 4.9 billion metric tons of
401 plastic are discarded in landfills and the environment (Geyer et al., 2017). Discarded plastic
402 degrades to micro- and nano-plastic, a critical situation because of the potential of plastic to
403 have contaminants attached onto it, or to carry microbes, which because of the size of the
404 micro- or nano-particles can move easily through different environmental media, and pass
405 to the food chain. Ngo et al. (2019) found micro-plastic in the influent, the sludge and the
406 effluent that is released from wastewater treatment plants. Yonkos et al. (2014) detected
407 micro-plastic in estuarine rivers, whereas O' Connor et al. (2019) and Panno et al. (2019)
408 found it present in both the unsaturated and saturated zones. Recently, Ragusa et al. (2021)
409 found that microplastics have entered the food chain, appearing even in human placenta.
410 This necessitates the recycling of plastic waste into secondary products and their use in
411 industrial, infrastructure, and environmental applications. A summary of various products
412 from plastic waste, the type of industry and method of application, together with the
413 advantages and disadvantages of plastic waste utilization, is presented in Table 2.

414 Increasing demand for rubber by various industries has led to the production of
415 numerous rubber products that at the end-of-life create a substantial environmental burden
416 due to their non-biodegradability. The majority of rubber waste originates from discarded
417 tires, and it is estimated that by 2030, approximately 1,200 million tires would be discarded
418 annually (Thomas and Gupta, 2016). This constitutes a serious challenge, especially for
419 developing countries that have insufficient landfills, and a lack of technical and practical
420 expertise in recycling and processing of rubber waste. Unsanitary disposal of rubber waste
421 may create a breeding ground for mosquitos and other disease vectors, in addition, to
422 contamination of the geoenvironment (Yung et al., 2013).

423 Current reuse of rubber waste includes tire-derived fuel, molded and extruded products,
424 rubber-modified asphalt and sealants, and ground-rubber applications in sport facilities
425 surfaces and walkways. Rubber waste utilization in civil engineering applications include
426 slope stabilization, sound barrier, road construction, vibration dampener, etc., while rubber-
427 waste-derived aggregates have been utilized as lightweight fill material in embankments
428 and retaining walls. For ameliorating the inferior geotechnical attributes of expansive clay,
429 ground rubber, as additive (Soltani et al., 2020), and synthetic polymer (polyacrylamide), as
430 binder (Soltani et al., 2019), have shown promise. Ground rubber additives also show
431 promise for improvement in liquefaction resistance of silty sand (Ghadr et al., 2021). Well-
432 graded sand with nominally 10 wt% pulverized waste tire material has shown promise to
433 act as adsorptive fill material for the removal of benzene, toluene, ethylbenzene, and xylene
434 (BTEX) components and heavy metals, whilst providing adequate shear capacity for many
435 load-bearing field applications (Shahrokhi-Shahraki et al., 2020). Rubber-waste-derived
436 aggregates can also be used in leachate collection and removal systems (LCRS) due to their

437 high K values, which are much greater than the standard recommended value of $K = 10^{-4}$
438 m/s for LCRS layers. Shredded rubber particles have found limited application in concrete
439 casting as aggregate replacement (Jalal et al., 2019), because they may reduce the concrete
440 strength due to the hydrophobicity and low surface energy of rubber, which prevents good
441 adhesion to the matrix (Nuzaimah et al., 2020). Finally, rubber waste applications are being
442 explored for thermal and sound insulation (Thai et al., 2020), and as vibration dampeners to
443 diminish/absorb the vibrational effects on structures.

444 More advanced reuse concepts, such as zero waste discharge that include zero-liquid-
445 discharge (ZLD) and zero-solid-waste have become mainstream practices. ZLD is a
446 wastewater management approach that aims to recover and reuse the entirety of the
447 industrial wastewater generated, resulting in zero discharge in the environment. ZLD was
448 limited by the efficiency, energy requirements and cost of the thermal and membrane
449 technologies on which it is based, but it is now driven by new regulations on effluent
450 limitations in several countries (Yaquub and Lee, 2019). For example, in the USA, the first
451 federal maximum pollutant concentrations, pre-treatment standards, and best pollutant
452 control technologies for effluent reduction from steam electric power-generating plants
453 were mandated (USEPA, 2015). China announced a new action plan in 2015, aiming to
454 reduce water pollution substantially by 2030. Measures in the Chinese action plan that
455 favour ZLD are, among others, control and reduction of pollutant discharge, financial
456 incentives to promote reuse of industrial, reclaimed and sea waters, as well as strengthening
457 regulations, inspection and penalty structures, technological and management practices, and
458 stakeholder participation. Finally, the EU has, since 2015, launched a Circular Economy

459 Action Plan (EU, 2015), which has motivated several major European industrial leaders to
460 commit to ZLD and the principles of circular economy.

461

462 **3. Geoenvironmental Applications for Land Improvement**

463 **3.1 Green developments in ground improvement and restoration**

464 Ground improvement works are challenging when problems of soft and weak estuarine
465 clays, highly compressible peats, offshore marine muds and sensitive clays are encountered
466 in infrastructure projects. Recent ground improvement solutions include recycling of
467 C&DW in the place of quarry-based raw materials; development of adsorptive load-bearing
468 fill from recycled by-product materials, for the removal of organic/inorganic contaminants;
469 and new, more efficient and environmentally-friendly construction practices and
470 technologies.

471 For instance, rather than importing engineering fill to a site, marginal fill material
472 already on-site, but with nominally too high moisture content can be successfully
473 incorporated in embankment construction operations, using geosynthetic inclusions that
474 provide both reinforcement and drainage functions and/or amended with suitable industrial
475 by-product materials. Limited life geosynthetics, fabricated from natural fibers, can replace
476 conventional synthetic prefabricated vertical drains (PVDs) during the embankment
477 foundation's consolidation stage. Lightweight fills, including recycled tire bales and
478 expanded clay aggregate can be used in the embankment-core construction. Rather than
479 employing surcharge preloading with PVDs to achieve acceptable residual settlements for
480 embankments on soft compressible soil deposits, the vacuum preloading method can be
481 used (Griffin and O'Kelly, 2014).

482 Major 'green' developments in the ground improvement sector include techniques and
483 processes that are bioinspired. These include, using naturally occurring/produced polymers

484 (biopolymers) for soil mixing and grouting applications; bio-calcification of sandy soils
485 using the Microbial-Induced Carbonate Precipitation - MICP method (DeJong et al., 2013),
486 which employs ureolytic bacteria, but more recently investigating indigenous to a given site
487 bacteria, and the use of nanomaterials (e.g., nanosilica) for grouting treatments. Even
488 modest amounts of bonding between soil solids can produce sufficient real cohesion and
489 significantly increase near-surface strength for coarse-grained soil deposits. As well as
490 reducing the carbon footprint, many of the above, though presently at bench scale, have
491 shown promise in replacing traditional cementitious and chemical additives. Biopolymers
492 have also been tested in the manufacturing of earthen blocks for improved load bearing and
493 durability performance.

494 Wind tunnel experiments have shown that the MICP technique of applying spray
495 treatment of the reagents (bacterial cell and urea-calcium chloride solutions) onto a loose
496 sand surface layer has succeeded in stabilizing this layer, with the potential to protect
497 coastal sand dunes. The MICP technique using multiple staged injections of the reagents
498 has also been shown to reduce internal erosion, one of the main causes of failure for
499 hydraulic earthen structures (Amin et al., 2017).

500 Nano-silica (aqueous silica nanoparticles) has shown promise for grouting applications,
501 producing a viscous gel property between soil particles to improve the liquefaction
502 resistance, geotechnical load-bearing capacity, and internal and surface layer erosion
503 resistances of loose to medium sandy deposits (Gallagher and Mitchell, 2002).

504 Foundations and linear infrastructure bearing on expansive soil deposits can experience
505 significant expansion/contraction during the absorption-desorption of a soil, leading to
506 foundation distortion, wall cracking, and undulation and cracking of road pavements, etc.

507 Rather than using traditional cementitious/calcium-based binders, addition of sulfonated oil
508 (a group of synthetic surfactants) has been shown to mitigate the swell–shrink volume
509 change potential of expansive soil at bench scale (Soltani et al., 2021).

510 Environmental geotechnics has been central to peatland management and restoration.
511 These dynamic eco-hydrological wetland systems (and substantial carbon sinks) are
512 increasingly under threat due to natural and anthropogenic pressures. One solution that has
513 proven effective in the field is the strategic construction of peat bunds (dams) at affected
514 areas around the bog margins. These bunds can gradually re-establish the natural peatland
515 hydrology and indigenous peat-forming vegetation through collection, storage and
516 controlled release of runoff from the high bog. Root reinforcement and slope
517 bioengineering stabilisation have the ability to replace classically engineered interventions
518 (e.g., piles, soil nails, ground anchors) with natural planting for stabilisation or remediation
519 of failures in natural and manmade slopes (Wood, 2013).

520 The use of geosynthetics in civil engineering often contributes to reductions in the cost
521 of imported materials and the amounts of waste generated, compared with the use of soil,
522 concrete, or steel (Jones, 2015). Important cost-savings related to materials' replacement
523 associated to geosynthetics are found in landfills, where the volume of space saved by
524 using thin geosynthetic materials instead of thicker mineral barriers is very significant. As
525 reinforcement material, geosynthetics can be used to improve low-quality soils or
526 alternative fill materials, such as C&DW, dredged materials, or other industrial non-
527 hazardous wastes.

528 The use of recycled C&DW as fill material of geosynthetic-reinforced structures (e.g.,
529 embankments, retaining walls) has shown very good overall performance. Geogrids and

530 geocells have also been used to improve the performance of unpaved and paved roads made
531 of recycled asphalt pavement (Gongora and Palmeira, 2012).

532 The use of dredged materials as backfill for geogrid-reinforced structures has been
533 evaluated through pull-out tests (Kondo et al., 2016). The coefficient of interaction between
534 uniaxial geogrids and the dredged materials has been found to be slightly smaller than the
535 value for clayey soils. Despite the lower performance of these to that of conventional
536 materials, the environmental benefits can be of importance.

537 In mining applications, geosynthetic barriers can be used to reduce the environmental
538 risks associated with contaminant migration and to improve the recovery of mine water
539 (Bouazza, 2013). Geosynthetic materials, such as geopipes, geotextiles, and geodrains are
540 also often incorporated into the drainage systems of tailing storage facilities or mining
541 waste (waste rock) storage facilities.

542 The dewatering of slurry-like wastes, such as municipal waste, agriculture waste, food
543 and food-processing waste, industrial and mining waste, and contaminated sediments can
544 also be performed through geotextile tubes, offering cost savings and environmental
545 benefits.

546 Savings regarding the amount of materials and related costs vary with project conditions.
547 A decrease of 30 % to 40 % in the aggregates, from the application of geosynthetics in road
548 construction over soft soils (shear strength < 30 kPa) was reported by Christopher (2014).
549 The International Geosynthetics Society (IGS) Sustainability Committee has stated that
550 geosynthetics can reduce the use of aggregate in infrastructure construction by over 50 %
551 and up to 90 % in some cases (IGS, 2021). In drainage applications, the use of a geotextile
552 filter wrapped around the open-graded aggregate allows a decrease in the dimensions of the

553 drain trench typically on the order of 0.3 m in width, without a decrease in flow capacity
554 (Christopher, 2014).

555

556 **3.2 Sustainable land remediation**

557 Land remediation involves site characterization, risk assessment, and remediation. Risk
558 assessment can be complex due to incomplete knowledge of the hydrogeological conditions
559 and of the physical, chemical, and biological processes operating at a site, the
560 contaminants' effects, uncertainties in the toxicity data, etc. ((Paleologos and Lerche, 1999;
561 Mohamed et al., 2020).

562 Several innovative remediation technologies have been developed to reduce the risk by
563 either removing the contaminants, transforming them into non-toxic forms, or
564 stabilizing/immobilizing them in soil and groundwater. Such technologies for soil
565 remediation include soil washing/flushing, soil vapour extraction, electrokinetic
566 remediation, thermal treatment, phytoremediation, and bioremediation, while for
567 groundwater, remediation applications include air sparging, permeable reactive barriers
568 (PRBs), chemical oxidation/reduction, and bioremediation (Shahrokhi-Shahraki et al.,
569 2020). The use of a particular clean-up technology is mostly site-specific, and the cost and
570 time needed for remediation can vary significantly, spanning hundreds of millions of
571 dollars in clean-up costs and several decades of application (National Research Council,
572 1999).

573 Some regulations have stipulated specific criteria for the selection of remediation
574 technology; for example, a nine-point criteria scheme developed by USEPA (2008) for
575 clean-up of Superfund sites requires measures to: 1) protect human health and the
576 environment; 2) comply applicable or relevant and appropriate requirements (ARARs); to

577 provide: 3) long-term effectiveness and permanence; 4) reduction of waste toxicity,
578 mobility, and/or volume; 5) short-term effectiveness; 6) implementability; 7) low cost; 8)
579 state acceptance; and 9) community acceptance.

580 Conventional remediation approaches are not always sustainable, as they do not always
581 account for broader environmental impacts, such as the extraction and use of natural
582 resources, the wastes created, and the energy used, and related greenhouse gas (GHG)
583 emissions for on- and off-site operations and transportation, and the value lost from the
584 residual degradation of a resource (Paleologos, 2008).

585 To address these deficiencies, some green and sustainable remediation (GSR)
586 approaches have emerged (ITRC, 2011; SURF, 2009; USEPA, 2008). USEPA proposed as
587 a green remediation (GR) concept the practice of considering all environmental effects of
588 clean-up during each phase of the process, and incorporating strategies to maximize the net
589 environmental benefit of the clean-up (USEPA, 2008). The Sustainable Remediation Forum
590 (SURF) promoted a sustainable remediation (SR) concept that uses sustainable practices
591 during the investigation, construction, remediation, redevelopment, and monitoring of
592 contaminated sites, with the objective of balancing economic viability, conserving natural
593 resources and biodiversity, and enhancing the quality of life in surrounding communities
594 (SURF, 2009). The Interstate Technology & Regulatory Council (ITRC) introduced GSR,
595 which is defined as the site-specific employment of products, processes, technologies, and
596 procedures that mitigate contaminant risk to receptors, while making decisions that are
597 cognizant of balancing community goals, economic impacts, and environmental effects
598 (ITRC, 2011).

599 ITRC proposed a tiered sustainable remediation framework that represents the
600 confluence of environmental, social and economic factors in decision-making (ITRC,
601 2011). Specific quantitative assessment tools, such as SiteWise™ and Spreadsheets for
602 Environmental Footprint Analysis (SEFA) have been developed by federal agencies, such
603 as the US Navy and USEPA, to quantify the metrics for environmental impacts. However,
604 tools to assess economic and social impacts are still being developed. Life cycle cost
605 analysis (LCCA) and cost-benefit analysis (CBA) methods are used for broader economic
606 impact assessments. Monetized environmental costs (e.g., social cost of carbon) are also
607 included as indirect sources of costs in such assessments (Reddy et al., 2019). Social
608 aspects of sustainability include consideration of interests of all stakeholders, although
609 social impacts are difficult to quantify (Reddy et al., 2014).

610 Resiliency of site remediation systems under changing climatic conditions and extreme
611 weather events are of growing concern to environmental remediation professionals. For
612 example, inundation of a contaminated site may adversely affect the bioremediation
613 effectiveness in hydrocarbon-contaminated soils. Similarly, salt-water intrusion into coastal
614 aquifers from a sea-level rise or any changes in groundwater elevations may have a
615 negative impact on groundwater remediation by PRBs or chemical oxidation.

616 Finally, while the environmental dimension of sustainable remediation is well addressed,
617 the economic and social dimensions are not yet fully developed and require additional
618 research. All stakeholders should be educated on the benefits of sustainable remediation.
619 Incorporating resiliency into sustainable remediation is also emerging as an urgent need to
620 the environmental remediation professionals.

621

622 **4. Clean Energy Production Using Thermo-active Geostructures**

623 The use of engineering projects to accomplish supplementary goals to their original purpose
624 has become more prevalent recently (Burra and Gupta, 2018). The final section of this
625 article highlights a perhaps not so well known area, where traditional ground structures
626 (e.g., pile foundations, tunnel linings, diaphragm walls) can be used as heat exchangers, as
627 thermo-active geostructures for energy production (Laloui and Rotta Loria, 2020). The total
628 number of such projects (< 200) still remains small compared to the total ground source
629 heat pump installations worldwide.

630 The heat exchange in thermo-active geostructures is usually ensured by a heat pump
631 system connected to heat exchanger pipes, embedded inside the geostructures during its
632 construction, as a closed-loop geothermal system. A heat carrier fluid circulates inside the
633 pipes to ensure the heat exchange between the geostructures and the heat pump. This
634 system can be used for heating/cooling demands in residential buildings, for agricultural
635 and industrial activities, to prevent the icing of pavements for transport infrastructures, etc.
636 In addition to the advantages similar to the conventional shallow geothermal energy
637 systems, energy geostructures use underground structures, already required for structural
638 reasons.

639 Between various types of energy geostructures, piles are the most common. Piles have
640 the potential to offer reduced capital cost compared to traditional vertical ground heat
641 exchangers, such as boreholes. In addition, as piles have a superficial resemblance to
642 boreholes, there exist already available thermal design methods that can be adapted for use
643 with piles. For instance, a thermal pile standard (GSHPA, 2018) has been developed from
644 the vertical borehole standard and various methods for geotechnical design of piles

645 subjected to thermal changes have been recently made available (Laloui and Rotta Loria,
646 2020). By contrast, for other geostructures, some demonstration projects using slabs, walls
647 and tunnels as ground heat exchangers exist, but there are no standard design or analytical
648 approaches, and every new project must proceed on a case-by-case basis.

649 Sani et al. (2019) presented an extensive review of research on energy piles and
650 identified the effects of heating and cooling on building foundations in order to successfully
651 design and install an energy pile system that will provide a highly efficient, cost effective
652 and long-term solution for the heating and cooling demands of a building. Bourne-Webb
653 and Bodas Freitas (2020) confirmed that thermal activation induces stress change and
654 deformation of the pile that depend on the boundary conditions (e.g.,
655 soil/pile/superstructure interaction). The most recent studies related to energy piles focused
656 on their long-term thermo-mechanical behaviour and group behaviour (Nguyen et al.,
657 2020).

658 For other energy geostructures, design methods are still under development. Numerical
659 investigations (Barla and Di Donna, 2018) have proved the feasibility of energy tunnels; the
660 exploitable heat of the tunnel lining was estimated at 10-20 W/m² when no groundwater
661 flow is present, and up to 50-60 W/m², when there is significant groundwater flow. A
662 comprehensive analysis of the energy performance and economic attractiveness of energy
663 segmental linings for subway tunnels (Cousin et al., 2020) demonstrated that while the
664 energy performance may be significantly enhanced, the most efficient design does not lead
665 to the lowest LCOE (levelized cost of energy) and the earliest profitability. Observations on
666 a real-scale experimental prototype of an energy tunnel (Barla et al., 2019) confirmed that
667 this technology is mature for industrial application. A preliminary study on the geothermal

668 potential assessment and thermal influences of planned tunnel infrastructure at the city-
669 scale of Basel (Switzerland) illustrated the applicability of the developed methods to
670 evaluate the general feasibility of the energetic use of tunnel structures (Epting et al., 2020).

671 For energy diaphragm walls, both energy and geotechnical aspects are still being
672 investigated. Several numerical tools have been recently developed to maximise the energy
673 performance of a diaphragm wall through the design of piping layout (Sterpi et al., 2020),
674 or to evaluate the conductive and advective exchanged heat by the wall and the surrounding
675 soil (Rammal et al., 2020). From the mechanical point of view, thermal activation of a
676 diaphragm wall would induce additional bending moment and horizontal displacement of
677 the wall. However, the computed stress variations are largely compatible with strength
678 limits.

679 Although the scientific literature on the design and operation of shallow geothermal
680 energy systems (including energy geostructures) has been increasing over the past years,
681 this technology can be considered as a decentralized source of energy without being fully
682 competitive yet (Tsagarakis, 2020). What hinders the wide penetration of these systems in
683 most countries are issues related to high installation costs, administration, stakeholders'
684 awareness, and marketing. A recent review of the legal framework in shallow geothermal
685 energy in several European countries (Tsagarakis et al., 2020) showed that a high diversity
686 exists on legislation provisions, regulations, standards, and institutional support. These
687 authors suggested that this discrepancy acts as a barrier for further development of the
688 shallow geothermal energy market. They concluded that issuing appropriate technical rules
689 and standardization among EU countries would result in an increase of these energy
690 systems' market. A common legislative EU framework will also benefit and affect other

691 countries, especially developing countries, for which shallow geothermal energy
692 applications are still in the early stages.

693

694 **5. Concluding Remarks**

695 The overarching objective of the current paper is to put at the forefront some significant
696 contributions in sustainable technologies and management practices across a broad range of
697 environmental geotechnical projects, thus highlighting the important role of the discipline
698 for the establishment of a green economy in the post COVID-19 era.

699 We have concentrated on three thematic areas, and recent developments related to
700 sustainability solutions in these areas, as well as providing recommendations to overcome
701 technological, regulatory, and administrative obstacles. In view of the increased
702 urbanization in developing countries, the reuse of solid waste in the construction industry,
703 given this industry's significant material and energy consumptions, as well as the quantity
704 of waste generated, are of critical importance. Reusing construction and demolition waste
705 (C&DW), excavated soil and rock, and industrial waste, such as rubber and plastic, can find
706 extensive application in road pavement layers, drainage projects, landfill cover and liners,
707 embankments, and other infrastructure projects, thereby resulting in significant savings in
708 resource exploitation, transportation, and waste disposal.

709 Stabilization/solidification (S/S) of marine sediments with binders and additives
710 represents a promising alternative for managing marine sediments dredged periodically in
711 harbour areas. Treated sediments may be used as aggregates for road construction,
712 cemented mortars, fill material in brick production, or in port piers, shores, and
713 breakwaters. Treatment with additives, such as biochar or mussel shell flour, presents a

714 more sustainable solution since it reduces the content of cement in the current cementitious
715 binders, and can achieve significant savings in carbon dioxide emissions during the clinker
716 production of cementitious binders.

717 Despite the trend in advanced countries toward recycling and waste-to-energy, landfills
718 constitute the most common municipal solid waste management practice. The complexity
719 of virus interaction with host soils and the potential for transport of viruses through clay
720 liners requires a rethinking of the material in landfill barriers. One example of such material
721 may be elemental sulphur, through the use of modified sulphur concrete (MSC) as a
722 component of landfill barrier systems, in order to prevent migration of leachate to
723 groundwater. The MSC has a lower K than that specified by USEPA for landfill barriers.
724 Furthermore, it is an inert material, and has very low leaching rate in variable-pH
725 environments, and good resistance to chemical and physical degradation. Its very low K
726 and extremely low pore interconnectivity may prove beneficial in hindering the migration
727 of medical contaminants, such as those carrying SARS-CoV-2, through landfill liners.

728 Sustainable ground improvement solutions include recycling of C&DW instead of using
729 quarry-based raw materials; development of adsorptive load-bearing fill from recycled by-
730 product materials, for the removal of organic/inorganic contaminants; novel foundation
731 systems instead of conventional concrete foundations; and the embedment of new, more
732 efficient and environmentally-friendly construction practices and technologies. Instead of
733 using traditional cementitious/calcium-based binders, foundations and linear infrastructure
734 constructed on expansive soil deposits may use sulfonated oil or ground rubber, recycled
735 from scrap tires, and synthetic polymer, as binder, to mitigate the swell–shrink volume
736 change potential.

737 Geosynthetics play a major role in drainage, barrier and final cover systems of landfills,
738 and in mining applications, and their use contributes to significant reductions in the cost of
739 imported materials, and quantity of waste generated, thus providing a more efficient use of
740 natural resources compared to traditional approaches that use soil, concrete, or steel.

741 At the same time, remediation solutions are required to address the multitude of
742 contaminated sites worldwide. Advanced developments that incorporate environmental,
743 economic, and social dimensions are presented herein.

744 Finally, the topic of thermo-active geostuctures concludes this paper, where, apart from
745 their infrastructure utility, these structures have the potential to contribute to the energy mix
746 as a renewable energy source.

747 Thus, the benefits of adapting the above technologies and practices include, among
748 others, waste minimization and promotion of reuse and recycling; preservation of natural
749 resources; improvement of waste management systems; reduction of the threats to soil and
750 groundwater contamination; and reduction of the carbon footprint and of greenhouse gas
751 emissions. Altogether, the presented topics may provide a blueprint for a path forward to
752 environmental geotechnics in achieving more sustainable and cost-effective solutions, and
753 the development of more resilient infrastructures and greener societies.

754

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759

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1072 **Figure captions**

1073 **Figure 1.** a) Activity chart of the Gulf of Taranto marine sediments (Italy) collected down
1074 to 39 m depth (Vitone et al., 2020); b) Casagrande plasticity chart of a sediment sample
1075 from Gulf of Taranto. Sed_1ASTM: standard procedure, Sed_1UP: unconventional
1076 procedure (Petti et al., 2020), A: activity; bsf: below sea floor.

1077 **Figure 2.** MSW generation (in thousand tonnes) in the three largest economies (OECD,
1078 2020)

1079 **Figure 3.** Treatment rates (%) of waste by various routes in the EU for 2010 to 2018,
1080 excluding major mineral wastes (Eurostat, 2020a).

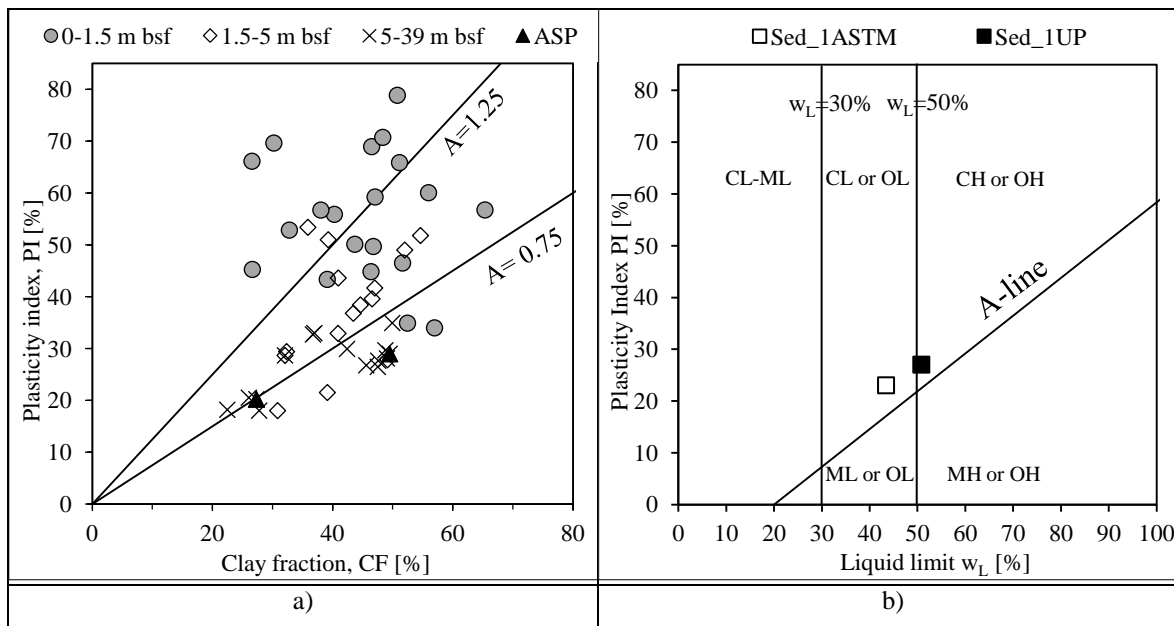
1081 **Figure 4.** Design of MSC-containment construction barrier (modified after Mohamed and
1082 El Gamal 2017)

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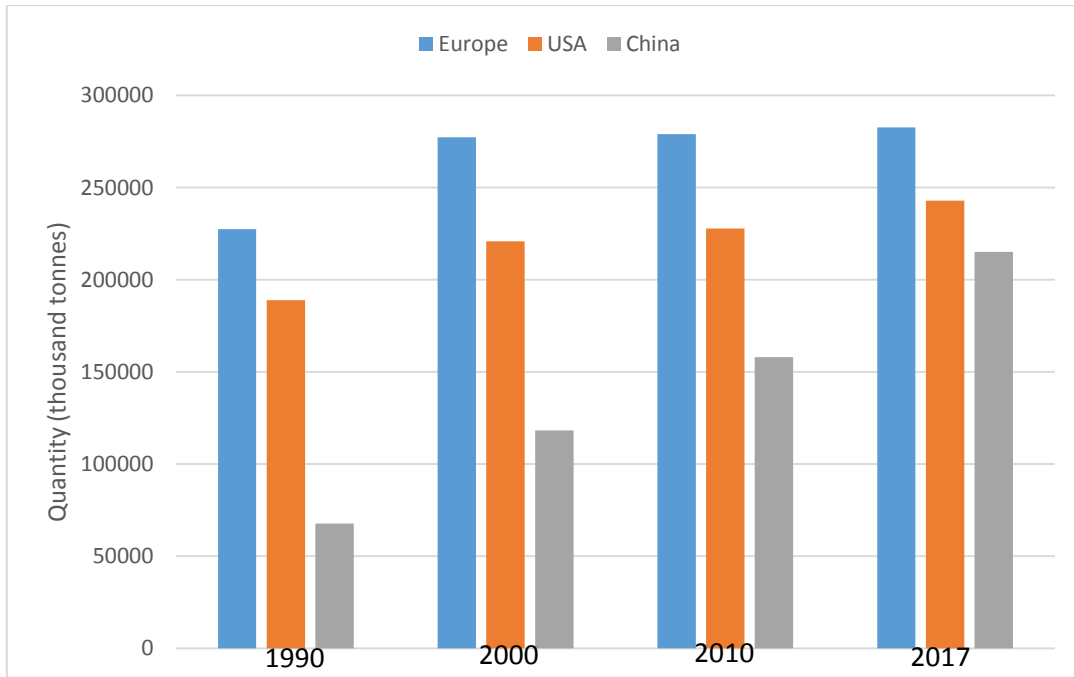
1085 **Tables**
 1086 **Table 1.** Physical and state properties of natural and treated sediments with 8% Portland
 1087 cement (Sed8PC), or 6% Portland cement with 2% MSF (Sed6PC2MSF) (curing time: 28
 1088 days).

1089 **Table 2.** State-of-the-art on plastics waste utilization for geoenvironmental applications.
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 1094 to 39 m depth (Vitone et al., 2020); b) Casagrande plasticity chart of a sediment sample
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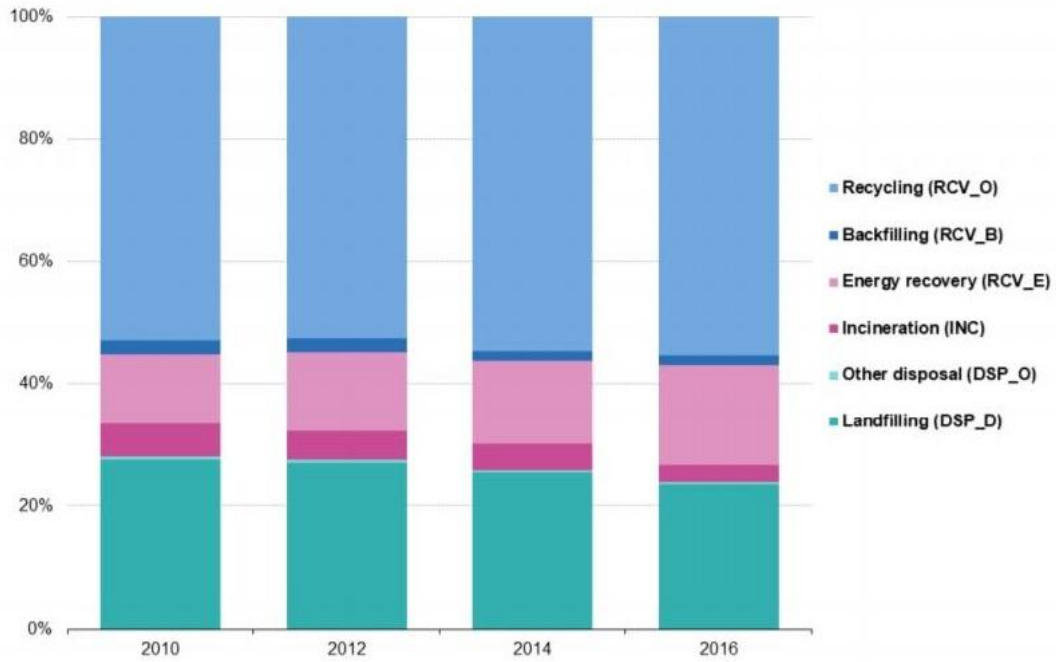
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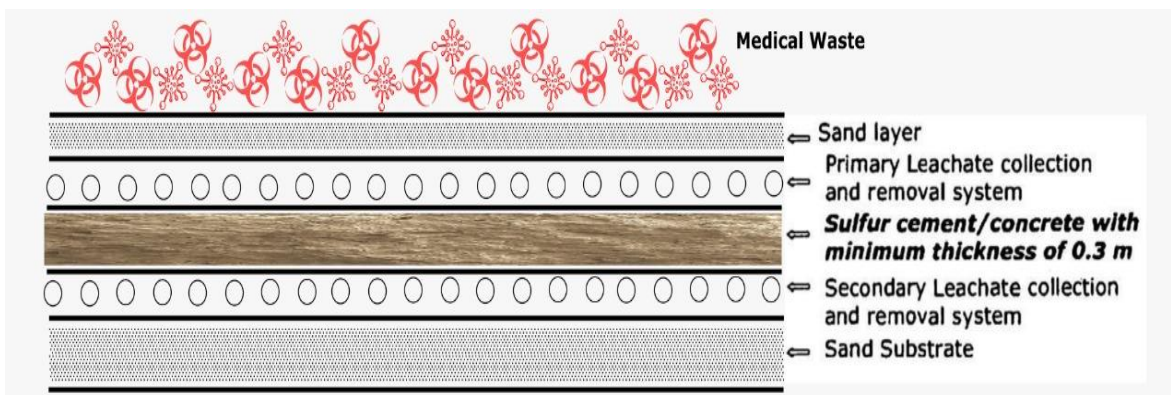
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 1113 El Gamal 2017, 2014).

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1115 **Table 1.** Physical and state properties of natural and treated sediments with 8% Portland
 1116 cement (Sed8PC), or 6% Portland cement with 2% MSF (Sed6PC2MSF) (curing time: 28
 1117 days).

Mix	w _L (%)	PI (%)	w ₀ (%)	CI (-)
Sed_UP	53.59	28.61	74.0	-0.72
Sed8PC	86.50	32.20	66.95	0.61
Sed6PC2MF	85.17	29.83	66.47	0.63

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w_L: Liquid limit, PI: Plasticity Index, w₀: Water content and CI: Consistency index.

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Table 2. State-of-the-art on plastics waste utilization for geoenvironmental applications.

Industry	Technique/method /field of application	Products	Advantages	Disadvantages	References
Energy	Incineration	Thermal energy	Direct energy recovery and reduction in volume of the waste	Higher initial cost Release of polychlorinated dibenzodioxins /furans and polycyclic aromatic hydrocarbons	Antelava et al. (2019)
	Pyrolysis	Bio-oil and syngas	Lower carbon footprint compared to incineration Production of hydrocarbon rich gas/oil with a heating value 25-45 MJ/kg Flexibility to produce liquid/solid products based on requirements	Vulnerable to inconsistency in the quality of the plastic waste Corrosion of reactors due to release of polychlorinated hydrocarbons and HCl from PVC degradation	Qureshi et al. (2020)
	Gasification	Synthesis gas	The synthesis gas is a desired feedstock for production of fuels such as dimethyl ether, methanol	Inefficient fluidization of the feedstock due to agglomeration of bed particles with plastic waste	Burra and Gupta (2018); Lopez et al. (2018)
	Hydrothermal carbonization	Hydrochar	Chemically activated porous hydrochar can be used for energy storage Co-hydrothermal carbonization of PVC and biomass helps in dichlorination	Adulteration of alkalis required to improve the dichlorination efficiency	Iniguez et al. (2019); Shen (2020); Zhao et al. (2020)

			and removal of inorganics from hydrochar Organic chlorides can be converted into water-soluble chlorides by avoiding polychlorinated dibenzodioxins/furans.		
	Chemical looping processes	Thermal energy, hydrogen or methane production	Opportunity for CO ₂ capture from thermal treatment of plastic waste	Sintering and agglomeration of the oxygen carriers during the process Reduction in oxygen carrying capacity and combustion efficiency	Jinchen et al. (2019) ; Sai et al. (2018)
Infrastructure	Cement matrix composites	Concrete , paver blocks, tiles, bricks	Replacement of conventional coarse and fine aggregates with plastics waste Production of lightweight construction material	Inferior mechanical properties due to poor interaction between cement and plastic aggregate	Goli et al. (2020); Shah et al. (2019)
	Polymer matrix composites	Wood-plastic composites, tiles and paver blocks	Replacement of cement based binders with plastic waste mitigate the CO ₂ emission from cement production Enhanced tensile strength and durability due to less water absorption	Inferior mechanical properties due to the immiscibility of the heterogeneous polymers in plastic waste Lack of low-cost compatibilizers hinders the upscaling process	Goli and Singh (2021); Basalp et al. (2020); Goli et al. (2020); Dhawan et al. (2019)
	Soil reinforcement	-	Useful for enhancing the strength and	Leaching of toxic chemical additives viz.,	Salimi and Ghazavi

			stability of soils for embankments, retaining structures and pavement subgrades	polybrominated diphenyl ether and heavy metals	(2019); Chae and An (2018); Peddaiah et al. (2018)
	Pavement construction	As a replacement to the asphalt binder	Enhances durability, softening point and fatigue life of the pavement	Lowering of cold cracking resistance with increase in plastic waste	Vargas and Hanandeh (2021); Appiah et al. (2017)
Environmental cleanup	Wastewater treatment	As adsorbent for removal of pollutants	Biochars derived from plastic waste adsorb dyes and heavy metals present in wastewater. Higher volatile matter is helpful in increasing the biochar porosity and thus the specific surface area for adsorption.	Sorption capacity of the biomass derived biochars is more as compared to plastic waste derived biochars	Singh et al. (2020, 2021); Miandad et al. (2018)

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