

18 **Garfi, M., Puigagut, J. (2016) Reusing industrial by-products to enhance**
19 **phosphorus removal in waste stabilization ponds: laboratory approach.**
20 **Desalination and Water Treatment Journal, 57 (4) (1857-1864)**

21 **Abstract**

22 Waste stabilization ponds (WSP), in spite of being a suitable technology for wastewater
23 treatment, present low phosphorus removal. This study aimed at evaluating the net
24 increase on phosphorus removal efficiency in microcosm WSP in which sludge was
25 conditioned with an adsorbent (industrial by-product) having a high phosphorus
26 retention capacity. In order to determine the best candidate to condition the sludge, four
27 different industrial by-products (granular bentonite; fly ashes from a municipal solid
28 waste incineration plant and two types of fly ashes from power plants) were tested for
29 their phosphorus adsorption capacity. Experimental results were fitted to Langmuir and
30 Freundlich models. All adsorbents showed a high phosphorus adsorption capacity.
31 Maximum phosphorous adsorption capacity estimated from Langmuir equations ranged
32 between 34.7 and 74.0 mg P/g adsorbent, being fly ashes from a power plant and
33 granular bentonite the adsorbents with the highest and lowest adsorption capacity,
34 respectively. Microcosms WSP were set up and the sludge conditioned with fly ashes
35 from a municipal solid waste incineration plant. Results showed that phosphorus
36 removal efficiency increased up to 90% by adding 5% of adsorbent (in terms of weight
37 of adsorbent to weight of sludge). Main conclusion is that of industrial by-products may
38 be a low cost solution for enhancing phosphorus removal in WSP.

39

40 **Keywords:** Benthonite; fly ashes; isotherm; waste stabilization ponds; phosphorus

41 **1. Introduction**

42 Phosphorous (P) is widely used either in the production of fertilizer for agricultural
43 activities or in explosives, pesticides and detergents [1]. Human activities have
44 significantly affected natural phosphorous cycles, which have resulted in some serious
45 ecological problems [1]. Excessive phosphorous in surface water is unhealthy for
46 aquatic ecosystems, since it causes eutrophication [2-4]. According to that, wastewater
47 needs proper treatment for the removal of phosphorous to levels that are acceptable for
48 natural systems [5]. Conventional processes proposed for phosphorus removal from
49 domestic wastewater are mostly based on chemical precipitation (such as electro-
50 coagulation, struvite precipitation and the use of iron, aluminium and calcium salts);
51 biological accumulation (based on operational processes enhancing the growth of
52 phosphate accumulating organisms) and adsorption (by aluminium hydroxide, ferric
53 oxides among others) [6]. Chemical and biological processes are expensive and increase
54 the amount of sludge generated during wastewater treatment. However, technologies
55 based on adsorption processes are easy to operate, generate little sludge and allow
56 phosphorous recycling processes to be applied [6,7]. Phosphorus removal in
57 conventional wastewater treatment systems has been widely addressed by applying
58 either physical-chemical precipitation or by enhanced biological. However, phosphorus
59 removal in natural wastewater treatment systems for the sanitation of small
60 communities or rural areas is a critical issue that still remains under improvement [4].

61 Waste stabilization ponds (WSP) have been considered as an effective and low-cost
62 technology for wastewater treatment in small communities [8,9]. WSP are shallow
63 basins in which wastewater is treated by bacteria (anaerobic/aerobic) and algae.
64 Pollutants removal in WSP is carried out by means of physical, chemical and biological
65 processes, which naturally occurs in aquatic systems. Furthermore, phosphorus removal

66 in WSP depends on a wide variety of environmental conditions such as temperature, pH,
67 E_H , and dissolved oxygen concentration and involves complex physical and bio-
68 chemical processes (i.e.: adsorption, precipitation, uptake by microorganisms and
69 sedimentation). Accordingly, phosphorus can be adsorbed by sediment, or it can be
70 released into water from the sediment [10] leading to a net phosphorus removal which is
71 usually less than 50% [11]. The amount of phosphorus adsorbed depends on the
72 capacity of the sediment to adsorb and desorb phosphorus from solution [8,12]. To this
73 regard, several authors proved that phosphorus adsorption could be enhanced by the
74 presence of iron (Fe), aluminium (Al) and calcium (Ca) at high concentration in the
75 sediment [8,13]. Some industrial by-products are rich in Fe, Al and Ca (such as fly ash,
76 furnace slag and alum sludge) and may be a low cost solution to enhance the
77 phosphorus adsorption/removal capacity of WSP sediments [2,4,13,14]. In spite of the
78 potential use of industrial by-products to enhance phosphorus removal in WSP, there is
79 scarce information in current literature.

80 This study aimed at evaluating the net increase on phosphorus removal efficiency in
81 microcosm waste stabilization ponds (WSP) in which sludge was conditioned with an
82 adsorbent (industrial by-product) having a high phosphorus retention capacity. In order
83 to determine the best candidate to condition the sludge, four different industrial by-
84 products (granular bentonite; fly ashes from a municipal solid waste incineration plant
85 and two types of fly ashes from power plants) were tested for their phosphorus
86 adsorption capacity. Afterwards, a microcosm WSP experiment was conducted at
87 laboratory scale in order to determine the net enhancement of phosphorus removal in
88 WSP by conditioning the sediment with fly ashes from a municipal solid waste
89 incineration plant.

90

91 **2. Materials and Methods**

92 **2.1 Industrial by-products**

93 Adsorbents studied were a granular residue of commercial granular bentonite (GB)
94 provided by the AEB group, fly ashes from the municipal solid waste incineration plant
95 of Mataró (MSW FA) and two types of fly ashes from two different power plants
96 (named under PP FA I and PP FA II). More precisely, PP FA I and PP FA II were
97 provided by the power plants of Cercs and Andorra (Teruel), respectively.

98 Adsorbents were characterized in terms of Total Solids (TS) and Volatile Solids (VS)
99 following standard methods [15].

100 Chemical composition of adsorbents was analysed by X-ray fluorescence spectrometry
101 in order to determine the concentration of Fe, Mn, Ti, Ca, K, P, Si, Al, Mg, Na oxides.

102 Physical and chemical characteristics of adsorbents are shown in Table 1.

103

104 **2.2 Isotherm experiments**

105 **2.2.1 Batch adsorption experiments**

106 Batch adsorption experiments were carried out in duplicate following the procedure
107 described by [16]. Briefly, Erlenmeyers of 250 mL were filled up with 50 mL of
108 distilled water to which KH_2PO_4 was added to reach the desired phosphorus
109 concentration (see below for the specific phosphorus concentrations tested).

110 Furthermore, adsorbents were pre-screened (<2mm) and 1 g was added to each
111 Erlenmeyer. Electrolyte solution (CaCl_2) was added to a molar concentration of 0.01
112 mols/L and bacterial growth was inhibited by adding chloroform at a final concentration
113 of 20 g/L. Phosphorus initial concentration (C_i) for each tested by-product are
114 summarized in Table 2. Five equal C_i (from 0 to 900 mgP/L) were used for GB, MSW

115 FA; whereas for PP FA I and PP FA II one higher concentration was also considered to
116 obtain a good correlation with Langmuir model and to obtain the Q parameter.
117 Flasks were continuously stirred for 24 hours, as suggested by [16]. Experiments were
118 carried out at room temperature (25°C). pH of the solution was measured by means of a
119 Crison pH-meter at the beginning and at the end of the experiment. After 24 hours,
120 samples were collected from the flasks and analysed for orthophosphate concentration
121 according to [15].

122

123 *2.2.2 Adsorption isotherm models*

124 Data obtained from the batch tests were fitted to both Freundlich and Langmuir
125 adsorption isotherm equations.

126 The Freundlich isotherm model, which is an empirically equation more appropriated for
127 heterogeneous substrates [17], is expressed as:

$$128 \quad q = K_d C_e^{1/n} \quad (1)$$

129

130 Where q is the amount of adsorbate per unit of adsorbent (mgP/g of adsorbent in this
131 study); C_e is the equilibrium solution concentration (mgP/L); K_d (mg^{1-1/n} l^{1/n}/g) is the
132 Freundlich adsorption capacity parameter and 1/n (dimensionless) is the Freundlich
133 adsorption intensity parameter. K_d and 1/n are obtained empirically and considered
134 constant for each adsorbent [18].

135 Freundlich isotherm can be also expressed as:

$$136 \quad (2) \quad \log q = \log K_d + \frac{1}{n} \log C_e$$

137

138 A linear plot of log q and log C_e provides the value for K_d and n in the form of intercept
139 and slope [2].

140 The Langmuir equation can be written as:

141 (3)
$$\frac{C_e}{q} = \frac{C_e}{Q} + \frac{1}{b Q}$$

142

143 Where Q is the maximum adsorption capacity (mgP/g of adsorbent in this study), and b
144 (l/mg) is a measure of the sorption energy. Langmuir adsorption allows to calculate the
145 maximum phosphorous adsorption capacity of the substrates, and consequently, to
146 estimate substrate longevity [13].

147 Q and b are determined from the slope and intercepts generated from a linear plot of
148 C_e/Q versus C_e [2].

149

150 ***2.3 Microcosm waste stabilization ponds***

151 Microcosms WSP consisted of nine 400 mL glass bottles filled up with 250 mL of a 5
152 mg PO₄-P/L solution, which is in the range of phosphorus concentration of domestic
153 wastewater in Spain [18], 15 mL of sludge from a municipal wastewater treatment plant
154 located in Barcelona and 0.1 or 5% of fly ashes from a municipal solid waste
155 incinerating plant (percentage expressed as weight of adsorbent to weight of sludge).
156 Percentages of fly ashes applied in this study were selected according to previous and
157 simplified trials in which phosphorus adsorption was qualitatively detected under sludge
158 to by-product mixtures applied in this study (percentage expressed as weight of
159 adsorbent to weight of sludge) (results not shown). Each experimental condition
160 (control, 0.1% and 5% of industrial by-product) was tested in triplicate. Moreover,
161 sludge layer thickness within glass bottles was that of 2 cm, while water column height
162 was that of 9 cm. This sludge to water height ratio is comparable to that of a WSP after
163 5 to 10 years of operation [20]. Sludge employed was characterized in terms of TS, VS,

164 chemical oxygen demand (COD), total P and total Nitrogen (N) according to [15]. A
165 summary of sludge characteristics is given in Table 3.

166 Microcosms WSP worked under batch conditions. Samples withdrawal and feeding was
167 carried out on a daily basis for one week. To this aim, 40 mL of overlaying water was
168 daily collected from the bottles and analysed for orthophosphate concentration,
169 dissolved oxygen and pH. Furthermore, in order to maintain the water level constant, 40
170 mL of phosphate solution at a concentration of 5 mg PO₄-P/L was carefully added after
171 sampling. Therefore, the microcosms WSP were operated at a HRT of ca. 6 days (which
172 is in the range of that described in literature for full-scale WSP [20]).

173 ***2.4. Statistical analyses***

174 Differences among time for each experimental condition considered were determined by
175 means of ONE-way repeated-measures ANOVA with three levels (control; 0.1% of
176 industrial by-product and 5% of industrial by-product). Homogeneity of variances and
177 normality of data were tested by performing a Levene test and a Kolmogorov-Smirnov
178 test, respectively. All statistical analyses were performed using SPSS v.19. Differences
179 among levels of the same factor were determined by means of a Tukey-test. Analyses
180 were considered statistically significant at p values below 0.05.

181

182 **3. Results and discussion**

183 All adsorbents tested showed high phosphorus adsorption capacity (Table 2). Moreover,
184 data obtained fitted quite well for all adsorbents studied ($R^2 > 0.70$) (Table 2), regardless
185 the model considered (Freundlich or Langmuir) (Figure 1). However, the Langmuir
186 model always showed a better correlation than the Freundlich model for almost all of
187 the adsorbents tested (except for the MSW FA where phosphorus adsorption was
188 described to a similar extent for both models) (Table 2 and Figure 1). Our results are in

189 agreement with current literature since Langmuir equations have been described to
190 provide a better fitting to data obtained from phosphorus adsorption experiments
191 conducted on waste materials such as fly ashes [21] or dried sludge and cement dust [2].
192 Moreover, using the Langmuir model over other models is of special interest since it
193 allows us to estimate the maximum (theoretical) phosphorus sorption capacity (Q) [13];
194 which may be useful to compare among different adsorbents in terms of adsorption
195 capacity and longevity. In line with this, GB showed the lowest value of Q (34.72
196 mgP/g of bentonite) compared to the rest of tested adsorbents. The highest value of Q
197 was that of the PP FA II (74 mgP/g). The Freundlich coefficient K_d ranged between 3.08
198 and $11.38 \text{ mg}^{1-1/n} \text{ l}^{1/n}/\text{g}$; being the highest value that of PP FA I ($11.31 \text{ mg}^{1-1/n} \text{ l}^{1/n}/\text{g}$).
199 Figure 1 shows a summary of all the experimental data obtained for all the industrial by-
200 products analysed. It was observed that for low equilibrium concentrations (up to 30
201 mgP/L) all adsorbents had the same phosphorous removal. The ranking order in terms
202 of maximum phosphorus adsorption capacity was that of: PP FA II > MSW FA > PP FA
203 I > GB. Maximum sorption capacity (Q) ranged from 34 to 74 mgP/g of adsorbent.
204 These values were very much higher than the values obtained from natural soils and
205 sediments in treatment ponds (< 2 mgP/g of sediment) [22] and natural materials like
206 gravel (<0.05 mgP/g of gravel) [23], sands (<0.2 mgP/g of sand) [24] or bentonite (0.93
207 mgP/g) [13]. Values of Q reported in the present study were also higher than those
208 reported for other waste materials such as alum sludge [2], furnace slag [21] or even fly
209 ashes from China power plants (between 8 and 45 mgP/g) [13]. However, it is
210 important to point out that maximum adsorption capacity of a material calculated from
211 isotherms experiments (as it is carried out in the present study) may lead to an
212 overestimation (up to 3 times overestimation) of the true adsorption capacity of the
213 material tested [25]. Therefore, authors suggest that longer study periods, closer to

214 materials lifespan, are required to truly assess the phosphorus retention capacity of the
215 tested materials. The magnitude of overestimation depends on several factors such as
216 the methodology employed (batch or column studies) [26], initial phosphorous
217 concentration and adsorbents tested. Therefore, it is of difficult predictability under the
218 conditions here considered and should be experimentally addressed.

219 According to [27] phosphorus is adsorbed and precipitated by reaction with Ca, Fe, Al
220 and Mg, which are released from the adsorbent to the solution. In this study the ranking
221 order in terms of maximum phosphorus adsorption capacity (PP FA II > MSW FA > PP
222 FA I > GB) seemed to be more correlated to the amount of calcium oxides than other
223 compounds. Indeed, the high P sorption capacity of PP FA II and MSW FA obtained
224 corresponded to the adsorbents having a high content of CaO (27 and 31 % for PP FA II
225 and MSW FA, respectively), while Fe₂O₃, Al₂O₃ and MgO content was lower or equal
226 to other adsorbents (Table 1). In line with this, the high values of pH observed in the
227 solution using PP FA II and MSW FA (Table 2) evidenced the presence of Ca²⁺ ions that
228 favored the adsorption [28]. The pH in the GB and PP FA I solutions (Table 2) indicated
229 that phosphorous adsorption was caused mainly by Al₂O₃ content, which is relatively
230 high in these by-products (Table 1) [13].

231

232 ***3.1 Enhancement of phosphorus removal in microcosm waste stabilization ponds***

233 Figure 2 shows the phosphorus concentration in overlaying water for all the
234 experimental conditions considered. Phosphorus removal in control experiments was far
235 lower than that observed in other experimental lines (around 10%), which suggested
236 that phosphorous uptake by microorganisms was negligible. Therefore, chemical
237 processes were the main responsible pathway for phosphorous removal in microcosms
238 WSP. Phosphorus concentration in overlaying water for the control and the

239 experimental lines conditioned with the lowest amount of adsorbent ranged from 3 to 6
240 mg PO₄-P/L. However, the phosphorus concentration was much lower for the
241 experimental line with the highest content of adsorbent (from <0.1 to 0.5 mg PO₄-P/L)
242 and statistically significant when compared to the rest of experimental conditions
243 (Figure 2). Phosphorus removal in the experimental line with sludge conditioned at a
244 5% with the MSW FA was close to 90%. On the other hand, the control line (without
245 conditioning) showed a phosphorus removal, in average, close to 10%.

246 Concerning the pH, it ranged from 7.2 to 7.6 for the control and the experimental line
247 with the lowest content of adsorbent, whereas it was significantly higher (ranging from
248 7.8 to 8.3) for the experimental line with the highest content of adsorbent. As mentioned
249 above, a high content of Ca²⁺ ions in the experimental line having the highest content of
250 fly ashes, which favored phosphorus adsorption and precipitation.

251 Finally, oxygen concentration in the overlaying water ranged from 8.5 to 9.5 mg/L,
252 regardless the experimental condition considered. Sediments strongly affect the
253 performance of WSP during wastewater treatment [29]. The experiment carried out in
254 this study proved that phosphorus removal in WSP can be enhanced by adding ashes
255 from municipal incinerating plants. However, it is worth mentioning that harmful
256 compounds present in such kind of wastes (such as heavy metals or chlorides) might
257 leach from the sediments [29]. The fate of such harmful pollutants is, however, unclear
258 under the circumstances here considered since it has been also demonstrated that
259 phosphorus adsorption can be used as a chemical process to stabilize heavy metals from
260 bottom ash combustion of municipal solid waste plants [30]. Overall, authors believe
261 that in spite of the potential use of industrial by-products for increasing the phosphorus
262 treatment efficiency of WSP, further studies must address the potential negative effects
263 of heavy metal leaching during treatment.

264

265 **5. Conclusions**

266 All adsorbents tested showed high phosphorus adsorption capacity and were generally
267 better described by the Langmuir model. Maximum adsorption capacity ranged from 34
268 to 74 mgP/g of adsorbent, being fly ashes either from municipal solid waste treatment
269 plants or power plants the materials with the highest capacity for phosphorus
270 adsorption.

271

272 Results presented in this study proved that sludge conditioning with fly ashes from a
273 municipal incinerating plant can substantially increase (up to 90%) the phosphorus
274 removal capacity of waste stabilization ponds.

275

276 **Acknowledgements**

277 Authors express their gratitude to Anna Martinez and Javier Carretero from Universitat
278 Politècnica de Catalunya (UPC) for their help during experiment deployment. Marianna
279 Garfí is grateful to Ministry of Economy and Competitiveness (Spain) (Plan Nacional
280 de I+D+i 2008-2011, Subprograma Juan de la Cierva (JDC) 2012).

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282 **References**

- 283 [1] Y. Liu and J. Chen, Phosphorus cycle. Encyclopedia of Ecology, pp. 2715–2724.
284 Elsevier, 3251; Riverport U.S.A, 2008.
- 285 [2] M. Mortula, M. Gibbons and A.G. Gagnon, Phosphorus adsorption by naturally-
286 occurring materials and industrial by-products, J. Env. Eng. Sci. 6(2) (2007) 157-
287 164
- 288 [3] H. Tiessen, Phosphorus in the Global Environment: Transfers, Cycles, and
289 Management. John Wiley and Sons, New York, 1995
- 290 [4] C. Vohla, M. Koiv, H.J. Bavor, F. Chazarenc, and U. Mander, Filter materials for
291 phosphorus removal from wastewater in treatment wetlands—A review. Ecol.
292 Eng. 37 (2011) 70–89
- 293 [5] R.H.Kadlec and R.L. Knight, Treatment Wetlands, pp. 893. Lewis Publishers, CRC
294 Press, Boca Raton, 1996.
- 295 [6] J.W. Choi, S.Y. Lee, K.Y. Park, K.B. Lee, D.J. Kim, and S.H. Lee, Investigation of
296 phosphorous removal from wastewater through ion exchange of mesostructure
297 based on inorganic material. Desalination, 266(1–3) (2011) 281–285
- 298 [7] X. Cheng, X. Huang, X. Wang, B. Zhao, A. Chen, and D. Sun, Phosphate adsorption
299 from sewage sludge filtrate using zinc-aluminum layered double hydroxides.
300 Hazard. Mater. 169(1-3) (2009) 958–964
- 301 [8] H. E. Maynard, H.E. Ouki, and S.C. Williams, Tertiary lagoons: a review of removal
302 mechanisms and performance. Water Res, 33(1) (1999) 1-13
- 303 [9] G.E. Alexiou and D.D. Mara, Anaerobic Waste Stabilization Ponds. A Low-Cost
304 Contribution to a Sustainable Wastewater Reuse Cycle. Appl. Biochem.
305 Biotechnol. 109 (2003) 241-252
- 306

- 307 [10] J.F. Peng, B.Z. Wang, Y.H. Song, P. Yuan, and Z. Liu, Adsorption and release of
308 phosphorus in the surface sediment of a wastewater stabilization pond. *Ecol. Eng.*
309 31 (2007) 92-97
- 310 [11] R.Y. Surampalli, S.K. Banerji, C.J. Pycha and E.R. Lopez, Phosphorus removal in
311 ponds. *Water Sci. Technol.* 31(12) (1995) 331–339
- 312 [12] S.C. Reed, E.J. Middlebrooks and R.H. Crites, *Natural Systems for Waste*
313 *Management and Treatment*, ed. N. M. Post and J. Halston. McGraw-Hill, U.S.A,
314 1998.
- 315 [13] D. Xu, J., Xu, J., Wu, and A. Muhammad, Studies on the phosphorus sorption
316 capacity of substrates used in constructed wetland systems. *Chemosphere*, 63
317 (2006) 344–352
- 318 [14] L. Zeng. X., Li, and J. Liu, Adsorptive removal of phosphate from aqueous
319 solutions using iron oxide tailings. *Water Res.* 38(5) (2004) 1318–1326
- 320 [15] *Apha-Awwa-Wpcf Standard Methods for the Examination of Water and*
321 *Wastewater* 20th ed. American Public Health Association, Washington, DC, 2001.
- 322 [16] P.S. Nair, T.J. Logan, A.N. Sharpley, L.E. Sommers, M.A. Tabatabai and T.L.
323 Yuan, Interlaboratory comparison of a standardized phosphorus adsorption
324 procedure. *J. Env. Qual.* 13 (1984) 591–595
- 325 [17] C.J. Crittenden, R.R. Trussell, D.W. Hand, K.J. Howe and G. Tchobanoglous,
326 *Water Treatment: Principles and Design*. MW, 2012
- 327 [18] R.L. Droste, *Theory and practice of water and wastewater treatment*. John Wiley
328 and Sons, Inc., New York, N.Y, 1997.
- 329 [19] E. Ortega de Miguel, Y. Ferrer-Medina, J.J. Salas-Rodríguez and C. Aragón-Cruz,
330 *Manual para la implantación de sistemas de depuración en pequeñas poblaciones*.

- 331 pp. 455, Ministerio de Medio Ambiente y Medio Rural y Marino. Madrid, España,
332 2011.
- 333 [20] K.L. Nelson, B.J. Cisneros, G. Tchobanoglous and J.L. Darby, Sludge
334 accumulation, characteristics, and pathogen inactivation in four primary waste
335 stabilization ponds in central Mexico. *Water Res.* 38 (2004) 111–127
- 336 [21] J. Chen, H. Kong, D. Wu, X. Chen, D. Zhang, and Z. Sun, Phosphate
337 immobilization from aqueous solution by fly ashes in relation to their
338 composition. *J. Hazard. Mater.* 139(2) (2007) 293–300
- 339 [22] L. Wen, and F. Recknagel, Balancing phosphorus adsorption and consumption
340 processes in experimental treatment ponds for agricultural drainage water. *Ecol.*
341 *Eng.* 28 (2006) 14-24
- 342 [23] P.F. Breen, A mass balance approach of assessing the potential of artificial
343 wetlands for wastewater treatment. *Water Res.* 24 (1990) 689–697
- 344 [24] C.A. Arias, M. Del Bubba and H. Brix H. Phosphorus removal by sands for use as
345 media in subsurface flow constructed reed beds. *Water Res.* 5 (2001) 1159-1168
- 346 [25] A. Drizo, C. Forget, R.P. Chapuis, and Y. Comeau, Phosphorus removal by EAF
347 steel slag—A parameter for the estimation of the longevity of constructed wetland
348 systems. *Environ. Sci. Technol.* 36 (2002) 4642–4648.
- 349 [26] V. Cucarella and G. Renman, Phosphorus sorption capacity of filter materials used
350 for on-site wastewater treatment determined in batch experiments—a comparative
351 study. *J Environ Qual.* 38(2) (2009) 381–392
- 352 [27] T. Zhu, P.D. Jenssen, T. Maechlum, T. Krogstad, Phosphorus sorption and
353 chemical characteristics in treatment wetlands. *Water Sci. Techn.* 35 (1997) 103–
354 108

355 [28] A. Ugurlu, and B. Salman, Phosphorus removal by fly ash. *Env. Int.* 24 (1998)
356 911–918

357 [29] T. Namèche, D. Chabir, and J.L. Vassel Characterization of Sediments in Aerated
358 Lagoons and Waste Stabilization Ponds. *Intern. J. Env. Analyt. Chem* 68(2)
359 (1997) 257–279

360 [30] B.S. Crannell, T.T. Eighmy, J.E. Krzanowski, J.D. Eusden Jr., S.L. Shaw, and
361 C.A. Francis, Heavy metal stabilization in municipal solid waste combustion
362 bottom ash using soluble phosphate. *Waste Manag.* 20 (2000) 135-148

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	GB	MSW FA	PP FA I	PP FA II
TS (%)	97.91	100	99.29	97.74
VS (%)	2.09	0	0.71	2.26
Fe ₂ O ₃ (%)	2.04	1.35	20.08	6.36
MnO (%)	0.02	0.05	0.04	0.07
TiO ₂ (%)	0.24	0.96	0.87	0.71
CaO (%)	1.00	31.25	7.35	27.40
K ₂ O (%)	0.86	4.33	1.32	1.54
P ₂ O ₅ (%)	0.03	1.41	0.44	0.36
SiO ₂ (%)	73.66	11.97	41.90	38.63
Al ₂ O ₃ (%)	13.44	5.30	25.22	16.36
MgO (%)	2.27	1.66	1.11	1.37
Na ₂ O (%)	2.10	4.01	0.33	0.22

379

380

Table 1. Chemical characteristics of industrial by-products:

381

Note: GB: granular bentonite; MSW FA: fly ashes from the municipal solid waste

382

incineration plant; PP FA I and PP FA II two types of fly ashes from two different

383

power plants; TS: Total Solids; VS: Volatile Solids

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	Ci (mgP/L)	Real Ci (mgP/L)	Ce (mgP/L)	pH (initial)	pH (final)	Langmuir model					Freundlich model				
						q (mg P/mg media)	Ce/q	b (l/mgP)	Q (mgP/g of adsorbent)	R ²	log Ce	log q	n	K _d (mg ^{1-1/n} l ^{1/n} /g)	R ²
GB	0	0	0	8.66	7.88	0	0	0.02	34.72	0.93			2.76	4.71	0.70
	100	103.08	0.57	6.68	7.45	5.10	0.11				-0.24	0.71			
	200	202.68	32.15	6.25	6.94	8.31	3.87				1.51	0.92			
	600	602.05	164.79	6.22	6.64	21.86	7.54				2.22	1.34			
	900	1015.01	388.27	6.70	6.97	31.23	12.43				2.59	1.49			
MSW FA	0	0	0	12.10	12.10	0	0	0.16	42.55	0.69			1.29	3.08	0.72
	100	100.65	3.97	9.50	12.05	4.78	0.83				0.60	0.68			
	200	202.68	2.51	13.25	11.65	10.01	0.25				0.40	1.00			
	600	587.47	23.89	12.55	11.85	27.82	0.86				1.38	1.44			
	900	966.43	19.03	12.05	11.65	47.25	0.40				1.28	1.67			
PP FA I	0	0	0	10.90	8.48	0	0	0.03	40.65	0.98			5.51	11.38	0.95
	100	94.68	0	6.50	7.85	4.71	0					0.67			
	200	186.58	0.41	5.95	7.65	9.07	0.04				-0.39	0.96			
	600	550.45	32.34	6.56	6.86	25.90	1.25				1.51	1.41			
	900	901.80	338.65	6.82	7.01	28.07	12.06				2.53	1.45			
	1800	1838.74	1014.32	6.99	7.24	40.92	24.79				3.01	1.61			
PP FA II	0	0	0	11.7	8.9	0	0	0.06	74.07	1.00			2.45	7.41	0.82
	100	100.65	1.54	9.50	8.95	4.79	0.32				0.19	0.68			
	200	210.46	1.54	7.60	9.05	9.99	0.15				0.19	1.00			
	600	592.33	14.17	7.85	8.85	28.08	0.50				1.15	1.45			
	900	908.13	19.03	7.45	8.90	43.85	0.43				1.28	1.64			
	2000	2059.58	606.91	7.70	9.10	72.25	8.40				2.78	1.86			

385 Table 2. Estimated isotherms parameters and correlation coefficients (R^2) for P adsorption on all by-products. *Note: GB: granular bentonite; MSW FA: fly ashes from the*
386 *municipal solid waste incineration plant; PP FA I and PP FA II two types of fly ashes from two different power plants; C_i : initial Concentration; C_e : equilibrium*
387 *solution concentration; q : amount of adsorbate per unit of adsorbent; b : measure of the sorption energy; Q : maximum adsorption capacity; n : empirical constant of*
388 *Freundlich isotherm model; K_d : empirical constant of Freundlich isotherm model*

Parameters	Values
TS (%)	2.9
VS (% TS)	65.9
COD (g O ₂ /kg _{TS})	968.2
P (mgP/g _{TS})	3.9
P (% TS)	0.40
N (% TS)	0.06

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Table 3. Physical and chemical characteristics of sludge used for microcosm WSP

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experiment. *Note: TS: Total Solids; VS: Volatile Solids; COD: chemical oxygen*

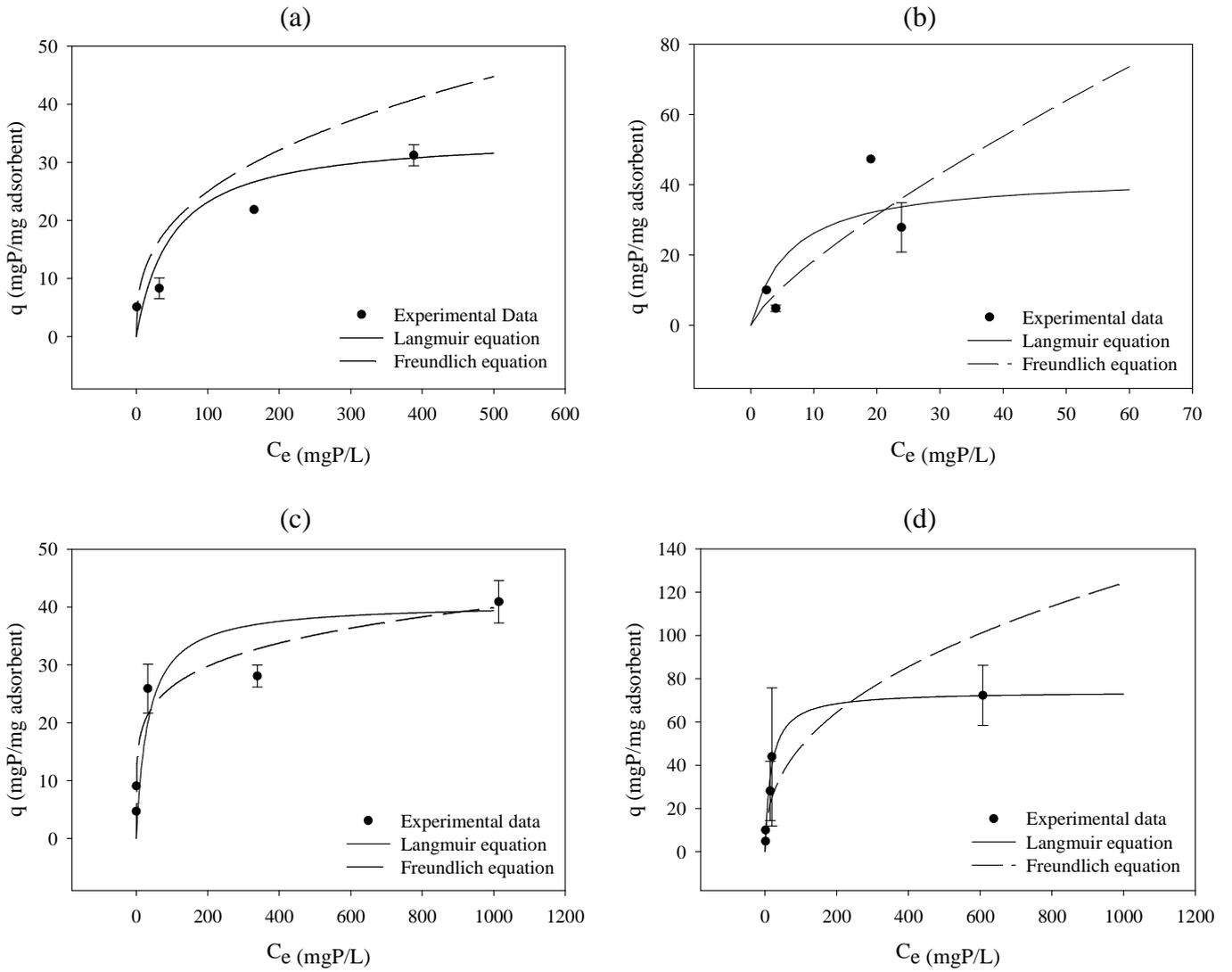
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demand; P; total phosphorous; N: total Nitrogen.

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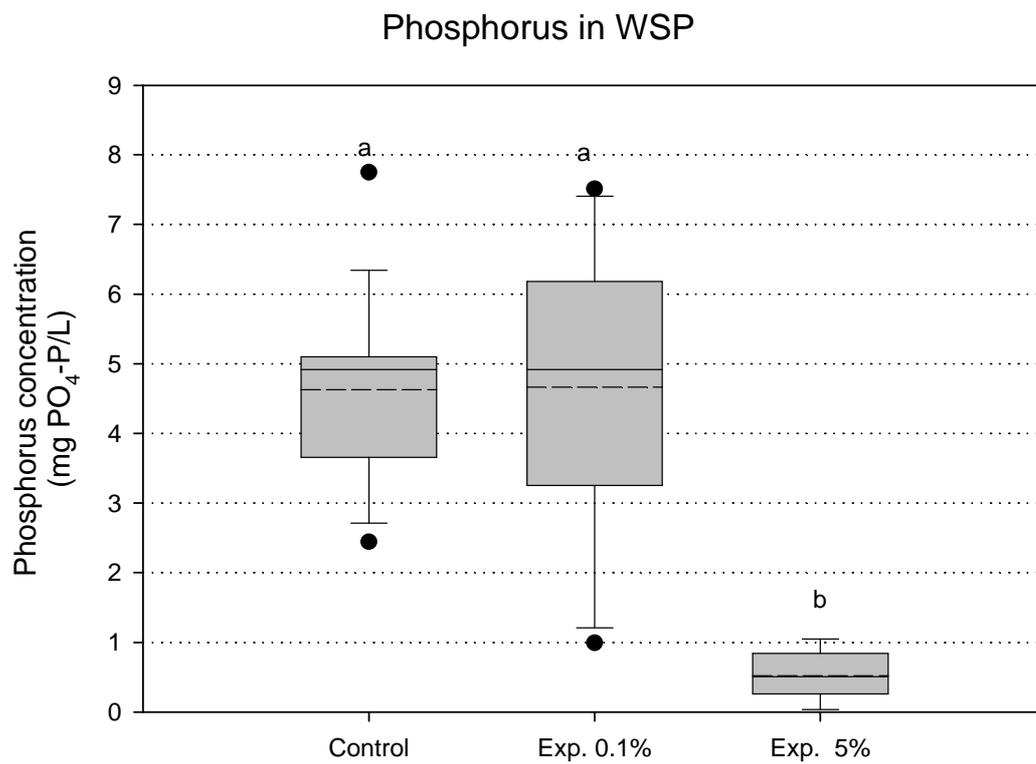
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398 Figure 1. P adsorption isotherms for GB (a), MSW FA (b), PP FA I (c) PP FA II (d).

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405 Figure 2. P concentration in overlaying water for each microcosm WSP. *Note: a and b*
406 are groups of statistical significance determined by a post-hoc test (Tukey test)

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