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### ► To cite this version:

Céline Lafarge, Manal Bitar, Leina El Hosry, Philippe Cayot, Elias Bou-Maroun. Comparison of molecularly imprinted polymers (MIP) and sol–gel molecularly imprinted silica (MIS) for fungicide in a hydro alcoholic solution. *Materials Today Communications*, 2020, 24, pp.101157. 10.1016/j.mtcomm.2020.101157 . hal-02613429

**HAL Id: hal-02613429**

<https://institut-agro-dijon.hal.science/hal-02613429v1>

Submitted on 22 Aug 2022

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1 **Comparison of molecularly imprinted polymers (MIP) and sol-gel**  
2 **molecularly imprinted silica (MIS) for fungicide in a hydro alcoholic**  
3 **solution.**

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5

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12

13 **Abstract**

14 The aim of this work was (i) to design the best molecularly imprinted silica (MIS) specific for  
15 iprodione, a fungicide polluting water, fruits, wine and (ii) to compare the performance of the  
16 optimal MIS with its analogue molecularly imprinted polymer (MIP), with the objective to  
17 obtained the highest imprinting factor possible. Iprodione was widely used in viticulture. It was  
18 recently banned by the European community because of its carcinogenic potential and its  
19 presence in or on foods.

20 The binding capacity performance of these polymers was investigated using batch binding  
21 studies in hydro alcoholic solutions (10 and 50 %). Langmuir, Freundlich and Temkin models  
22 have been used to fit adsorption isotherms. The optimal MIS was obtained using APTMS as  
23 functional monomer, low solvent volume and high cross linker quantity during its synthesis.

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24 Increasing the quantity of crosslinker and decreasing the solvent volume during the MIS  
25 synthesis enhanced the imprinting factor and the binding capacity.

26 The optimal MIS had a higher imprinting factor but a lower binding capacity than the optimal  
27 MIP specific to iprodione. The imprinting factor of the optimal MIS was 135 times higher than  
28 the optimal MIP. Unlike MIP, MIS kept its molecular recognition nature even under extremely  
29 polar media such as the aqueous sample.

30

### 31 **Keywords**

32 Molecularly imprinted silica, molecularly imprinted polymer, fungicide, adsorption isotherm

33

### 34 **1. Introduction**

35 The worldwide increase in the usage of pesticides during the last decades has resulted in the  
36 accumulation of their residues in the environment. These residues can cause serious detrimental  
37 effects on human health and on the ecosystem<sup>1</sup>. Therefore, the maximum residue limits (MRL)  
38 were established by the Codex Alimentarius Commission and the European Union to regulate  
39 the use of pesticides. Thus, the monitoring of these compounds is extremely important to ensure  
40 that only permitted levels of pesticide are used. Several techniques have been developed for  
41 pesticide detection: conventional analytical methods (gas chromatography, high performance  
42 liquid chromatography, immunoassay, capillary electrophoresis) and advanced detection  
43 methods such as biosensor (electrochemical, optical, piezoelectric, *etc...*)<sup>1</sup>.

44 Although very effective, these techniques are expensive, time-consuming and difficult to  
45 miniaturize for detection in the field. In this context, molecularly imprinted polymers (MIP)  
46 specific to pesticides can overcome some of these difficulties, both for its extractions and  
47 detections: significant reduction in extraction time and improvement in the concentration of the  
48 target molecule for subsequent analysis. That is why since 2000, molecular imprinting science

49 and its applications of molecularly imprinted polymers have been attracting the interest of the  
50 scientific community, hence the broad increase of literature in the field. Over 1237 references  
51 within the field of molecular imprinting science and technology for the period 1931 – 2018  
52 have been collected. However, numerous developments still need to be made, particularly in  
53 terms of the synthesis method of molecularly imprinted silica.

54

55 For this project, we focused on the iprodione (other name glycophen, PubChem CID 37517).  
56 Iprodione is a dicarboximide fungicide widely used in viticulture in most agricultural countries,  
57 but also in other crops activities like fruits production, green lawns etc..<sup>2-4</sup>. It was banned  
58 recently by the European Community because of its carcinogenic and endocrine disrupting  
59 characters<sup>5</sup>. Though this interdiction, iprodione must be detected because of possible residues  
60 in soil. It is a very stable molecule and its degradation in the soil takes a long time<sup>6</sup>. In fact, in  
61 a soil treated for the first time, the time to 50% loss of iprodione was greater than 35 days.  
62 Iprodione has also to be easily detected for the monitoring of possible non-authorized uses like  
63 the elimination of stocks etc... Various molecular imprinted polymers (MIP) have been recently  
64 developed and applied for the selective determination of residual pesticides<sup>7</sup>. A brief overview  
65 of this research area shows that the majority of the studied imprinted polymers are acrylate  
66 based molecularly imprinted polymers (MIP) (Table 1). The most used functional monomer is  
67 the methacrylic acid (MAA). It is commonly chosen by default as monomer as soon as the  
68 target molecules are neutral or basic. In fact, MAA has the capacity of being an H donor and  
69 acceptor with strong abilities to create dipole-dipole interactions and can develop hydrogen and  
70 ionic interactions with basic molecules<sup>8</sup>. MIP synthesis is relatively cheap and easy. However,  
71 a severe limitation of this type of imprinting is the requirement for an organic solvent in which  
72 all compounds are soluble.

73 Pesticides are generally poorly soluble in water. This chemical property is favorable to MIP  
74 synthesis protocols that use organic solvents. Initially, the selection of low water soluble  
75 molecules was done to reduce lixiviation in groundwater and water pollution<sup>9</sup>. For nebulization  
76 in the fields, pesticides are dispersed in water using a surfactant<sup>10</sup>. These poorly soluble in  
77 water molecules should nevertheless not be too liposoluble in order to avoid bioaccumulation.  
78 Like per example pentachlorophenolas who is known to contaminate underground water<sup>11</sup> due  
79 to its high solubility in water (20 mg·L<sup>-1</sup>) when, on the other hand, chlordane and DDT are very  
80 hydrophobic (water solubility 0.056 and 0.024 mg·L<sup>-1</sup> respectively) , stable and toxic, and  
81 therefore, bioaccumulate. Iprodione is relatively hydrophobic and slightly soluble in water  
82 (13.9 mg·L<sup>-1</sup>). It is more soluble in organic solvents: in ethanol (25 g·L<sup>-1</sup>), which explains the  
83 high risk of contamination of wine, in acetone (300 g·L<sup>-1</sup>), in dimethylformaide (500 g·L<sup>-1</sup>), or  
84 in dichloromethane (500 g·L<sup>-1</sup>).

85 A convenient alternative to MIP is sol – gel molecularly imprinted silicas (MIS), even if  
86 pesticides are not very water-soluble<sup>12</sup>. The use of a co-solvent (water miscible solvent such as  
87 ethanol or acetone) can favor the solubilization of pesticide without perturbing the  
88 polymerization of the silane. In fact, the synthesis of MIS is relatively easy: it can be done at  
89 room temperature and atmospheric pressure. Their advantage remains in their synthesis in a  
90 water / ethanol mixture, which respects one of the principles of green chemistry by using safe  
91 solvents contrary to those used in MIP synthesis. Moreover, MIS are more chemically stable  
92 and specific towards the target species than acrylate based MIP<sup>13</sup>, also, they allow faster  
93 diffusion of analytes<sup>14</sup>. The interest in these materials is growing and their applications are  
94 broad: phenobarbital<sup>13</sup>, caffeine<sup>14</sup>, nitroarmatic explosives<sup>15</sup>, pesticides in almond oil<sup>16</sup>, nitro  
95 musk compounds in water<sup>17</sup>. However, the studies about MIS using fungicide as template are  
96 very scare (Table 1).

97 All these studies proved the efficiency of MIP and MIS but, to the best of our knowledge, this  
98 study is the first that compares the molecular imprinting of iprodione between these two types  
99 of polymers. The aim of this work was to design the best MIS specific for iprodione fungicide  
100 and to compare its performance with its MIP analogue. The binding capacity performance of  
101 these polymers was investigated in a hydroalcoholic solution towards iprodione.

102

## 103 **2. Materials and methods**

### 104 **2.1. Chemicals**

105 Iprodione (97%, CAS number 36734-19-7, Hazard class carcinogenicity category 2 (CMR 2),  
106 H351, H400, H410), (3-Aminopropyl-)trimethoxysilane (APTMS 97%, CAS number 13822-  
107 56-5, Hazard class H314, H315, H318, H319), 1-[3-(Trimethoxysilyl)propyl]urea (urea, 97%,  
108 CAS number 23843-64-3, Hazard class H315, H318, H335), N-[3-  
109 (Trimethoxysilyl)propyl]aniline (aniline, 97%, CAS number 3068-76-6, Hazard class H302,  
110 H314, H315), tetraethoxysilane (TEOS,  $\geq 99\%$ , CAS number 78-10-4, Hazard class H226,  
111 H319, H332, H335), ammonium hydroxide ( $\text{NH}_4\text{OH}$  28 – 30%, CAS Number 1336-21-6,  
112 Hazard class H314, H400), ethanol ( $\geq 99.8\%$ , CAS Number: 64-17-5, Hazard class H225),  
113 allylamine (98%, CAS 107-11-9, Hazard class H225, H301, H311, H331, H411), ethylene  
114 glycol dimethacrylate (EGDMA,  $\geq 99\%$ , CAS number 97-90-5, Hazard class H317, H335), 2,2-  
115 dimethoxy-2-phenylacetophenone (DMPAP,  $\geq 99\%$ , CAS number 24650-42-8, Hazard class  
116 H302, H373, H400, H410, H412), toluene ( $\geq 99.8\%$ , CAS Number: 108-88-3, Hazard class  
117 reproductive toxicity category 2 (CMR 2), H225, H304, H315, H336, H361d, H373) and  
118 acetonitrile ( $\geq 99.9\%$ , CAS Number: 75-05-8, Hazard class H225, H302, H312, H319, H332)  
119 were purchased from Sigma Aldrich, France. Water used in all experiments was deionised and  
120 obtained from an Elga Ionic system PURELAB Option

121

122        **2.2. Synthesis of the sol-gel molecularly imprinted silica (MIS) and non-imprinted sol-**  
123                    **gel polymers silica (NIS)**

124    The synthesis protocol used for this study and the different chemical reactions that might be  
125    involved in the MIS synthesis and the interactions between the MIS and iprodione have been  
126    presented previously <sup>12</sup>. MIS were prepared at 40°C in a thermostatic water bath under magnetic  
127    stirring. The template molecule, iprodione, was first solubilized in ethanol. Then, water was  
128    added, followed by the functional monomer and the crosslinker TEOS (tetraethoxysilane).  
129    Finally, aqueous solution of ammonium hydroxide (NH<sub>4</sub>OH, 100 mmol) was introduced. The  
130    reaction mixture was left under stirring for 20 hours. Then the mixture was sonicated for 10  
131    minutes. The polymers were separated from the liquid phase by centrifugation at 10 000 g for  
132    10 minutes at room temperature. In order to eliminate iprodione and free the specific cavities,  
133    the polymers were washed several times with pure ethanol until iprodione was no longer  
134    detectable by reversed phase high performance liquid chromatography (HPLC). After washing,  
135    the polymers were dried for 6 h at 60 °C. In parallel, NIS (Non Imprinted Silica) was  
136    synthesized under the same synthesis conditions as those of MIS, but without using the template  
137    molecule. NIS served as a control polymer.

138    Several factors, including the nature of functional monomer, molar ratios of crosslinker /  
139    functional monomer / solvent were studied to optimize the synthesis of MIS. Table 2  
140    summarizes the different MIS synthesized depending on the experimental conditions and the  
141    structure of functional monomers tested for the synthesis of molecularly imprinted silica (MIS)  
142    and for the molecularly imprinted polymers (MIP) are presented in **Figure 1**.

144        **2.3. Synthesis of the molecularly imprinted polymers (MIP) and non-imprinted**  
145                    **polymers (NIP)**

146 The synthesis of MIP (non-covalent synthesis method) was done as previously described <sup>8</sup>. MIP  
147 were prepared with 1 mmol of allylamine as functional monomer, 4 mmol of crosslinker  
148 (EGDMA) and 0.1 mmol of template (iprodone) and the polymerization was carried out in 1  
149 mL of toluene using 0.05 mmol of DMPAP initiator. In parallel, non-imprinted polymers (NIP)  
150 were prepared with the same protocol but without the template. NIP served as a control  
151 polymer.

152

#### 153 **2.4. Binding properties of imprinted polymer (MIS) and non-imprinted polymer (NIS)** 154 **towards iprodione**

155 The binding capacity was estimated by batch adsorption. 10 mg of imprinted polymer (MIS 1,  
156 MIS 4, MIS 5, MIS 6, MIS 7, MIS 8) or non-imprinted polymer (NIS 1, NIS 4, NIS 5, NIS 6,  
157 NIS 7, NIS 8) were suspended in 20 mL of iprodione solution at  $10^{-5}$  M (10 %, v/v,  
158 ethanol/water). The mixture was stirred for two hours at 25 °C. After, the supernatant was  
159 filtered using a 0.22 µm filter and analysed by HPLC for the determination of iprodione. For  
160 each analysis, three replicates were done.

161

#### 162 **2.5. Kinetic adsorption study of iprodione to MIS**

163 The kinetic profile of iprodione binding to MIS was performed in the same experimental  
164 conditions than those previously described, except for the concentration of iprodione solution.  
165 An iprodione solution at  $5 \cdot 10^{-4}$  M (10 %, v/v, ethanol/water) was used. At different times of  
166 stirring at 25 °C, the supernatant was filtered using a 0.22 µm filter and analysed by HPLC for  
167 the determination of iprodione. Three replicates were done by sample.

168

#### 169 **2.6. Isotherm study**



170 10 mg of imprinted polymer (MIS 4, MIS 5', MIS 8 or MIP) or non-imprinted polymer (NIS 4,  
171 NIS 5', NIS 8 or NIP) were suspended in 20 mL iprodione solutions at different concentration  
172  $10^{-5}$ ,  $5 \cdot 10^{-4}$ ,  $10^{-4}$ ,  $5 \cdot 10^{-4}$ ,  $10^{-3}$  M with ethanol/water mixture (50 %, v/v) as solvent. After one  
173 hour of stirring at 25 °C, the supernatant was filtered using a 0.22 µm filter and analysed by  
174 HPLC for the determination of iprodione. The results presented are the means of three  
175 replicates.

176 The sorption isotherms obtained were tested with the Langmuir, Freundlich, and Temkin  
177 isotherm equations. The model equations are shown in table S1. The Langmuir isotherm model  
178 assume that the adsorption of molecules occurs at specific homogeneous sites of the adsorbent  
179 and, once a molecule occupies a site, no additional adsorption can occur there (monolayer  
180 coverage). The Freundlich isotherm model assumes the molecules undergoes adsorption onto  
181 the heterogeneous surface of adsorbent. This model describe a multilayer adsorption with  
182 interaction between adsorbed molecules. The Temkin isotherm model assumes that the  
183 adsorption heat of all molecules decreases linearly with the increase in coverage of the  
184 adsorbent surface, and that adsorption is characterized by a uniform distribution of binding  
185 energies, up to a maximum binding energy<sup>18,19</sup>.

186

## 187 **2.7. High-performance liquid chromatography**

188 For HPLC iprodione analysis, a Shimadzu HPLC (LC-20AT) pump equipped with a UV-  
189 Visible detector (SPD-20A), a Restek column (Pinnacle II, C18 5 µm, 150 x 4.6 mm) and a pre-  
190 column (C18, 5 µm, 10 x 4 mm) were used. Separations were conducted at room temperature.  
191 Isocratic acetonitrile / water (60/40, v/v) was used as mobile phase and the flow rate was  
192 1mL/min. Iprodione detection was done at 220 nm. A calibration curve was constructed over  
193 the range  $5 \cdot 10^{-4}$  and  $10^{-8}$  M of iprodione ( $r^2 = 0.9993$ ). The amount of iprodione retained by the

194 polymer was calculated by the difference between the initial concentration of iprodione and the  
195 free concentration of iprodione in the supernatant.

196

## 197 **2.8. Scanning electron microscope (SEM)**

198 The morphological characterization of the samples was performed by a scanning electron  
199 microscope. The samples were suspended in ethanol. Then a drop was placed on a silicon grid  
200 and examined using a Hitachi VPSU1510 scanning electron microscope. More than four views  
201 were recorded by sample. Representative images were presented with the accelerating voltage  
202 and the magnification used.

203

## 204 **2.9. Statistical analysis**

205 The Statistica V8 software was used for Anova. Significance was established at  $p < 0.05$ . Fisher  
206 t-test was used to determine significant differences between values.

207

## 208 **3. Results and discussion**

### 209 **3.1. Synthesis of sol – gel molecularly imprinted silica (MIS) optimization**

210 An optimal MIS must satisfy the following two criteria: present a strong absorption of iprodione  
211 and have a better specificity compared to NIS. Several factors, including the nature of functional  
212 monomer, molar ratios of crosslinker / functional monomer / solvent were studied to optimize  
213 the synthesis of MIS. Table 2 summarizes the different MIS synthesized depending on the  
214 experimental conditions.

215

#### 216 **3.1.1. Effect of functional monomer nature**

217 The choice of the functional monomer depends largely on the imprinted molecule. Indeed, it is  
218 interesting to match the functionality of the functional monomer to that of the imprinted

219 molecule (template), in order to maximize the interactions between them and to create highly  
220 specific cavities designed for the template molecule. The monomer must be stable and soluble  
221 in the chosen solvent. In our study, three different monomers were chosen considering their  
222 ability to interact with iprodione (**Figure 1**):

223 - (3-Aminopropyl)-trimethoxysilane (labelled APTMS). This monomer has a hydrogen bond  
224 acceptor group.

225 - 1-[3-(Trimethoxysilyl)propyl]urea (labelled urea) which has a donor group and a hydrogen  
226 bond acceptor group.

227 - N-[3-(Trimethoxysilyl)propyl]aniline (labelled aniline) which has a hydrogen bond acceptor  
228 group and a benzene ring which can establish  $\pi$ - $\pi$  interactions.

229

230 In a typical MIS synthesis, according to the literature <sup>14,15</sup>, the following molar ratio (1 / 4/ 20)  
231 for (template / functional monomer / crosslinker) were commonly used. Following this literature  
232 review, the three selected functional monomers (APTMS, urea, aniline) have been tested  
233 depending on this molar ratio (1 / 4/ 20) and the following MIS labelled MIS 1, MIS 6, MIS 7  
234 were obtained. The binding properties results obtained are presented in **Figure 2**. MIS 6  
235 (synthesized with aniline residue) and MIS 1 (synthesized with APTMS) showed the same  
236 quantity of adsorbed iprodione (around 1 mg / g of polymer). For these two functional  
237 monomers, the same type of functional monomer - iprodione interactions, hydrogen bonds,  
238 were involved. On the other side, MIS 7 (synthesized with aniline residue) had an average  
239 adsorption of 5.86 mg / g of polymer, five times larger than these counterparts. The binding  
240 capacity of the polymer is a critical factor. In the case of aniline, the types of functional  
241 monomer - iprodione interactions involved were hydrogen bonds and  $\pi$ - $\pi$  interactions. This  
242 higher retention can be explained by the  $\pi$ - $\pi$  interactions involved between the phenyl ring of  
243 aniline residue and of iprodione. This expected  $\pi$ - $\pi$  interactions were more favorable than

244 hydrogen bonding (APTMS - iprodione and urea moieties - iprodione) for the formation of the  
245 pre-polymerization complex and thus for molecular printing.

246 No NIS were obtained with urea function (NIS 6) and aniline function (NIS 7) used as  
247 functional monomers with the molar ratios used. To confirm these results, the experiment was  
248 done in duplicate. We also noticed that the polymerization between the samples was different  
249 and consequently the MIS physical forms were different. Our experimental conditions gave  
250 very small granules for MIS 1 while soft polymer monoliths were obtained for MIS 6 and MIS  
251 7. Consequently, before analysis, MIS 6 and MIS 7 were crushed and ground into a powder  
252 with a mortar and pestle.

253  
254 As the involved interactions were different and the obtained binding capacity interesting, the  
255 functional monomers aniline (MIS 7) and APTMS (MIS 1) were kept for the further studies.  
256 Therefore, we can suppose that the change of the (template / functional monomer / crosslinker)  
257 molar ratio and solvent volume could be a solution to obtain NIS 7.

258

### 259 **3.1.2. Crosslinker quantity and volume solvent effect**

260 The volume of the solvent is also a key element in the MIS synthesis. To study it, two different  
261 volumes of solvents were used for the synthesis. **Figure 3** shows that the decrease of solvent  
262 volume during the synthesis step with APTMS as functional monomer induced an increase of  
263 the quantity of adsorbed iprodione (MIS 1 and MIS 4). This observation could be explained by  
264 the dilution effect. The higher the solvent volume, the lower the reactants meeting probability,  
265 the fewer the cavities specific to iprodione. Therefore, there is a great interest in decreasing the  
266 solvent volume during the MIS synthesis.

267

268 Another important reagent for the synthesis of molecularly imprinted silica is the amount of  
269 crosslinker. The monomer and the crosslinker react mainly in aqueous solution to form silanol  
270 (Si-OH) groups through hydrolysis, then siloxane bonds (Si-O-Si) are formed by condensation  
271 reaction with silanol groups around the template molecule favouring the creation of a strong  
272 pre-complex template/monomer and an important reticulation of the sorbent to create more-  
273 well designed cavities. In other words, the crosslinker controls the morphology of the polymer:  
274 gel, micro or macroporous. It also provides a mechanical stability to silicate with the template  
275 molecule (rigidity), as well as a stability of the sites of interactions between the functional  
276 monomer and the template molecule. Liu et al.<sup>20</sup> showed that an excess of crosslinker can  
277 change the physicochemical interactions between monomers and template molecules. In fact,  
278 if the network is too flexible, the template may not be retained. On the other hand, if the  
279 network is too reticulated, the template diffusion may be reduced.

280 On this basis, MIS 5 was synthesized with a small volume of solvent but with an increase of  
281 the crosslinker amount. MIS 5 had the highest iprodione binding capacity, three times more  
282 than the other counterparts MIS 1 and MIS 4 (around 6 mg / g polymer).

283 On the contrary, with aniline as functional monomer, the trend was completely different (Figure  
284 3). The increase of the crosslinker quantity and the decrease of the solvent volume implied a  
285 decrease in the amount of adsorbed iprodione (MIS 7 and MIS 8). It should be noted that the  
286 amount of crosslinker was greater for MIS 8 (1 / 4 / 59) than MIS 5 (1 / 4 / 20). However, contrary  
287 to the previous results, a NIS was obtained (NIS 8). MIS 8 and NIS 8 were this time in powder  
288 form.

289  
290 To evaluate the specific binding property of MIS and NIS towards iprodione and to highlight  
291 the non-specific interactions that result from the iprodione adsorption, the imprinting factor (IF)  
292 has been calculated using the following equation<sup>21</sup>:

293 
$$IF = \frac{K(MIS)}{K(NIS)} = \frac{B(MIS) \times F(NIS)}{F(MIS) \times B(NIS)}$$

294 With:

- 295 - F: the free concentration of iprodione (mol/L) in the supernatant  
296 - B: the amount of iprodione bound (adsorbed) by the polymer (mg of iprodione/g of  
297 polymer) calculated by difference between the initial concentration of iprodione (mol/L)  
298 and F.

299 The higher the imprinting factor, the higher the specific interactions. Therefore, the imprinted  
300 polymers exhibit a good performance with the template molecule. The imprinting factors were  
301 approximately around 1 for MIS1, MIS 4 and MIS 5 (Table 3) meaning the absence of specific  
302 cavities designed for iprodione with no significant differences ( $p = 0.66$ ). Table 3 and Figure 3  
303 show that MIS 5 had the best imprinting factor and the best amount of adsorbed iprodione. This  
304 observation could be explained by the increase of the specific interactions between iprodione  
305 and the polymer with this molar ratio of reagent used. Therefore, with APTMS as functional  
306 monomer, there is a great interest to increase the crosslinker quantity and to reduce the solvent  
307 volume during the MIS synthesis. In fact, an increase of crosslinker quantity and a reduction of  
308 solvent volume would normally increase the reticulation and reduce the porosity of the polymer.

309 The imprinting factor of MIS 8 was not significantly different than those obtained with APTMS  
310 as a functional monomer (Table 3). MIS 8 was less selective than MIS 5 but better than MIS 4  
311 (Figure 3). To try to understand this difference, the morphology of each MIS has been studied  
312 by microscopy. SEM images (Figure 4) show the morphology of MIS with different  
313 magnifications. MIS 5 and MIS 1 seem to be aggregates. A very fine homogeneous population  
314 of about 400 nm in diameter characterized them. At the opposite, MIS 7 and MIS 8 were  
315 characterized by a heterogeneous population with irregular shapes and greatly variable  
316 dimensions ranging respectively from 99  $\mu\text{m}$  to 952  $\mu\text{m}$  for MIS 7 (with a majority of 200  $\mu\text{m}$ )

317 and from 578 nm to 861  $\mu\text{m}$  for MIS 8. The heterogeneity of MIS 7 populations explained by  
318 the gridding done. Due to the heterogeneity of the MIS 8 population and its larger size, this  
319 specific surface area may be smaller than MIS 5 and MIS 1 and could explain the difference of  
320 binding capacity observed previously by comparison.

321  
322 Whatever the studied MIS, no differences were observed on the amount of adsorbed iprodione  
323 between MIS and NIS (Figure 3). In order to be able to observe a clear difference between MIS  
324 and NIS in the amount of adsorption iprodione and to correctly perform the isotherm studies of  
325 each polymer, the concentration of iprodione solution used have to be increased. The problem  
326 encountered is the low solubility of iprodione using 10% ethanol / water, (v/v) as solvent. In  
327 this condition, the solubility limit of iprodione is  $2 \cdot 10^{-4}$  M. The iprodione solubility increases  
328 with the increase of ethanol proportion. That is the reason why we decided to work with a  
329 solution containing 50% ethanol / water (v/v) where the solubility limit of iprodione is  $1.2 \cdot 10^{-3}$   
330 M. To confirm the results obtained previously, the isotherms were performed on MIS 4, MIS 5  
331 and MIS 8.

332

### 333 **3.1.3. Isotherm study**

334 Isotherm studies were performed on both imprinted and non-imprinted polymers. Previously,  
335 equilibrium binding experiments were performed to determine the time necessary to reach this  
336 equilibrium (Figure 5). It is observed that the initial binding rate was very high with a very fast  
337 uptake profile. In fact, the system reached an equilibrium after 20 minutes. This means that the  
338 porosity of the silica matrix had a favorable effect on the diffusion time of the target molecules  
339 into the recognition sites. The fact that MIS showed fast kinetics for iprodione adsorption is  
340 advantageous. Based on this characterization, all further experiments, whatever the studied  
341 MIS, were determined within 60 minutes.

342

343 In order to compare MIS 8 with its APTMS analogue, a new MIS, labelled MIS 5', was  
344 synthesized with the same (template / functional monomer / crosslinker) ratio molar 1 / 4 / 59  
345 used for MIS 8 (Table 2). **Figure 6** shows the isotherms for MIS 4, MIS 5' and MIS 8 and their  
346 respective control polymer NIS as a function of iprodione solution concentrations. The results  
347 show that all the MIS can bind iprodione in larger amounts than the analogous NIS and binding  
348 capacity for MIS increase with the rise of iprodione concentration solution. The results obtained  
349 in a 50% ethanol solution (v/v) confirm those obtained in a 10% ethanol solution (v/v): MIS 5'  
350 had the highest adsorption capacity of iprodione, followed by MIS 8 and MIS 4 in decreasing  
351 order of adsorption capacity. In addition to having the best iprodione binding property (around  
352 25 mg of iprodione bound per g of MIS), MIS 5' had the best imprinting factor (about 271,  
353 **Table 3**) meaning the presence of specific interactions between iprodione and the functional  
354 monomer. This result indicates that in this case, the increase of crosslinker content enhanced  
355 the specific interaction between MIS and iprodione and so show the selectivity of MIS 5'. In  
356 order to get a better view on the adsorption of iprodione by MIS, the Langmuir, Freundlich and  
357 Temkin isotherm models were applied to fit the experimental data. Linear regression is  
358 frequently used to determine the best-fitting isotherm. The applicability and suitability of the  
359 isotherm equation to the equilibrium data were compared by evaluating the values of the  
360 correlation coefficients. The results are presented in **Table 4** and **Figure 7**. The regression  
361 coefficients  $r^2$  ranged from 0.83 to 0.97 (r from 0.91 to 0.98) for Freundlich model, from 0.76  
362 to 0.89 (r from 0.87 to 0.94) for Temkin model and from 0.30 to 0.80 (r from 0.55 to 0.89) for  
363 Langmuir model. With the Pearson's table (critical values of correlation coefficient), using a  
364 value of level of significance for a two-tailed test of 0.05, and with 5 points (freedom degree =  
365 3), the critical r value is 0.878. These values of regression coefficients reflect a good fit of the  
366 Freundlich model and Temkin model but it can be noticed that the Langmuir model is not



367 suitable for fitting the present data. Therefore the Freundlich model is most suitable and that  
 368 applicability follows the order: Freundlich > Temkin model. Freundlich model is the best suited  
 369 model in our study suggesting that the adsorption occurs in multilayers and in heterogeneous  
 370 sites of this material with a non-uniform distribution of heat of adsorption over the surface<sup>22,23</sup>.  
 371 Moreover as the experimental data fitted well to Tempkin isotherm, we can added that iprodione  
 372 adsorption occurred because the heat of adsorption of iprodione in the layer decreases linearly  
 373 because of increased surface coverage.

374

375 When the Freundlich equation has been determined to be a suitable binding isotherm model for  
 376 MIS, two additional binding parameters can be calculated incorporating the parameters of the  
 377 Freundlich: the number of binding sites,  $N_{K_1-K_2}$  (Eq. 1) and the weighted average affinity,  
 378  $K_{K_1-K_2}$  (Eq. 2).  $K_1$  of  $K_2$  values are within the boundaries  $K_{min}$  and  $K_{max}$  as defined by Eq. 3  
 379 <sup>24,25</sup>.

$$380 \quad N_{K_{min}-K_{max}} = a(1 - n^2)(K_{min}^{-n} - K_{max}^{-n}) \quad \text{Equation 1}$$

$$381 \quad K_{K_{min}-K_{max}} = \left(\frac{n}{n-1}\right) \left(\frac{K_{min}^{1-n} - K_{max}^{1-n}}{K_{min}^{-n} - K_{max}^{-n}}\right) \quad \text{Equation 2}$$

$$382 \quad K_{max} = \frac{1}{C_{e(min)}} \quad \text{and} \quad K_{min} = \frac{1}{C_{e(max)}} \quad \text{Equation 3.}$$

383 with  $C_e$  the free concentration of iprodione (mM) in the solution.

384

385 Using Freundlich isotherm model, no significant  $n$  values were observed between MIS 4, MIS  
 386 5' and MIS 8 (Table 4). A more homogeneous system will have an  $n$  value approaching unity  
 387 and a more heterogeneous system will have an  $n$  value approaching zero. As  $n$  values were  
 388 close to the value 1, MIS 4, MIS 5' and MIS 8 also show high degree of binding site  
 389 homogeneity.

390 On the other hand, important variations were observed for the parameter  $K_F$  (Table 4). The  $K_F$   
391 values show that the MIS 5' had significantly the highest binding capacity following by MIS 8  
392 and then MIS 4. The comparison of the average number of binding sites  $N$  confirms that MIS  
393 5' displayed significantly much higher binding capacities (31, 8  $\mu\text{mol/g}$ ) than MIS 8 and MIS  
394 4 (p value = 0,0157). Moreover, the average association constant  $K_{K_{\text{min}}-K_{\text{max}}}$  is around two times  
395 greater for the MIS 5' than for MIS 8 and MIS 4 (p value = 0, 0046). No significant differences  
396 were observed for MIS 8 and MIS 4 about the value of  $N$  and  $K_{K_{\text{min}}-K_{\text{max}}}$ . This higher capacity  
397 for MIS 5' should be attributed to a gain in the specific sites in line with this higher imprinting  
398 factor.

399 The experimental data fitted well to Tempkin isotherm indicating that iprodione adsorption  
400 occurred because the heat of adsorption of iprodione in the layer decreases linearly because of  
401 increased surface coverage<sup>18,19</sup>. No significant  $K_T$  values were observed between MIS 4, MIS  
402 5' and MIS 8 (Table 4, p value = 0, 418) meaning a constant maximum bonding energy  
403 whatever the MIS. The calculated values of sorption heat,  $B$  value and  $b$  value, were  
404 significantly different for MIS 4 as opposed to MIS 5' and MIS 8, which had similar values.  
405 Very low values of  $b$  obtained in the present study suggesting that the uptake of iprodione onto  
406 MIS was by physisorption. In fact, the physisorption processes are reported to have adsorption  
407 energies less than  $-40$  kJ/mol and characterized by very weak forces, such as Van der Waals  
408 forces and hydrogen bonding<sup>26,27</sup>.

409 On the basis of these results, MIS 5' was chosen as the best MIS and these performances were  
410 compared to that of an analogue MIP.

411

### 412 3.2. Comparison of MIS MIP performances

413 A MIP was synthesized using a functional monomer analogous to APTMS. Allylamine was  
414 chosen (Figure 1). Previous studies were performed to determine the optimal (template /

415 functional monomer / crosslinker) molar ratio. Isotherm studies were performed on MIS 5' and  
416 optimized MIP (Figure 8). The results show that MIS 5' and optimized MIP can bind iprodione  
417 and the binding capacity increased with the rise of iprodione solution concentration. The  
418 quantity of iprodione adsorbed was very different between MIS 5' (around 25 mg/g polymer)  
419 and MIP (around 120 mg/g polymer). It was 5 times lower for MIS than for MIP.  
420 However, the difference in the adsorption of iprodione between MIS and NIS was greater than  
421 the difference between NIP and MIP. In fact, the imprinting factor was of 271 for MIS and only  
422 2 for MIP (Table 3). MIS 5' presented a high specific recognition of iprodione. The imprinting  
423 factor of MIP is in agreement with the previous study<sup>8</sup>, where a value of 2.40 was determined.  
424 The imprinting factor of MIS is considerably higher than ones reported in the literature for  
425 molecularly imprinted sorbent materials, ranging from 0.8 to 39.85<sup>12,14,28</sup>. The large imprinting  
426 factor value of this MIS is an indication of the great analytical potential of silica-based  
427 molecularly imprinted materials. This high selectivity is promising for further development in  
428 this area. Our hypothesis to explain this difference of imprinting factors between MIP and MIS  
429 is the homogeneity of the silica polymer. MIS 5' show high degree of binding site homogeneity  
430 ( $n$  value 0.86). MIP had an  $n$  value of 0.47 meaning a binding site heterogeneity (Table 4). At  
431 the opposite, for the binding affinity ( $K_F$ ), which refers to the strength of binding interaction,  
432 MIP had a higher binding capacity ( $K_F$  of 490) than the MIS 5' ( $K_F$  of 202). We can supposed  
433 that this higher binding capacity could be due to non-specific interactions. The imprinting factor  
434 takes into account the non-specific interactions which are due to the interaction between the  
435 template and the crosslinker. The average number of binding sites  $N$  confirms this assumption:  
436 MIS 5' displayed significantly much lower binding capacities (31,8  $\mu\text{mol/g}$ ) than MIP (229  
437  $\mu\text{mol/g}$ ). Moreover, the average association constant  $K_{K_{\text{min}}-K_{\text{max}}}$  is around five times greater for  
438 the MIP than for MIS 5'.

439 The values obtained from the Temkin isotherm were:  $K_T = 75 \text{ g}/\mu\text{mol}$  and  $312 \text{ g}/\mu\text{mol}$  for  
440 respectively MIS 5' and MIP and  $b$  values =  $104 \text{ J/mol}$  and  $40 \text{ J/mol}$  for respectively MIS 5'  
441 and MIP, indicating that the adsorption of iprodione onto MIS or MIP occurred via  
442 physisorption involving low energies interactions between iprodione - MIS and between  
443 iprodione - MIP.

444  
445 Scarce are the papers describing the comparison between MIS and MIP. A direct comparison  
446 between MIS and MIP was performed for the analysis of propranolol <sup>29</sup>. The findings were that  
447 the MIP exhibited higher uptake towards propranolol, but this was accompanied by a high  
448 degree of nonspecific binding. The MIS had lower uptake, but remarkably lower nonspecific  
449 binding (<10%). Another comparative study of the potential of MIP and MIS for molecular  
450 imprinting of 2-aminopyridine showed that the MIP retained approximately 50% of the  
451 template in rebinding studies in chloroform compared to 100% for the MIS. However, this  
452 higher affinity for the MIS was accompanied by a higher degree of non-specific binding. While  
453 the MIP performed poorly in acetonitrile, the MIS maintained a high degree of discrimination  
454 <sup>30</sup>.

455

#### 456 **4. Conclusion**

457 The optimal MIS was obtained with APTMS as functional monomer, low solvent volume and  
458 high crosslinker quantity during its synthesis. It showed a very fast uptake profile for iprodione.  
459 The data modeling revealed that the adsorption process follows the Freundlich model. The  
460 optimal MIS had a higher imprinting factor but a lower binding capacity than the optimal MIP  
461 specific to iprodione. The imprinting factor of MIS was 135 times higher than MIP. Unlike  
462 MIP, MIS kept its molecular recognition nature even under extremely polar media such as the  
463 aqueous sample. This work emphasizes the high potential of MIS as molecularly imprinted

464 materials for analytical applications and provides promising insights into the future  
465 development of MIS. Practically, MIS is as simple as MIP to prepare. MIS technology seems  
466 to allow more specific binding than MIP but less sensitivity. To compensate the lower  
467 sensitivity compared to MIP, a bigger column for SPE and more MIS quantity plus a bigger  
468 volume of sample during the loading phase would be necessary to identify traces in a beverage  
469 (wine for ex.) or in washing water of fruits. The next step to the study is to assess the selectivity  
470 of MIP and MIS towards pesticides.

471

#### 472 **Funding sources and acknowledgements**

473 This work was supported by the Regional Council of Burgundy and the European Union via  
474 FEDER (“Fonds Européen de Développement Régional”) funding. We are grateful to AgroSup  
475 Dijon for co-funding this research program. The authors thank Alison Vezel for her contribution  
476 to this work.

477

#### 478 **Conflict of interest statement**

479 The authors declare that there is no conflict of interest. No conflicts, informed consent, human  
480 or animal rights are applicable for this work.

481

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543 **Figure captions**

544

545 **Figure 1:** Structure of functional monomers tested for the synthesis of molecularly imprinted  
546 silica (MIS) (a, b, c) and for the molecularly imprinted polymers (MIP) (d) and structure of  
547 iprodione (template, e)

548 **(a)** (3-Aminopropyl)trimethoxysilane

549 **(b)** 1-[3-(Trimethoxysilyl)propyl]urea

550 **(c)** N-[3-(Trimethoxysilyl)propyl]aniline

551 **(d)** allylamine

552 **(e)** iprodione

553

554 **Figure 2:** Binding capacity of polymer toward iprodione for MIS 1, MIS 6 and MIS 7 per 10  
555 mg of polymer in a solution of iprodione at  $10^{-5}$  M (10% ethanol / water, v/v). Bars represent  
556 standard deviation.

557

558 **Figure 3:** Binding capacity of polymer towards iprodione for MIS 1, MIS 4, MIS 5, MIS 7 and  
559 MIS 8 and their control polymer NIS respective per 10 mg of polymer in a solution of iprodione  
560 at  $10^{-5}$  M (10% ethanol / water, v/v). Bars represent standard deviation.

561

562 **Figure 4:** SEM images of (a) MIS 1, (b) MIS 5, (c) MIS 8 and (d) MIS 7. Scale bar and  
563 magnifications are mentioned on the SEM images.

564 **Figure 5:** Kinetic adsorption of MIS to iprodione solution (50% ethanol / water, v/v). Bars  
565 represent standard deviation.

566

567 **Figure 6:** Binding isotherme of MIS 4, MIS 5' and MIS 8 toward iprodione at 25°C after 1h of  
568 contact time with solution of iprodione (50% ethanol / water, v/v). Bars represent standard  
569 deviation.

570

571 **Figure 7:** Isotherms models of the adsorption of iprodione by MIS 4. Sorption isotherms  
572 obtained at 25°C after 1h of contact time with solution of iprodione (50% ethanol / water, v/v)

573 (a) **Langmuir** plot

574 (b) **Freundlich** plot

575 (c) **Temkin** plot

576

577 **Figure 8:** Binding isotherme of MIS 5' and MIP toward iprodione at 25°C after 1h of contact  
578 time with solution of iprodione (50% ethanol / water, v/v). Bars represent standard deviation.

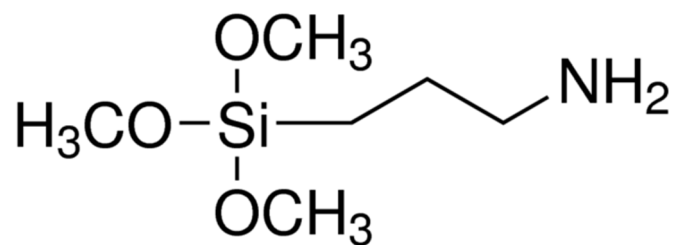
579

580

581 **Figure 1**

582

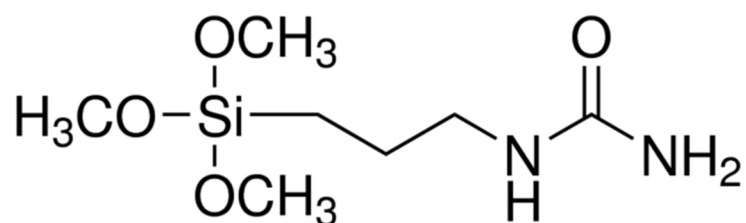
583 (a)



584

585

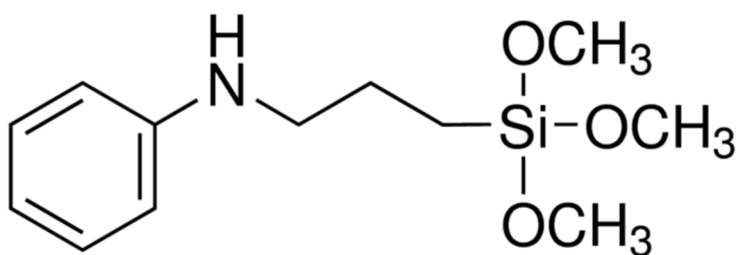
586 (b)



587

588

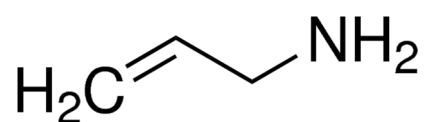
589 (c)



590

591

592 (d)

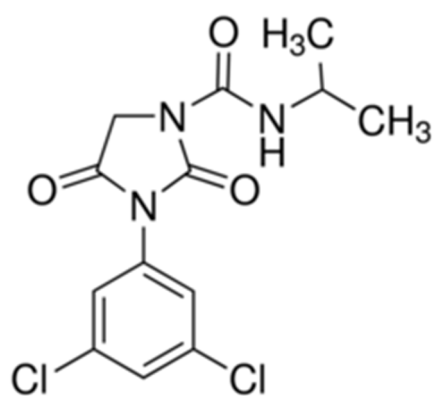


593

594

595

596 (e)

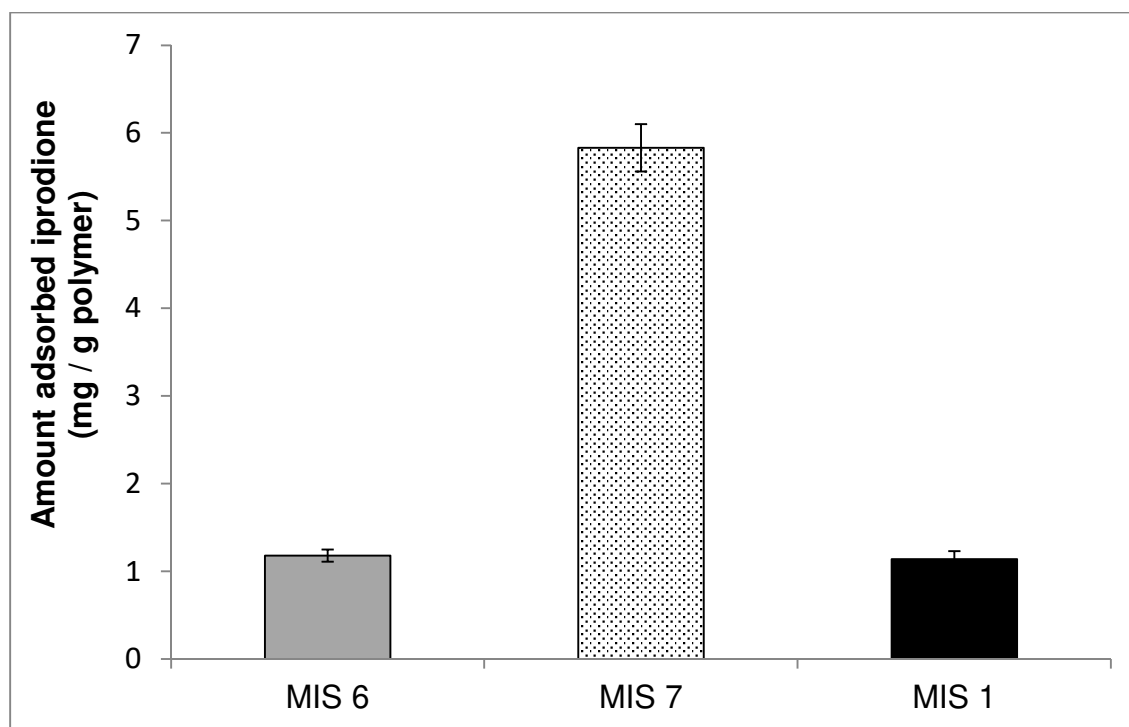


597

598

599 **Figure 2**

600



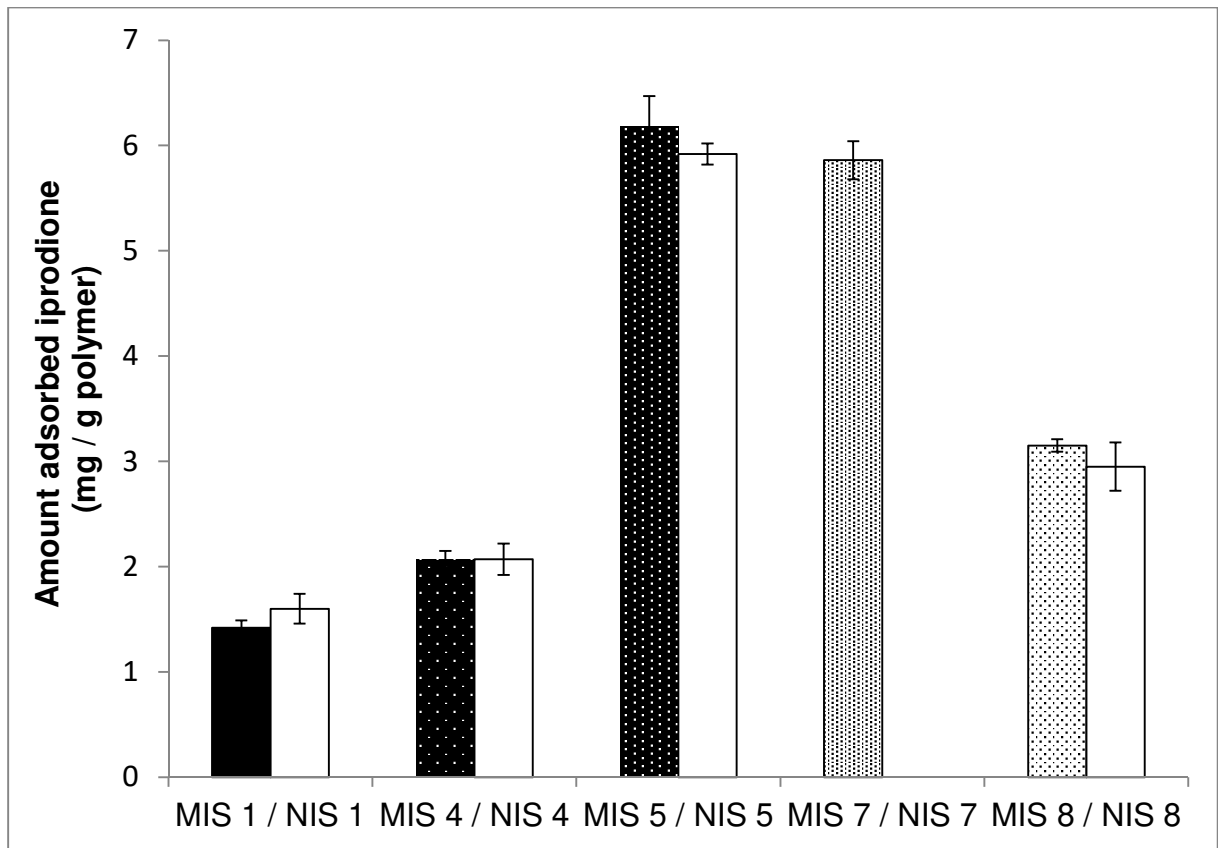
601

602

603

604 **Figure 3**

605

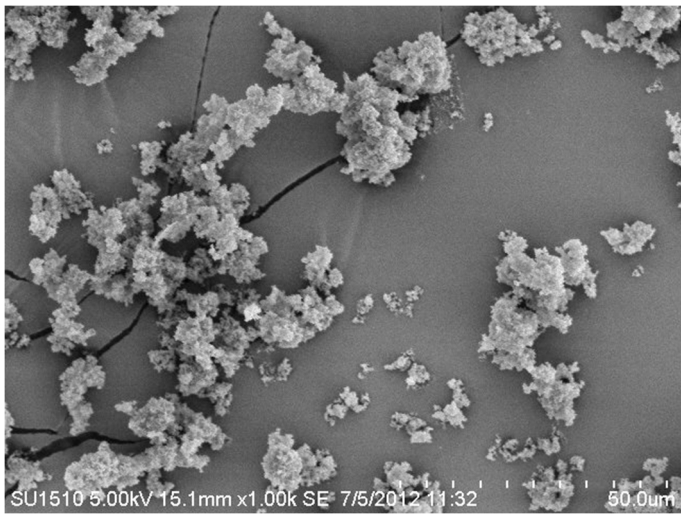


606

607

608 **Figure 4**

609 **a)**

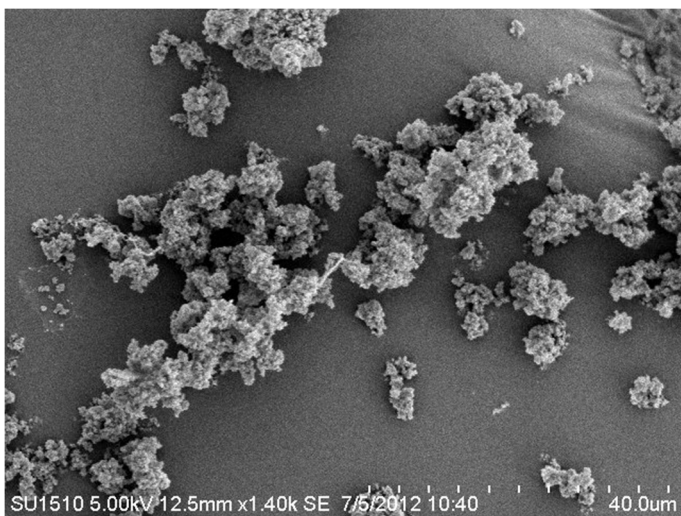


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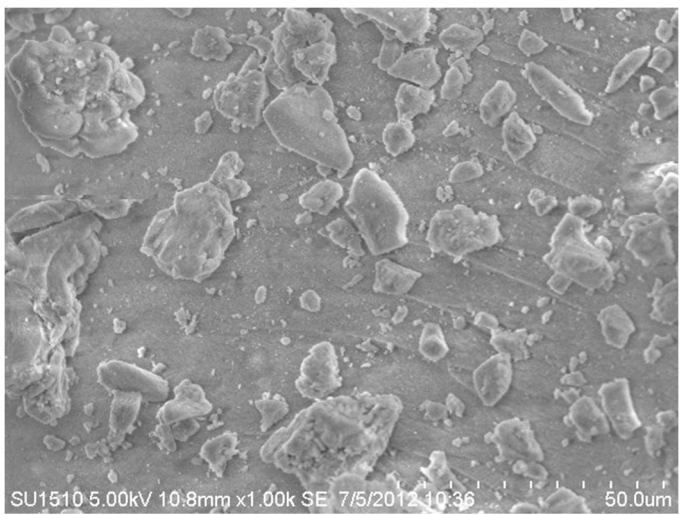
**b)**



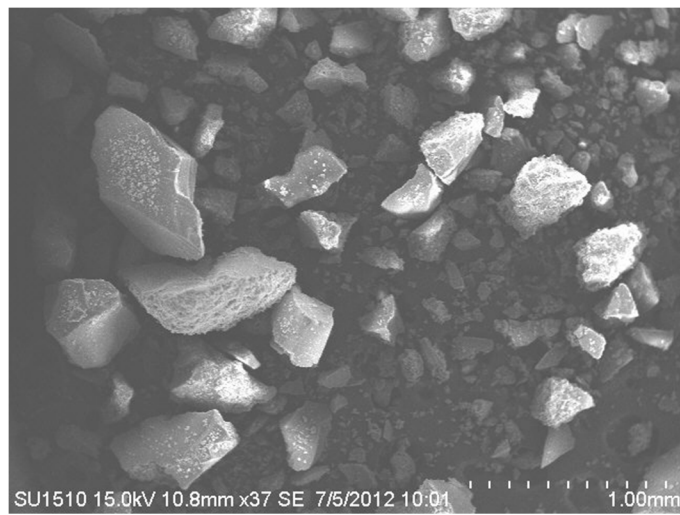
613

614

**c)**



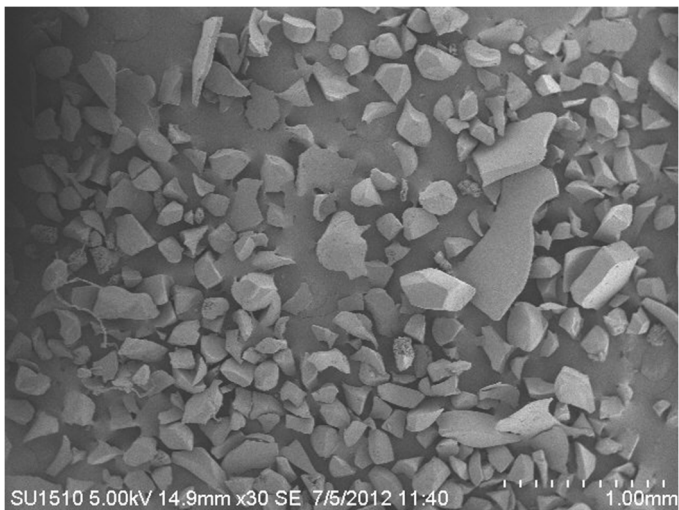
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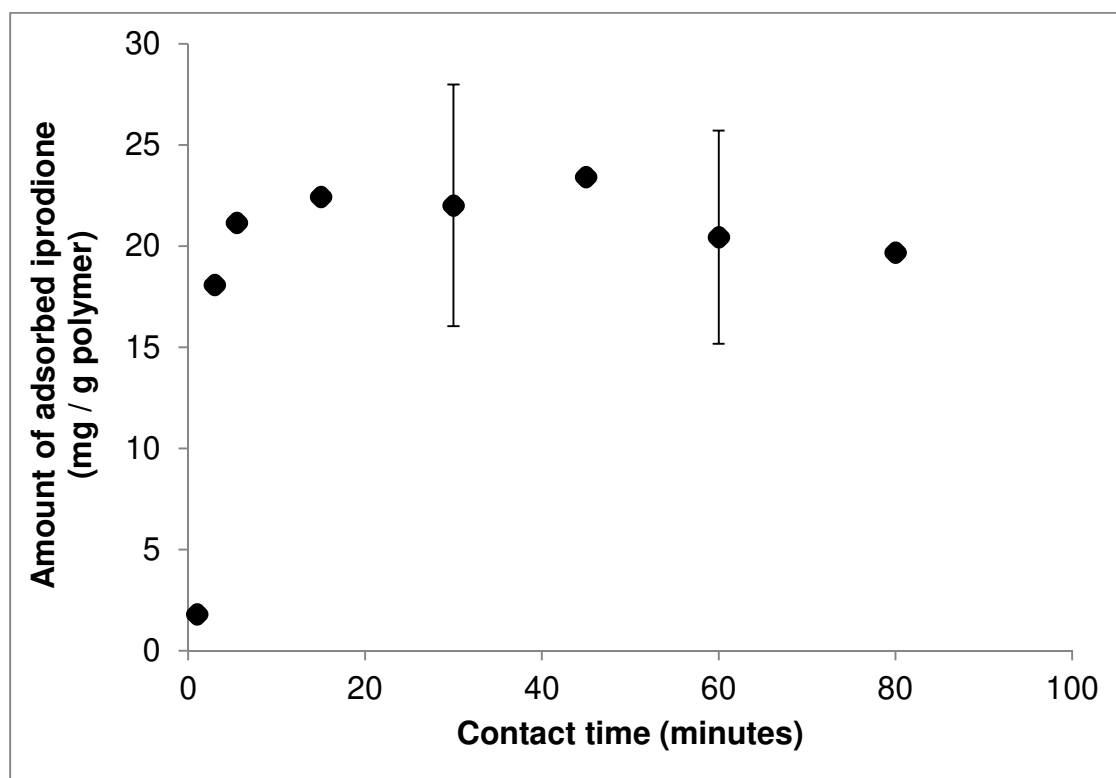
d)



617

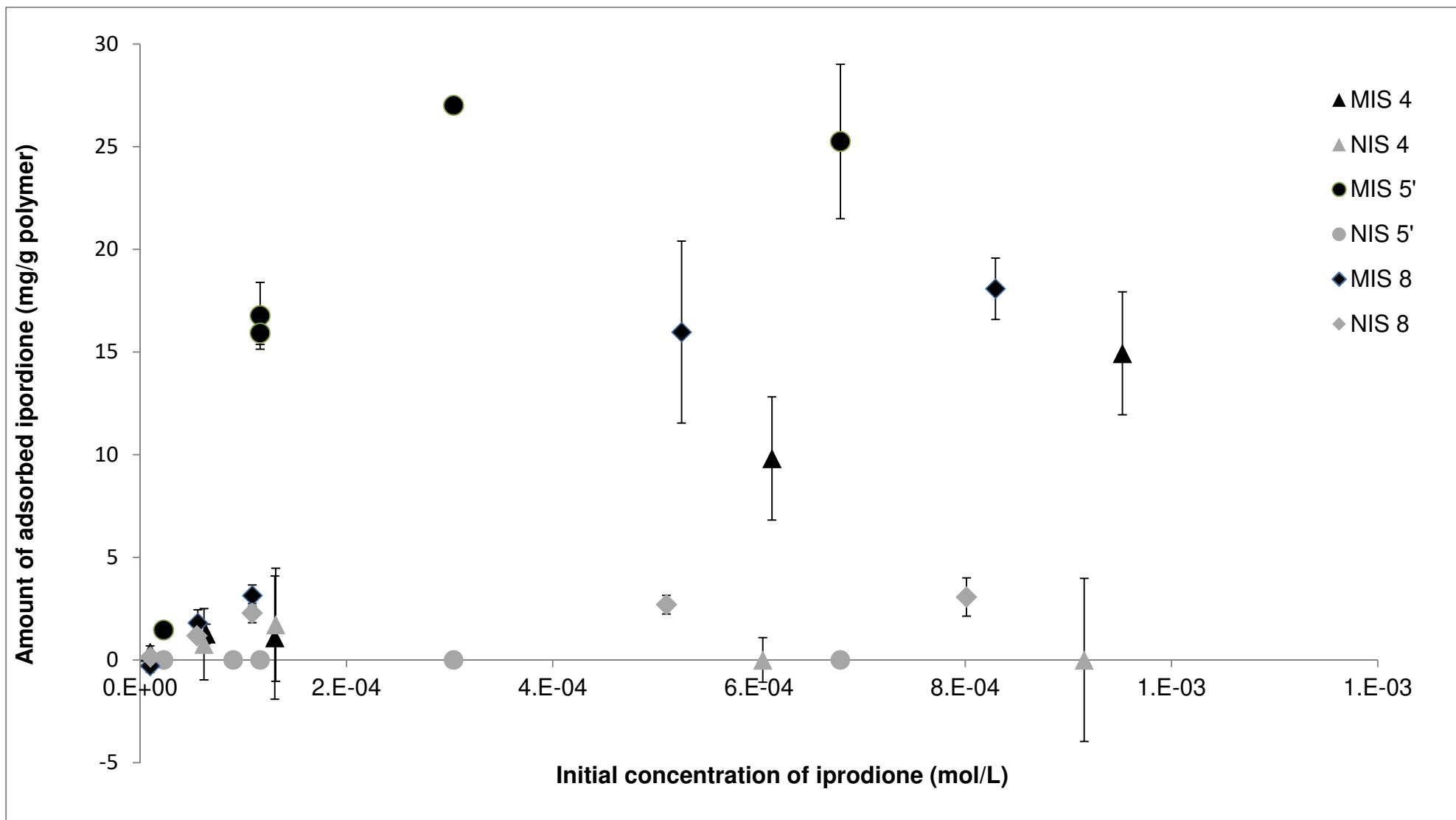
618

619 **Figure 5**



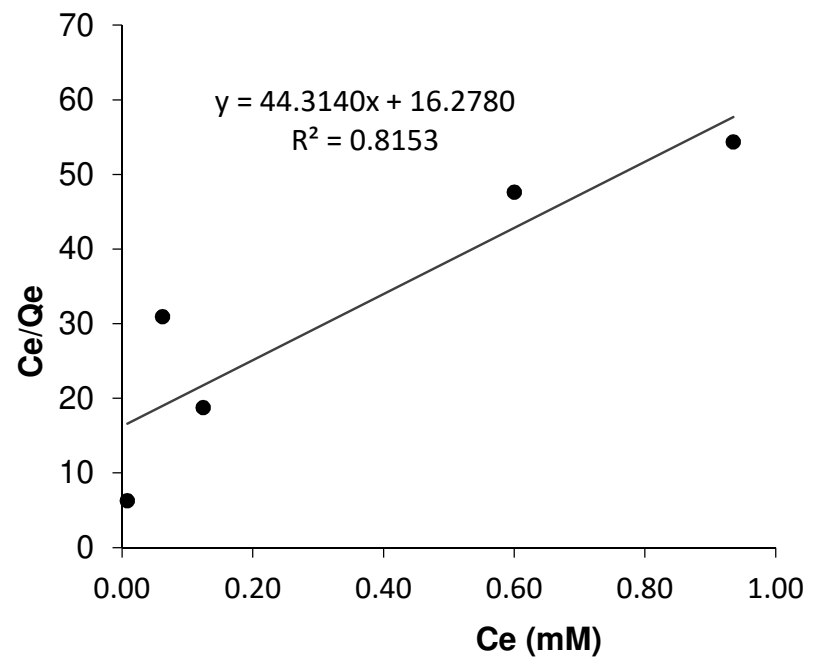
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621



624 **Figure 7**

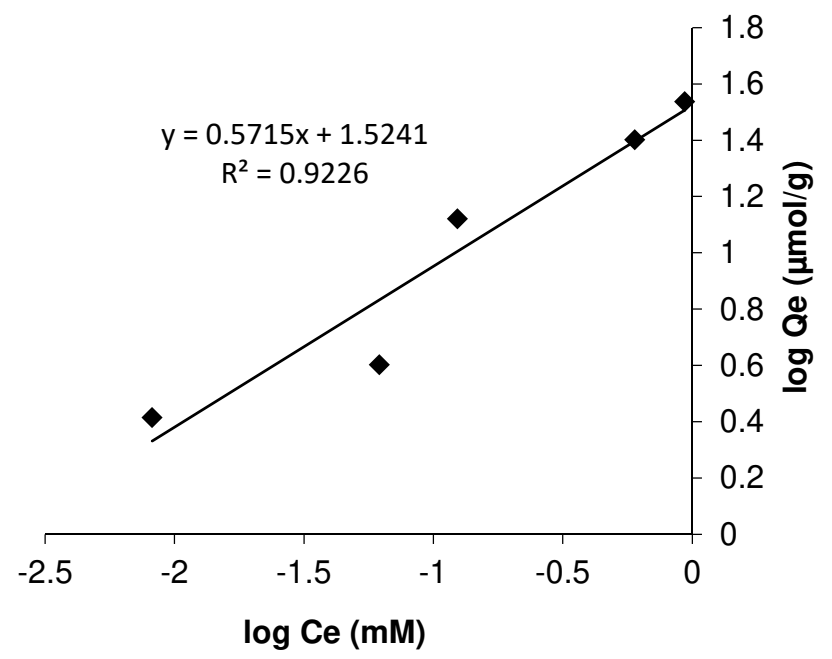
625 **(a)**



626

627

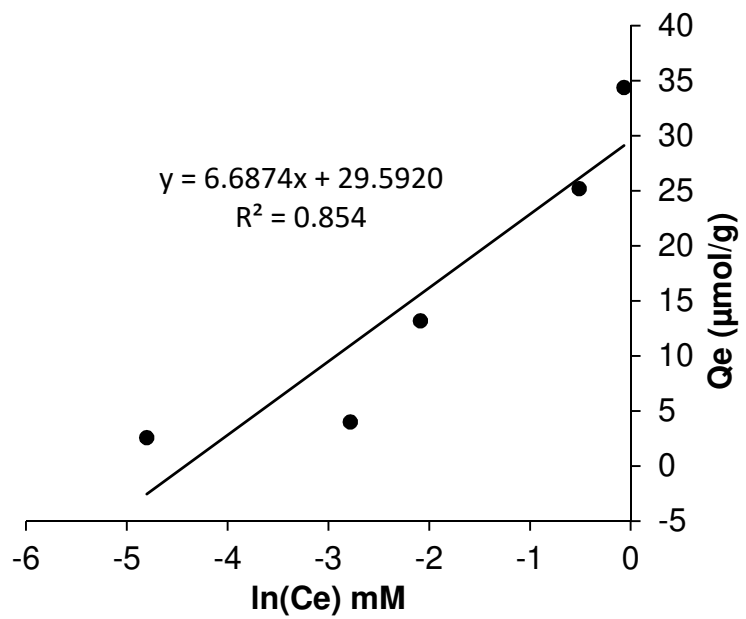
628 (b)



629

630

631 (c)

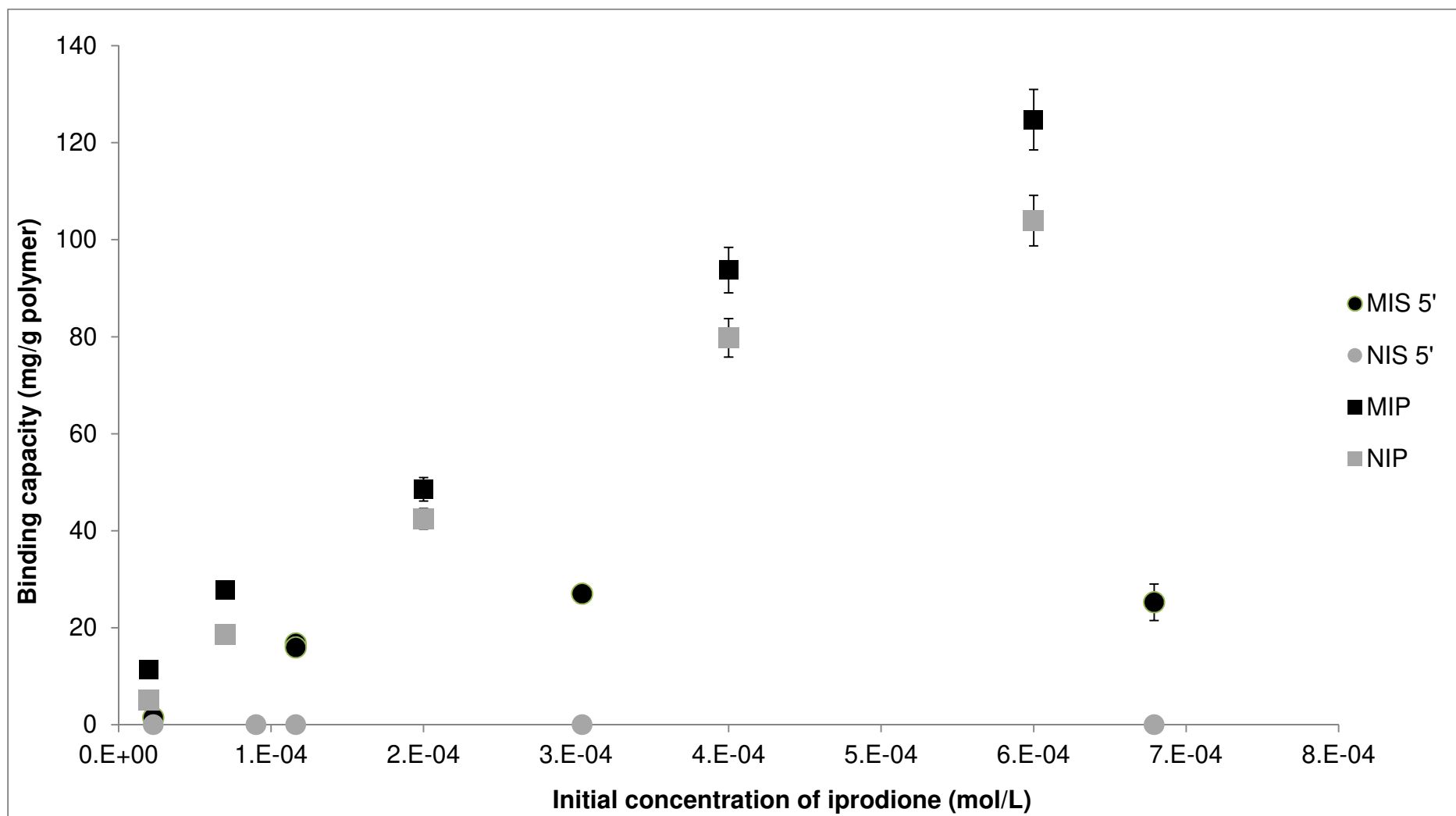


632

633

634

635 **Figure 8**



636

637

638 **Table 1:** Nature of molecularly imprinted polymer using fungicide as template

Nature of molecularly imprinted polymer	Template	Nature of sample	Functional monomer	Reference
Molecularly imprinted polymer (MIP)	imidazole fungicides (climbazole, clotrimazole, miconazole)	river water	methacrylic acid (MAA)	32
	dicarboximide fungicide (iprodione)	white wine	methacrylamide (MAM)	8
	imidazole fungicide (climbazole)	river and tap water	methacrylic acid (MAA)	33
	triazine (terbutylazine)	river water	methacrylic acid (MAA)	34
	triazine (terbutylazine)	surface waters and an industrial effluent	methacrylic acid (MAA)	35
	triazine (terbutylazine)	groundwater	methacrylic acid (MAA)	36
	triazine (terbutylazine)	river water	methacrylic acid (MAA)	37
	triazine (terbutylazine)	tap water and groundwater	methacrylic acid (MAA)	38
	triazine (terbutylazine)	grape juice and soil extract	methacrylic acid (MAA)	39
	benzimidazole fungicide (thiabendazole)	river and tape water	methacrylic acid (MAA)	40
	chlorinated fungicide (fenarimol)	apple, banana, and tomato	methacrylic acid (MAA)	41
	benzimidazole fungicide (thiabendazole and carbendazim)	orange peel	methacrylic acid (MAA)	42
	anilinopyrimidine fungicide (pyrimethanil)	red wine	methacrylic acid (MAA)	43
	benzimidazole fungicide (thiabendazole)	spiked river, tap and well water	methacrylic acid (MAA)	44
	triazole fungicides (triadimefon)	cucumber	methacrylic acid (MAA)	45
	triazole fungicide (difenoconazole)	tap water and grape juice	methacrylic acid (MAA)	46
morpholine fungicide (dimethomorph)	ginseng powder	methacrylic acid (MAA)	47	
Molecularly imprinted sol-gel polymer (MIS)	dicarboximide fungicide (iprodione)	white wine	(3-Aminopropyl)trimethoxysilane (APTMS)	12
	dicarboximide fungicide (iprodione)	hydroalcoholic medium	(3-Aminopropyl)trimethoxysilane (APTMS)	48



639

	Triazine (atrazine)	sugar cane juice	(3-Aminopropyl)trimethoxysilane (APTMS)	<sup>49</sup>
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640 **Table 2:** Samples codes of different MIS and NIS synthesized for this study depending on different natures of functional monomers and different  
 641 molar ratios of reagents.

<b>template / functional monomer / crosslinker molar ratio</b>	<b>1/4/20</b>	<b>1/4/20</b>	<b>1/4/50</b>	<b>1/4/59</b>	<b>1/4/20</b>	<b>1/4/20</b>	<b>1/4/59</b>
Functional monomer	APTMS	APTMS	APTMS	APTMS	Urea	Aniline	Aniline
Ethanol / water ratio (mL)	2.3 / 1.3	1.15 / 0.44	1.15 / 0.44	1.15 / 0.44	2.3 / 1.3	2.3 / 1.3	1.15 / 0.44
Code number of MIS synthesized	MIS 1	MIS 4	MIS 5	MIS 5'	MIS 6	MIS 7	MIS 8
Code number of NIS synthesized	NIS 1	NIS 4	NIS 5	NIS 5'	NIS 6	NIS 7	NIS 8

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644 **Table 3:** Imprinting factors obtained for MIS and MIP depending on the nature of the solution (10 % or 50 % (v/v) ethanol / water solution). In  
 645 each line, mean values were calculated using three repetitions  $\pm$  standard deviation. Means with different superscripts (a – c) are significantly  
 646 different at  $p < 0.05$  using Fisher t-test.

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<b>Nature of the solution</b>	<b>MIS 1</b>	<b>MIS 4</b>	<b>MIS 5</b>	<b>MIS 5'</b>	<b>MIS 6</b>	<b>MIS 7</b>	<b>MIS 8</b>	<b>MIP</b>
from 10 % (v/v) ethanol/water solution	$0.96 \pm 0.11$	$0.99 \pm 0.07$	$1.15 \pm 0.42$	nd	nd	nd	$1.13 \pm 0.06$	nd
from 50 % (v/v) ethanol/water solution	nd	$99 \pm 31^b$	nd	$271 \pm 43^c$	nd	nd	$6 \pm 2^a$	$2 \pm 0.1^a$

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649 **Table 4:** Adsorption isotherms constants from Langmuir, Freundlich, Temkin models obtained at 25°C with 50 % (v/v) ethanol / water solution.  
 650 In each line, mean values were calculated using three repetitions  $\pm$  standard deviation. Means with different superscripts (a – c) are significantly  
 651 different at  $p < 0.05$  using Fisher t-test.

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<b>Isotherms</b>	<b>Constants</b>	<b>MIS 4</b>	<b>MIS 5'</b>	<b>MIS 8</b>	<b>MIP</b>
Freundlich	$r^2$	$0.91 \pm 0.02$	$0.83 \pm 0.05$	$0.93 \pm 0.03$	$0.97 \pm 0.05$
	n	$0.75 \pm 0.17^a$	$0.86 \pm 0.04^a$	$0.91 \pm 0.10^a$	$0.47 \pm 0.02^b$
	$K_F$ ( $\text{mM}^{-1}$ )	$38 \pm 5^a$	$202 \pm 35^c$	$76 \pm 11^b$	$490 \pm 24^d$
	$K_{(K_{\text{MIN}} - K_{\text{MAX}})}$ ( $\text{mM}^{-1}$ )	$3.6 \pm 0.4^a$	$6.3 \pm 0.3^b$	$3.8 \pm 0.2^a$	$32 \pm 1.6^c$
	N ( $\mu\text{mol/g}$ )	$12 \pm 5.2^a$	$31.8 \pm 6.7^b$	$15.5 \pm 1.8^a$	$229 \pm 11.5^c$
Temkin	$r^2$	$0.76 \pm 0.09$	$0.89 \pm 0.09$	$0.89 \pm 0.09$	$0.82 \pm 0.04$
	$K_T$ ( $\text{g}/\mu\text{mol}$ )	$57 \pm 23^a$	$75 \pm 14^a$	$75 \pm 14^a$	$312 \pm 15^b$
	B ( $(\mu\text{mol/g})/\text{mM}$ )	$9.3 \pm 2.5^a$	$24.5 \pm 4.4^b$	$24.5 \pm 4.4^b$	$62 \pm 3^c$
Langmuir	b ( $\text{J/mol}$ )	$282 \pm 81^c$	$104 \pm 19^b$	$104 \pm 19^b$	$40 \pm 2^a$
	$r^2$	$0.30 \pm 0.45$	$0.61 \pm 0.13$	$0.43 \pm 0.36$	$0.80 \pm 0.04$

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Sol-gel  
Molecularly Imprinted Polymer  
MIS specific for Iprodione

Vs.

Acrylate  
Molecularly Imprinted Polymer  
MIP specific for Iprodione

