



**HAL**  
open science

## From algal polysaccharides to cyclodextrins to stabilize a urease inhibitor.

Danièle Pro, Samuel Huguet, Mustapha Arkoun, Caroline Nugier-Chauvin,  
Jose María García-Mina, Alain Ourry, Dominique Wolbert, Jean-Claude Yvin,  
Vincent Ferrières

### ► To cite this version:

Danièle Pro, Samuel Huguet, Mustapha Arkoun, Caroline Nugier-Chauvin, Jose María García-Mina, et al.. From algal polysaccharides to cyclodextrins to stabilize a urease inhibitor.. Carbohydrate Polymers, 2014, 112, pp.145-51. 10.1016/j.carbpol.2014.05.075 . hal-01063896v2

**HAL Id: hal-01063896**

**<https://hal.science/hal-01063896v2>**

Submitted on 14 Oct 2014

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Highlights**

2  
3  
4  
5  
6  
7  
8  
9

- A new formulation of NBPT, a known urease inhibitor, with cyclodextrin was prepared
- The complex CD/NBPT was fully characterized
- The stability of NBPT and that of CD/NBPT in acidic media were studied by NMR
- $IC_{50}$  of the CD/NBPT complex was determined

Accepted Manuscript

9 **From algal polysaccharides to cyclodextrins to stabilize a urease inhibitor**

10

11 Danièle Pro,<sup>a,b</sup> Samuel Huguet,<sup>a,b</sup> Mustapha Arkoun,<sup>c,d</sup> Caroline Nugier-Chauvin,<sup>a,b</sup> José  
12 Maria Garcia-Mina,<sup>e</sup> Alain Ourry,<sup>c,d</sup> Dominique Wolbert,<sup>a,b</sup> Jean-Claude Yvin,<sup>f</sup> Vincent  
13 Ferrières\*,<sup>a,b</sup>

14

15 <sup>a</sup> Ecole Nationale Supérieure de Chimie de Rennes, CNRS, UMR 6226, 11 Allée de Beaulieu,  
16 CS 50837, 35708 Rennes Cedex 7, France

17 <sup>b</sup> Université européenne de Bretagne, France

18 <sup>c</sup> Université de Caen Basse-Normandie, UMR 950 Ecophysiologie Végétale, Agronomie et  
19 nutritions N, C, S. Esplanade de la paix, 14032 Caen, France

20 <sup>d</sup> INRA, UMR 950 Ecophysiologie Végétale, Agronomie et nutritions N, C, S. Esplanade de  
21 la paix, 14032 Caen, France

22 <sup>e</sup> Timac Agro International, Poligono de Arazuri-Orcoyen Calle C nº32 E-31160 Orcoyen,  
23 Spain

24 <sup>f</sup> Timac Agro International, 27 Avenue Franklin Roosevelt, 35408 Saint Malo, France

25

26

27 Corresponding author: Vincent Ferrières

28 Tel: (+33) 23 23 80 58

29 Fax: (+33) 2 23 23 81 99

30 [vincent.ferrieres@ensc-rennes.fr](mailto:vincent.ferrieres@ensc-rennes.fr)

31

32

32 **From algal polysaccharides to cyclodextrins to stabilize a urease inhibitor**

33

34 Danièle Pro,<sup>a,b</sup> Mustapha Arkoun,<sup>c,d</sup> Caroline Nugier-Chauvin,<sup>a,b</sup> José Maria Garcia-Mina,<sup>e</sup>35 Alain Ourry,<sup>c,d</sup> Jean-Claude Yvin,<sup>f</sup> Vincent Ferrières<sup>\*,a,b</sup>

36

37 <sup>a</sup> Ecole Nationale Supérieure de Chimie de Rennes, CNRS, UMR 6226, 11 Allée de Beaulieu,

38 CS 50837, 35708 Rennes Cedex 7, France

39 <sup>b</sup> Université européenne de Bretagne, France40 <sup>c</sup> Université de Caen Basse-Normandie, UMR 950 Ecophysiologie Végétale, Agronomie et

41 nutritions N, C, S. Esplanade de la paix, 14032 Caen, France

42 <sup>d</sup> INRA, UMR 950 Ecophysiologie Végétale, Agronomie et nutritions N, C, S. Esplanade de

43 la paix, 14032 Caen, France

44 <sup>e</sup> Timac Agro International, Poligono de Arazuri-Orcoyen Calle C nº32 E-31160 Orcoyen,

45 Spain

46 <sup>f</sup> Timac Agro International, 27 Avenue Franklin Roosevelt, 35408 Saint Malo, France

47

48 **Abstract:** *N*-Butyl-phosphorotriamide (NBPT) is a fertilizer widely used for its urease

49 inhibiting properties. Nevertheless, formulations currently commercialized are complex and

50 do not avoid severe decrease of activity due to the low stability of the bioactive compound

51 under acidic conditions. According to its structure, NPBT was thought to be able to interact

52 with both polar additives, by its phosphoramidate function, and hydrophobic ones, through its

53 alkyl chain. In this context, and in order to simplify formulations of this bioactive compound,

54 a panel of natural polysaccharides was studied, including starch,  $\beta$ -(1,3)-glucans,

55 carraghenans and alginates. We also used cyclodextrins, characterized the most stable

56 inclusion complex with  $\alpha$ -cyclodextrin and evaluated the stability of NBPT thus protected  
57 against hydrolysis under acidic conditions.

58

59 **Keywords:** NBPT; Carraghenans; Alginates; (1,3)-Glucans; Starch; Cyclodextrins

60

## 61 **1. Introduction**

62 The small molecule of urea is the source of two major scientific discoveries. Not only it is the  
63 first molecule chemically synthesized by Wöhler in 1828, but the study of its biodegradation  
64 allowed the first crystallization of an enzyme, the Jack Bean urease, in 1926 by Sumner  
65 (Sumner, 1926), who was subsequently awarded by the Nobel Prize for this breakthrough in  
66 1946. Meantime, urea has become an important component of many fertilizers. However, as  
67 only 30% of the available nitrogen is absorbed by plants, improving the efficiency of the  
68 nitrogen use in agriculture generally requires adding inhibitors acting on nitrification and/or  
69 ureases. The application of the latter significantly reduces ammonia volatilization, as well as  
70 damages to seedlings. Plants are also able to assimilate nitrogen as urea, and urease inhibitors  
71 promote this type of nutrition, which is also beneficial for plant growth (Trenkel, 2010).  
72 Finally, the use of such compounds able to increase the lifetime of urea in soils is not  
73 exclusive to agriculture, but find applications in dairy farming where they can significantly  
74 decrease nitrogen emissions due to urine and manure (Leinker, Reinhardt-Hanisch, Hartung &  
75 von Borell, 2005; Zaman, Nguyen, Blennerhassett & Quin, 2008).

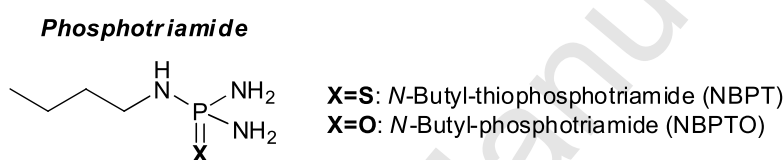
76 Numerous studies have led to the marketing of a large panel of molecules having anti-ureasic  
77 activities [for instance hydroquinone, phosphotriamide compounds (Domínguez et al., 2008;  
78 Font et al., 2008; Trenkel, 2010)], or able to influence nitrification phenomena [ammonium  
79 thiosulfate, thiourea, or more complex products, i.e. pyrimidinic, triazolic, thiadiazolic  
80 derivatives, dicyandiamide (DCD) (Nelson & Huber, 1992; Trenkel, 2010)], both contributing

81 to improve nitrogen absorption by plants. In addition to the range of such bioactive molecules,  
82 many formulations are proposed. Inhibitors may be available as pure compounds or directly  
83 incorporated into fertilizers. They can also be formulated in liquid or solid phases. This allows  
84 matching a wide range of treatments to soil characteristics and infrastructure of the users. For  
85 instance, commercial forms of DCD are an excellent example of adaptability, since it is  
86 possible to obtain this single molecule or in combination with other inhibitors of nitrification  
87 possibly mixed with urea, or even incorporated into fertilizers containing ammonium salts and  
88 many other nutrients. Similarly, *N*-butyl-thiophosphotriamide (NBPT) can be purchased in a  
89 liquid formulation (Agrotain), but also in a solid one containing DCD, or in solid granules  
90 with urea and DCD. Consequently, commercially available inhibitors stabilize nitrogen for  
91 several days to several weeks.

92

93 The development of new compounds and/or formulations is part of an integrated approach to  
94 farming, keeping in mind that control of the global impact on environment is a priority.  
95 However, decades of use of urease inhibitors, and of basic researches, highlighted the  
96 complexity of using them efficiently. Among influencing parameters are the quality of soils  
97 (pH, nature of the organic matter and possibility to find colloids, porosity, biodiversity linked  
98 with numerous microorganisms), abiotic factors (temperature, water quality), and own  
99 properties of the inhibitors (volatility, hydrophilic/hydrophobic balance, stability and mobility  
100 in soils) (Subbarao et al., 2006). In this context, we have initiated a program and first  
101 proposed to covalently connect known nitrification inhibitors to mono- and disaccharides,  
102 especially in order to increase their ecocompatibility (Pro et al., 2012). Herein, we propose  
103 another approach lying on the opportunity to formulate the known urease inhibitor NBPT  
104 (Fig. 1) with natural polysaccharides and derivatives thereof. It is recognized that NBPT has  
105 already inhibition properties ( $IC_{50} = 100$  nM), but this thiophosphoramidate is readily converted

106 into its *O*-counterpart NBPTO that is the real inhibitor in soils ( $IC_{50} = 1 \text{ nM}$ ). However, two  
 107 major limitations are generally encountered with this inhibitor patented in 1985 (Kole,  
 108 Swerdloff, Rogic, Hendrickson & Van Der Puy, 1985): the first one is its hydrophobicity that  
 109 requires more or less complex formulations, and the second but more limiting one relies on its  
 110 low stability, and so loss of activity, in acidic media (Domínguez et al., 2008). The ability of  
 111 carbohydrates to adopt many conformations, and/or to interact with their aqueous  
 112 environment (basic vs. acidic, presence of salts) (Cui, 2005), offers great opportunities to  
 113 develop new formulations.



114

115 **Fig.1.** Structure of the studied urease inhibitor NBPT.

116

## 117 2. Material and methods

### 118 2.1. Materials

119 Polysaccharides used in this study are commercially available. NBPT was provided by Timac  
 120 Agro International (Dinard) and was further purified by recrystallisation from water.  $^1\text{H}$ ,  $^{13}\text{C}$ ,  
 121  $^{31}\text{P}$  NMR spectra were recorded with a Brüker ARX 400 spectrometer at 400 MHz, 100 MHz,  
 122 and 162 MHz for  $^1\text{H}$ ,  $^{13}\text{C}$  and  $^{31}\text{P}$ , respectively. Chemical shifts are given in  $\delta$  units (ppm).  
 123 Coupling constants  $J$  were calculated in Hertz (Hz). Abbreviations were used to precise signal  
 124 multiplicity: s (singlet), d (doublet), t (triplet), m (multiplet), dd (double doublet)... The  
 125 HRMS were measured at the Centre Regional de Mesures Physiques de l'Ouest (CRMPO,  
 126 Université de Rennes 1) with a MS/MS ZabSpec TOF Micromass using *m*-nitrobenzyllic  
 127 alcohol as a matrix and accelerated caesium ions for ionization.

128

129 2.2. Degradation tests in acidic media by  $^{31}\text{P}$  NMR

130 The necessary amount of formulation for having 10 mg of NBPT was mixed with 250  $\mu\text{L}$   
 131 water in NMR tubes (blank solution consisted in 40 mg Agrotain in 250  $\mu\text{L}$  of water). The  
 132 solution was heated until complete dissolution of NBPT. 250  $\mu\text{L}$  of acidic buffer solution  
 133 ( $\text{CH}_3\text{COOH}/\text{CH}_3\text{COONa}$ , 500 mM, pH 5.5) was added. Then, a fused capillary containing a  
 134 invariant  $\text{H}_3\text{PO}_4$  solution in  $\text{D}_2\text{O}$  was inserted, and the degradation of NBPT was monitored  
 135 by  $^{31}\text{P}$  NMR. The degradation of NBPT was deduced from the decrease of the signal at 60.5  
 136 ppm (corresponding to the NBPT) compared to the constant -0.3 ppm peak's area  
 137 (corresponding to the  $\text{H}_3\text{PO}_4$ ).

138

139 2.3. Formulations with cyclodextrin  $\text{CD}\alpha$  and determination of the inclusion complex thanks  
 140 to the Job's method

141 A solution of  $\alpha$ -cyclodextrin ( $\text{CD}\alpha$ ) in water (10 mM) and a solution of NBPT in methanol  
 142 (10 mM) were prepared. Different ratio of both solutions were mixed together in test tubes  
 143 (from 0:10 to 10:0), for a total volume of 1 mL, before freeze-drying. The resulting solid was  
 144 dissolved into 1 mL of  $\text{D}_2\text{O}$ , and analyzed by  $^1\text{H}$  NMR. For each ratio of NBPT ( $r$ , Eq. 1) and  
 145 for each proton ( $i$ ) of NBPT, the variation of chemical shift ( $\Delta\delta_r^i$ ) was calculated as (Eq. 1):

$$146 \quad r = [\text{NBPT}]/([\text{NBPT}] + [\text{CD}\alpha]) \text{ (Eq. 1)}$$

$$147 \quad \Delta\delta_r^i = \delta_r^i - \delta_1^i \text{ (Eq. 2)}$$

148 For each ratio of  $\text{CD}\alpha$  ( $1-r$ ) and for each proton ( $j$ ) of  $\text{CD}\alpha$ , the variation of chemical shift  
 149  $\Delta\delta_{1-r}^j$  was calculated as (Eq. 3):

$$150 \quad \Delta\delta_{1-r}^j = \delta_{1-r}^j - \delta_0^j \text{ (Eq. 3)}$$

151 Then  $r.\Delta\delta_r^i$  and  $(1-r).\Delta\delta_{1-r}^j$  were plotted against  $r$ . Resulting curves went through a maximum,  
 152 at the  $r$  value corresponding to the ratio of the inclusion complex.

153



## 154 2.4. Determination of the association constant

155 The association constant was obtained according to the method of Benesi-Hildebrand (Benesi  
156 & Hildebrand, 1949). A solution of NBPT in methanol (5 mM) and a solution of CD- $\alpha$  in  
157 water (125 mM) were prepared. Different amounts of these two solutions were mixed with  
158 water for a total volume of 500  $\mu$ L, a constant concentration of NBPT (1 mM), and a varying  
159 concentration of CD- $\alpha$  (from 50 to 100 mM).

160 Then, mixtures were freeze-dried and the resulting solid dissolved into 500  $\mu$ L of D<sub>2</sub>O, before  
161 <sup>1</sup>H NMR analysis. For each concentration of CD- $\alpha$  ([CD- $\alpha$ ]), and for each proton (*i*) of  
162 NBPT, the variation of chemical shift  $\Delta\delta_{[\text{CD-}\alpha]}^i$  was calculated thanks to equation 4:

$$163 \quad \Delta\delta_{[\text{CD-}\alpha]}^i = \delta_{[\text{CD-}\alpha]}^i - \delta_0^i \text{ (Eq. 4)}$$

164 Then,  $1/\Delta\delta_{[\text{CD-}\alpha]}^i$  was plotted against  $1/[\text{CD-}\alpha]$ . Resulting curves obey to a linear equation.

165 The association constant of the complex ( $K_a$ ) and the variations of chemical shifts of NBPT in  
166 the pure complex ( $\Delta\delta_{\text{Cpx}}^i$ ) were deduced from equations of the intercept and the slope of the  
167 curves:

$$168 \quad \text{intercept} = 1/\Delta\delta_{\text{Cpx}}^i \text{ (Eq. 5) and slope} = 1/K_a \cdot \Delta\delta_{\text{Cpx}}^i \text{ (Eq. 6)}$$

169 This method was applied on the four signals corresponding to the butyl chain of the NBPT.

170 The four estimations of the association constant were averaged.

171

172

## 173 2.5. Evaluation of the inhibitory activity

174 One milliliter of buffer solution (KH<sub>2</sub>PO<sub>4</sub>/K<sub>2</sub>HPO<sub>4</sub>, 70 mM, pH 7), 1 mL of inhibitor solution  
175 (at different concentrations), and 10  $\mu$ L of jack bean urease solution (2.8 mg/mL, Sigma U-  
176 1500 35.500) were mixed in test tubes and incubated for 30 min at 37 °C (blank solution  
177 consisted of the same mixture without inhibitor). Afterward, 1 mL of urea solution (6 mg/mL)  
178 was added, with incubation again for 30 min at 37 °C. The reaction was stopped by the

179 addition of 2 mL of 0.033 N HCl. Each inhibitor dose was tested in triplicate. The level of  
180 ammonium released was determined photometrically, using the ammonium Test from Merck  
181 (Ref 1.14752.0001). The inhibition percentage  $Inh(\%)$  was calculated as:

$$182 \quad Inh(\%) = 100 - 100(A_{Inh}/A_B) \text{ (Eq. 7)}$$

183 where  $A_{Inh}$  and  $A_B$  are the absorbance at 692 nm in the test tubes, with and without inhibitor,  
184 respectively.

185

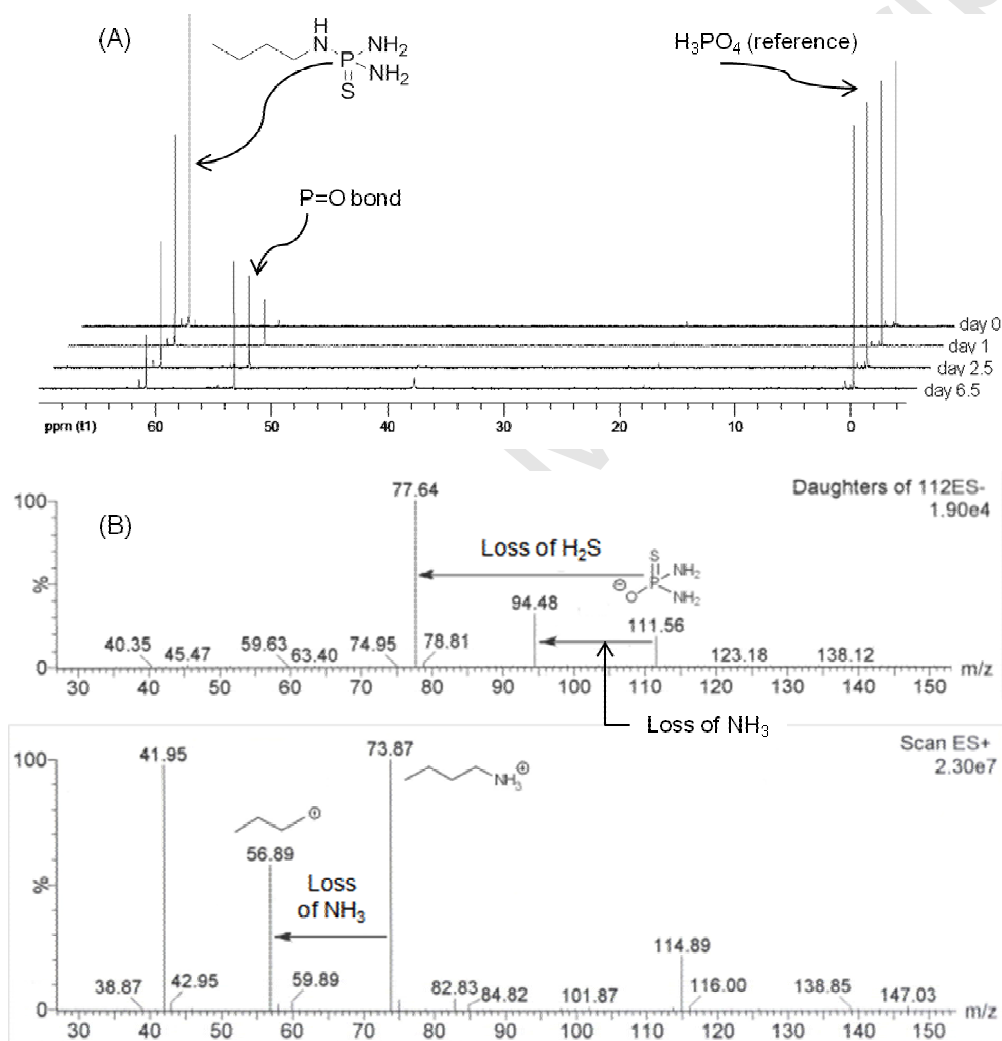
### 186 **3. Results and discussion**

187 Before managing formulations with polysaccharides, a simple method for monitoring  
188 degradation of NBPT, solubilized in a solvent, under acidic conditions was developed. While  
189 some analysis were already proposed (Abraham, Benson & Jardine, 1983; Douglass &  
190 Hendrickson, 1991), NMR data, and more especially  $^{31}\text{P}$  NMR in the case of phosphorous-  
191 containing compounds, offers the opportunity to also give structural data of resulting products  
192 (Fig. 2). In order to mimic acidic soils, this study was therefore performed in an acetate buffer  
193 at pH 5.5 over one week. It was firstly observed that the intensity of the initial signal at nearly  
194 60 ppm disappeared in favor of another one at 53 ppm. Secondly, no more NBPT could be  
195 detected after one week in this medium. Moreover, the high field chemical shift  
196 corresponding to the newly formed compound indicated a break of at least one P-N linkage,  
197 substituted by a P-O bond. This result was subsequently complemented and corroborated by a  
198 high resolution mass spectrometry (HRMS) analysis (Fig. 2). Indeed, two peaks at  $m/z$  111.56  
199 and 73.87 appeared, thus demonstrating the apparition of diamoniphosphoric acid (DATP)  
200 and *n*-butylamine, respectively. This showed the favored cleavage between the P atom and the  
201 N one connected to the butyl chain, both P-NH<sub>2</sub> linkages remaining stable. Moreover, under  
202 the conditions used, no NBPTO was observed. That means that the P=S bond is stable under  
203 conditions used and that S/O exchange occurs only in soils, probably thanks to bacterial

204 activity. Finally, the monitoring of the degradation of NBPT over one week allowed us to  
 205 show that it followed a first order kinetics at pH 5.5 ( $k = 2.2 \times 10^{-6} \pm 0.8 \times 10^{-6} \text{ s}^{-1}$ ,  $n = 15$ ; See  
 206 Supplementary materials).

207

208



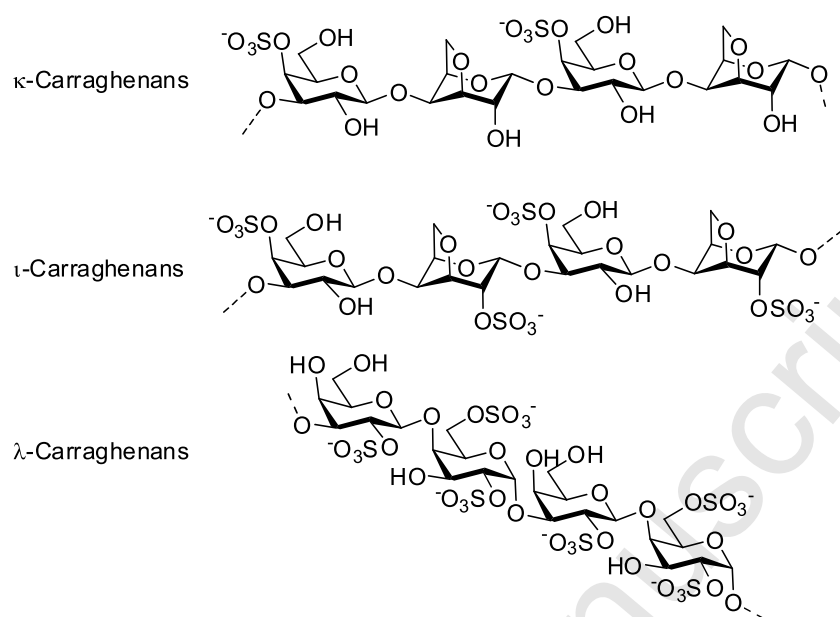
209

210 **Fig. 2.** (A)  $^{31}\text{P}$  NMR monitoring and (B) HRMS analysis of the degradation of NBPT at pH

211 5.5.

212

213 With this analytical method in hand, it was further planned to build the inhibitor around an  
214 environment conducive to its preservation in acidic media. However, NBPT must remain free  
215 in order to emerge this background, and be gradually released to exert the desired biological  
216 function on urease. On the basis of conformational and physico-chemical adaptability of  
217 polysaccharides, we first studied carraghenans (Fig. 3), well known carbohydrates extracted  
218 from red seaweeds *Rhodophyceae*.  $\kappa$ - and  $\iota$ -Carraghenans are characterized by sequence of D-  
219 galactopyranosyl (D-Galp) residues having alternatively  ${}^4C_1$  and  ${}^1C_4$  conformations, the latter  
220 resulting from a 3,6-anhydro-bridge, and they can adopt double strand conformations.  $\lambda$ -  
221 Carraghenans are also built of sulfated D-Galp entities, but differ from the latter families by  
222 the absence of anhydro-bridge and by the number of anionic groups, thus resulting in tertiary  
223 ribbon structure (Cui, 2005 ). Despite their charges, carraghenans are able to interact with  
224 small volatile compounds (Hambleton, Fabra, Debeaufort, Dury-Brun & Voilley, 2009). We  
225 thus hypothesized that it could possibly interact either with the butyl chain of NBPT, even  
226 weakly, or also with the more polar phosphoramidate part of the inhibitor, or both functions. On  
227 this basis, the studied inhibitor was dissolved in saturated solution of  $\kappa$ -,  $\iota$ - or  $\lambda$ -carraghenans  
228 buffered at pH 5.5. Its degradation was monitored by  ${}^{31}P$  NMR and compared to that of NBPT  
229 formulated as Agrotain. Unfortunately, no protecting effect was observed and the  
230 disappearance of NBPT in carbohydrate solutions over a period of 6 days followed a kinetic  
231 comparable with that of commercially available formulation (See Supplementary Materials).



232

233 **Fig. 3.** Primary structures of  $\kappa$ -,  $\iota$ -, and  $\lambda$ -carraghenans.

234

235 In a second stage, alginates were also tried to potentially carry the target thiophosphoramidate.

236 As carraghenans, they present anionic groups, i.e. carboxylates, but not sulfates. We thus

237 anticipated that carboxylate groups in alginates could quench some protons from the media,

238 thus preventing NBPT hydrolysis. Moreover, L-guluronic entities, but not D-mannuronic

239 residues, may form cavities which can accommodate divalent cations such as calcium (Fig. 4).

240 Thus, in the presence of calcium salts, the polyguluronic chains gather around cations,

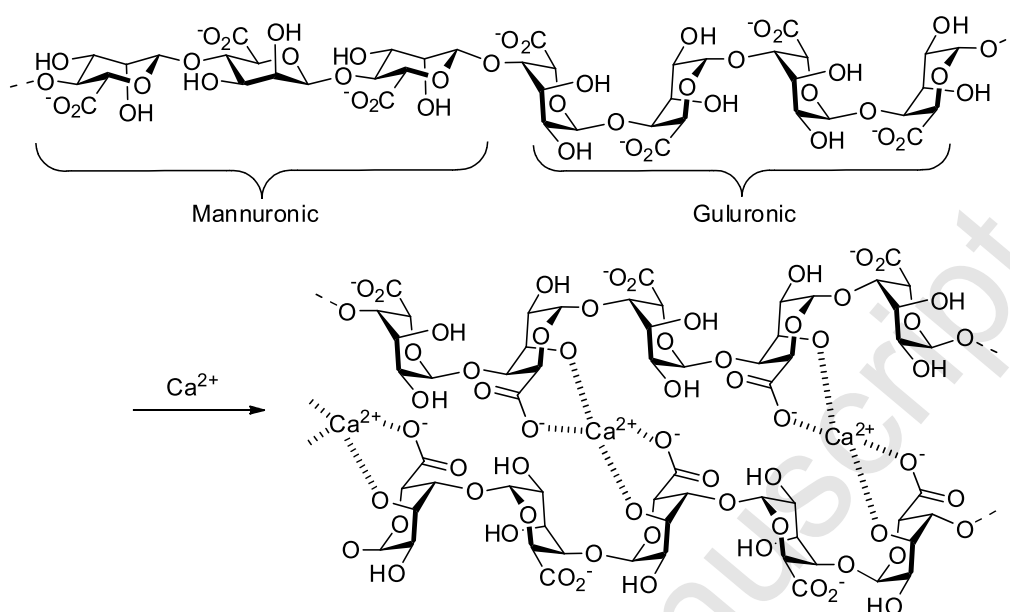
241 creating a network of channels with some facial amphiphilicity. We have however observed

242 no significant improvement of the formulations, using alginates alone or these

243 polysaccharides in the presence of calcium salts to provide beads. The latter cannot retain

244 efficiently the NBPT molecules since they diffuse into the aqueous solution within only a few

245 minutes.

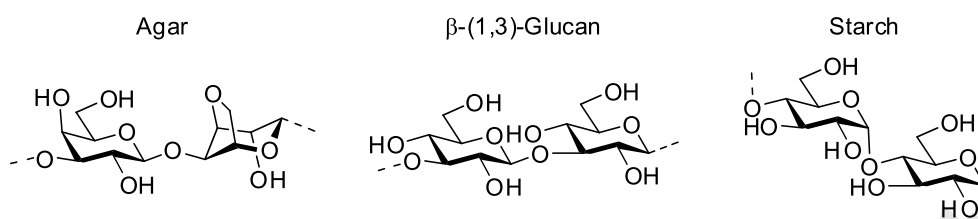


246

247 **Fig. 4.** A conformational model for alginates.

248

249 These results led us to turn to neutral polysaccharides. Agar present tertiary conformations  
 250 close to that of  $\kappa$ - and  $\iota$ -carraghenans; laminarines, also called  $\beta$ -(1,3)-glucans, can organize  
 251 in triple helix, and was already used to guide the synthesis of hydrophobic nanomaterials  
 252 (Lehtovaara & Gu, 2011; Young, Dong & Jacobs, 2000); starch was also selected since it is  
 253 well established that it can encapsulate iodine, lipids, surfactants by formation of inclusion  
 254 complexes (Heinemann, Escher & Conde-Petit, 2003) (Fig. 5). Once again, no stabilization  
 255 was obtained using both agar and laminarines. Nevertheless, a slight improvement was  
 256 observed using starch previously unstructured in a boiling aqueous solution. Indeed, 60% of  
 257 NBPT remained unchanged after nine days while Agrotain was decomposed at 60% over the  
 258 same period. We hypothesize that this positive effect can be assigned to the presence of  
 259 helices that prefigure maltocyclodextrins.

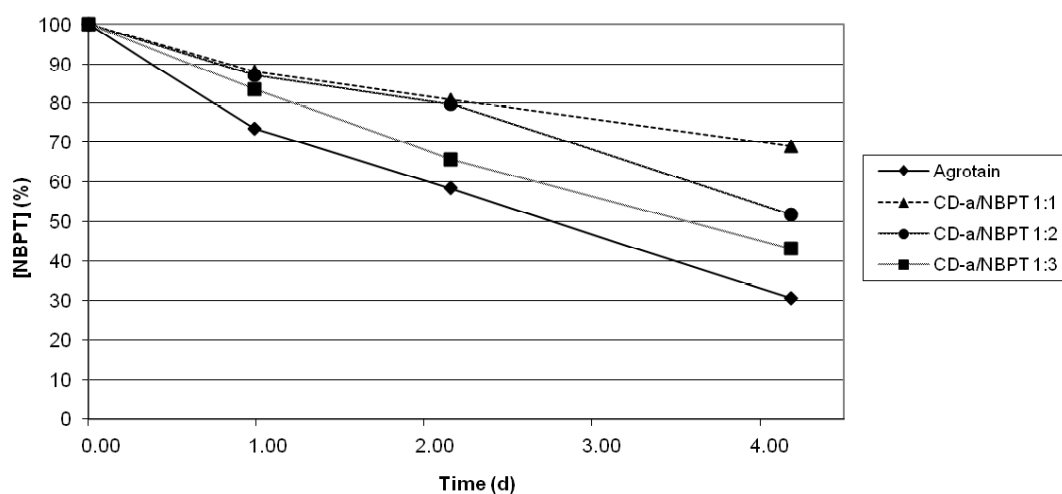


260

261 **Fig. 5.** Main skeleton for agar,  $\beta$ -(1,3)-glucans and starch.

262

263 Therefore, this result encouraged us to use pure cyclodextrins instead of polysaccharides,  
 264 since they are commonly used in the pharmaceutical industry but also in the food and plant  
 265 health fields (Shen, Yang, Wang, Zhou & Chen, 2012). We expected that the lipophilic cavity  
 266 of a cyclodextrin interact with the NBPT butyl chain to form a complex able to protect the  
 267 inhibitor from surrounding acidic medium. It was firstly easily established that the more  
 268 suitable cyclodextrin likely to favorably interact with NBPT was the smaller one containing  
 269 six glucosyl residues ( $\alpha$ -cyclodextrin, CD- $\alpha$ ) (Fig. given in Supplementary Material).  
 270 Secondly, the optimal molar ratio CD- $\alpha$ /NBPT was experimentally determined as 1:1, and  
 271 Fig. 6 shows that at least 70% of NBPT remained stable after four days at pH 5.5, while 60%  
 272 of NBPT from Agrotain formulation was hydrolyzed under the same conditions. This  
 273 corresponds to an increase of 75% stability

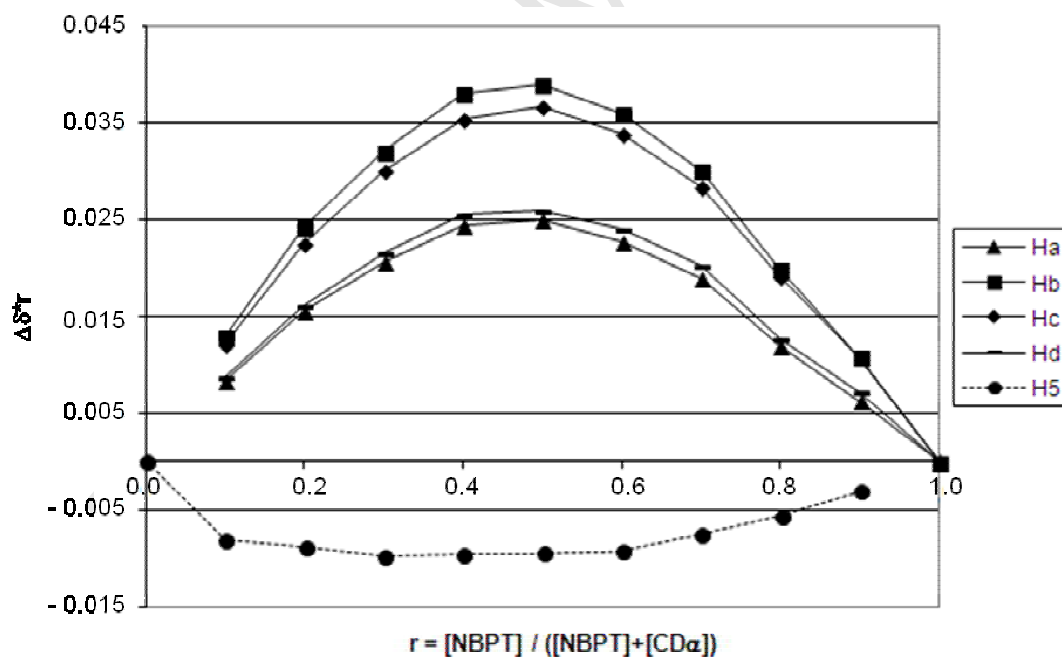


274

275 **Fig. 6.** Stabilization of NBPT according to the molar ratio CD- $\alpha$ /NBPT.

276

277 Finally, the precise nature of the suspected complex was determined by  $^1\text{H}$  NMR thanks to the  
 278 Job's plot method (Marçon, Mathiron, Pilard, Lemaire-Hurtel, Dubaele & Djedaini-Pilard,  
 279 2009). This approach is based on the correlation between the complex concentration in  
 280 solution and the chemical shift variations of protons in both the host (CD- $\alpha$ ) and the guest  
 281 (NBPT; see Supplementary Material). More particularly, the complex concentration is  
 282 proportional to the  $\Delta\delta_X \cdot r_X$  where  $\Delta\delta_X$  corresponds to the chemical shift variation for proton X  
 283 and  $r_X$  is the ratio  $[\text{NBPT}]/([\text{NBPT}]+[\text{CD-}\alpha])$ . Because of low variations observed from  
 284 protons of CD- $\alpha$ , the Job graphic was drawn from signals corresponding to the butyl chain  
 285 (Fig. 7). A 1:1 complex was thus unambiguously established.



286

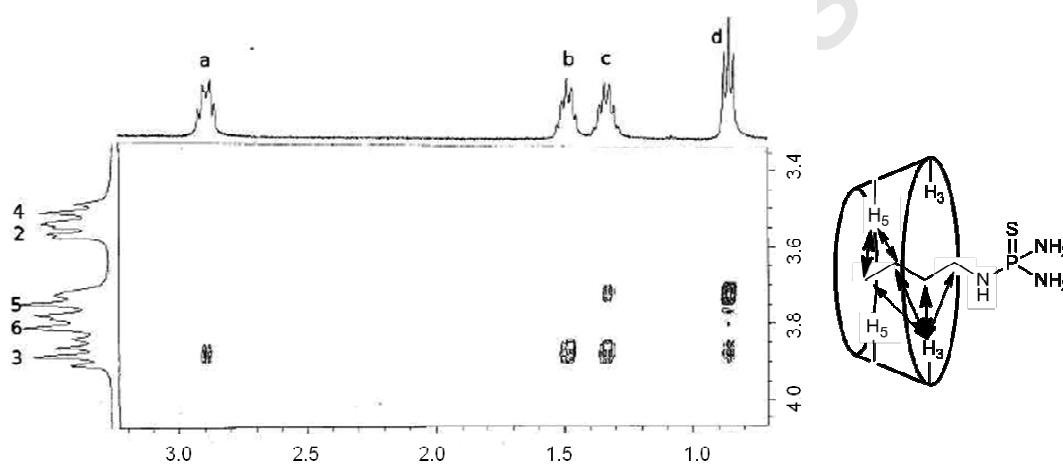
287 **Fig. 7.** Determination of the CD $\alpha$ /NBPT according to the Job's plot method (Marçon,  
 288 Mathiron, Pilard, Lemaire-Hurtel, Dubaele & Djedaini-Pilard, 2009). Ha-Hd are for the alkyl  
 289 chain of NBPT and H5 for the CD $\alpha$ .



290

291 Moreover, this study was complemented by a T-ROESY NMR analysis (Fig. 8) in order to  
 292 identify precise molecular interactions between the inhibitor and its ligand. The resulting  
 293 spectrum clearly established that H-5 of the maltocyclodextrin are close to the ethyl terminal  
 294 group of the alkyl chain of NBPT, and that H-3 of the former, exposed from the bigger crown,  
 295 could interact with all protons of the butyl chain, but more particularly with the core CH<sub>2</sub>.

296



297

298 **Fig. 8.** Focus on NMR T-ROESY spectrum of the inclusion complex CD $\alpha$ /NBPT.

299

300 Finally, in order to characterize the dynamic of the equilibrium, the association constant  $K_a$   
 301 was determined according to the Benesi-Hildebrand method, applied on <sup>1</sup>H NMR signals  
 302 corresponding to the butyl chain of the NBPT (Benesi & Hildebrand, 1949). Using a large  
 303 excess of CD- $\alpha$  and a constant concentration in NBPT, all resulting straights corresponding to  
 304 the protons of NBPT gave a value of  $94 \pm 4 \text{ M}^{-1}$ , slightly in favor of the formation of the  
 305 complex.

306

307 Having these physicochemical data in hands, the inhibitory activity of the established more  
308 stable complex was evaluated *in vitro* at pH 7, under optimal conditions for the activity of  
309 Jack bean urease. A value of 1.5  $\mu\text{M}$  was obtained, i.e. 15 times higher than the  $\text{IC}_{50}$  of free  
310 NBPT (100 nM). As expected, ligation of NBPT by the  $\alpha$ -cyclodextrin was accompanied by a  
311 significant decrease of inhibiting property, but this lower activity has to be put into  
312 perspective with increased stability over time at pH 5.5 and with the significant simplicity of  
313 the formulation. To conclude this study, the 1:1 inclusion complex as well as solutions of CD-  
314  $\alpha$ /NBPT with excess cyclodextrin (ratio: 2:1 and 5:1) were deposited on an acidic soil.  
315 Monitoring of the urea concentration showed that this simple new formulation had similar  
316 efficiency than that of Agrotain (See Supplementary Material). Since activity *in vitro* was  
317 more interesting for the complex, limitations could be attributed to the bacterial activity from  
318 the soil.

319

#### 320 **4. Conclusion**

321 Our study is part of the current trend to formulate bioactive compounds, especially in the field  
322 of agriculture, as simple as possible using a limiting number of additives, obviously  
323 environmentally friendly. In this context, a new formulation of NBPT, a urease inhibitor  
324 widely used as fertilizer, was searched with the main goal of increasing its stability over time  
325 under acidic conditions. Our approach was based on molecular characteristics of this  
326 thiophosphotriamide since it presents a polar phosphoramidate function and a lipophilic butyl  
327 chain. Therefore, a panel of polysaccharides, neutral or charged, with different  
328 physicochemical properties, was tested. Nevertheless, the best results were obtained with the  
329  $\alpha$ -cyclodextrin used as additive. The 1:1 inclusion complex was fully characterized and  
330 presented moderate inhibition activity (1.5  $\mu\text{M}$ ) but a significant increased stability at pH 5.5  
331 compared to that of commercial Agrotain (75% after 4 days). The resulting inclusion complex

332 is a stable solid which is highly hydrosoluble. Application of solutions in an acidic soil finally  
333 showed that inclusion complex of NBPT in cyclodextrin- $\alpha$  had similar inhibition efficiency  
334 than Agrotain.

335

### 336 **Aknowledgements**

337 DP is really grateful to the Région Bretagne, Ille et Vilaine, and Rennes Métropole for PhD  
338 fellowship. The present results are part of the AZOSTIMER project, awarded by the Pôle de  
339 Compétitivité Mer Bretagne and supported by the TIMAC Agro International (Groupe  
340 Roullier). The authors thank Jean-Paul Guégan (ENSCR) for NMR recording.

341

### 342 **References**

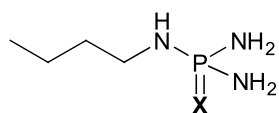
- 343 Abraham, R. T., Benson, L. M., & Jardine, I. (1983). Synthesis and pH-dependant stability of purine-6-  
344 sulfenic acid, a putative reactive metabolite of 6-thiopurine. *J. Med. Chem.*, *26*, 1523-1526.
- 345 Benesi, H. A., & Hildebrand, J. H. (1949). A spectrophotometric investigation of the interaction of  
346 iodine with aromatic hydrocarbons. *J. Am. Chem. Soc.*, *71*, 2703-2707.
- 347 Cui, S. W. (2005). *Food carbohydrates : Chemistry, physical properties, and applications*.
- 348 Domínguez, M. J., Sanmartín, C., Font, M., Palop, J. A., San Francisco, S., Urrutia, O., Houdusse, F., &  
349 García-Mina, J. M. (2008). Design, synthesis, and biological evaluation of phosphoramidate derivatives  
350 as urease inhibitors. *J. Agric. Food Chem.*, *56*, 3721-3731.
- 351 Douglass, E. A., & Hendrickson, L. L. (1991). HPLC method for the analysis of the urease inhibitor N-  
352 (n-butyl)thiophosphoric triamide and its metabolites. *J. Agric. Food Chem.*, *39*, 2318-2321.
- 353 Font, M., Dominguez, M.-J., Sanmartin, C., Palop, J. A., San-Francisco, S., Urrutia, O., Houdusse, F., &  
354 García-Mina, J. M. (2008). Structural Characteristics of Phosphoramidate Derivatives as Urease  
355 Inhibitors. Requirements for Activity. *J. Agric. Food Chem.*, *56*(18), 8451-8460.
- 356 Hambleton, A., Fabra, M.-J., Debeaufort, F., Dury-Brun, C., & Voilley, A. (2009). Interface and aroma  
357 barrier properties of iota-carrageenan emulsion-based films used for encapsulation of active food  
358 compounds. *J. Food Eng.*, *93*(1), 80-88.
- 359 Heinemann, C., Escher, F., & Conde-Petit, B. (2003). Structural features of starch-lactone inclusion  
360 complexes in aqueous potato starch dispersions : the role of amylose and amylopectin. *Carbohydr.*  
361 *Polymers*, *21*, 159-168.
- 362 Kolc, J. F., Swerdloff, M. D., Rogic, M. M., Hendrickson, L. L., & Van Der Puy, M. (1985). *U.S. Patent*  
363 *4,530,714*.
- 364 Lehtovaara, B. C., & Gu, F. X. (2011). Pharmacological, structural, and drug delivery properties and  
365 applications of 1,3-beta-glucans. *J. Agric. Food Chem.*, *59*, 6813-6828.
- 366 Leinker, M., Reinhardt-Hanisch, A., Hartung, E., & von Borell, E. (2005). Reducing ammonia emissions  
367 by using urease inhibitors. *Landtechnik*, *6*, 342-343.
- 368 Marçon, F., Mathiron, D., Pilard, S., Lemaire-Hurtel, A. S., Dubaele, J. M., & Djedaini-Pilard, F. (2009).  
369 Development and formulation of a 0.2% oral solution of midazolam containing  $\alpha$ -cyclodextrin. *Int. J.*  
370 *Pharm.*, *79*, 244-250.

- 371 Nelson, D. W., & Huber, D. (1992). *Nitrification inhibitors for corn production*. National Corn Hand-  
372 book
- 373 Pro, D., Arkoun, M., Huguet, S., Daniellou, R., Nugier-Chauvin, C., Morvan, J., Wolbert, D., Ourry, A.,  
374 Yvin, J.-C., & Ferrières, V. (2012). Impact of glycosylation on physico-chemical and biological  
375 properties of nitrification inhibitors. *Tetrahedron*, *68*, 7095-7102.
- 376 Shen, C., Yang, X., Wang, Y., Zhou, J., & Chen, C. (2012). Complexation of capsaicin with  $\beta$ -  
377 cyclodextrins to improve pesticide formulations: effect on aqueous solubility, dissolution rate,  
378 stability and soil adsorption. *J. Incl. Phenom. Macrocycl. Chem.*, *72*(3-4), 263-274.
- 379 Subbarao, G. V., Ito, O., Sahrawa, K. L., Berry, W. L., Nakahara, K., Ishikawa, T., Watanabe, T.,  
380 Suenaga, K., Rondon, M., & Rao, I. M. (2006). Scope and strategies for regulation of nitrification in  
381 agricultural systems - Challenges and opportunities. *Crit. Rev. Plant Sci.*, *25*, 303-335.
- 382 Sumner, J. B. (1926). The isolation and crystallization of the enzyme urease. *J. Biol. Chem.*, 435-441.
- 383 Trenkel, M. E. (2010). *Slow- and controlled-release and stabilized fertilizers. An option for enhancing*  
384 *nutrient use efficiency in agriculture*. International fertilizer industry association.
- 385 Young, S.-H., Dong, W.-J., & Jacobs, R. R. (2000). Observation of a partially opened triple-helix  
386 conformation in 1,3-beta-glucan by fluorescence resonance energy transfer spectroscopy. *J. Biol.*  
387 *Chem.*, *275*, 11874-11879.
- 388 Zaman, M., Nguyen, M. L., Blennerhassett, J. D., & Quin, B. F. (2008). Reducing NH<sub>3</sub>, N<sub>2</sub>O and NO<sub>3</sub> -N  
389 losses from a pasture soil with urease or nitrification inhibitors and elemental S-amended  
390 nitrogenous fertilizers. *Biol. Fertil. Soils*, *44*, 693-705.
- 391
- 392
- 393
- 394

394

## Captions

395

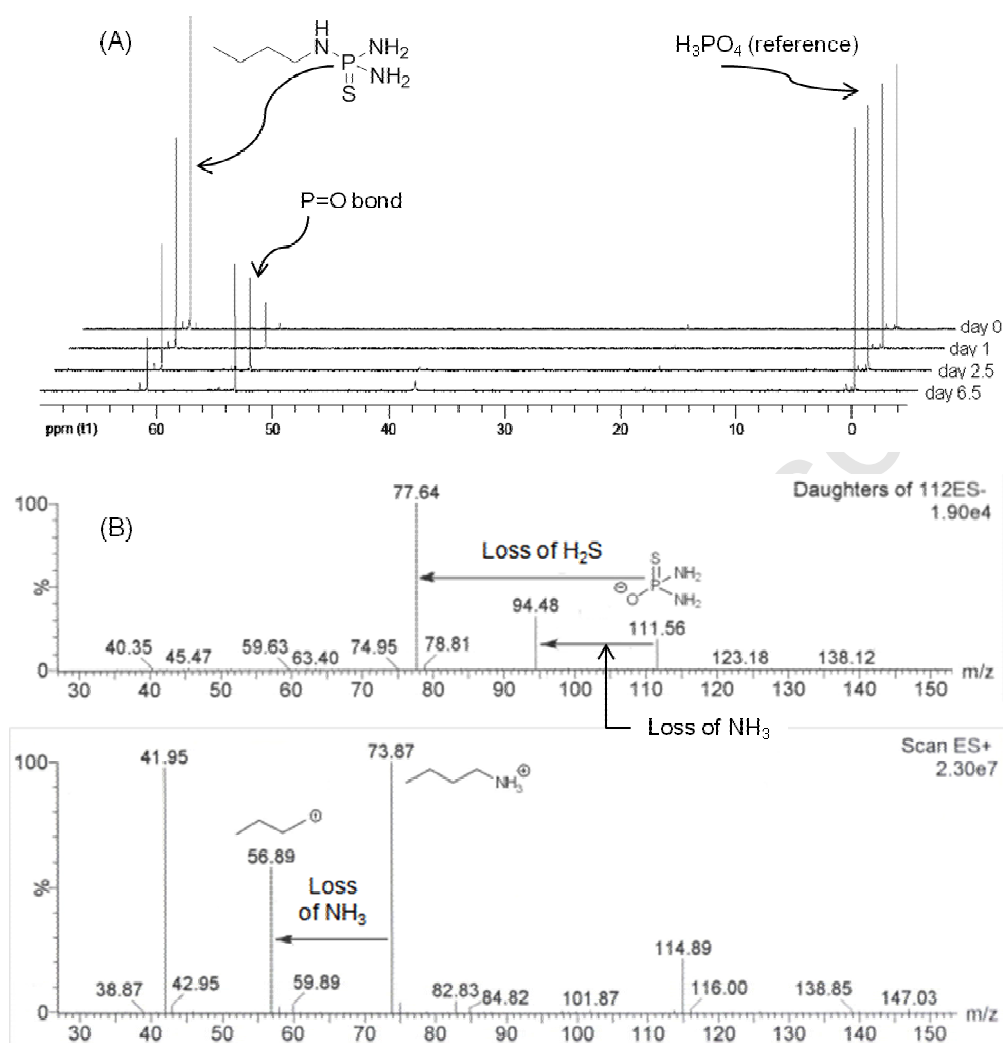
**Phosphotriamide**

396

**X=S:** *N*-Butyl-thiophosphotriamide (NBPT)**X=O:** *N*-Butyl-phosphotriamide (NBPTO)397 **Fig.1.** Structure of the studied urease inhibitor NBPT.

398

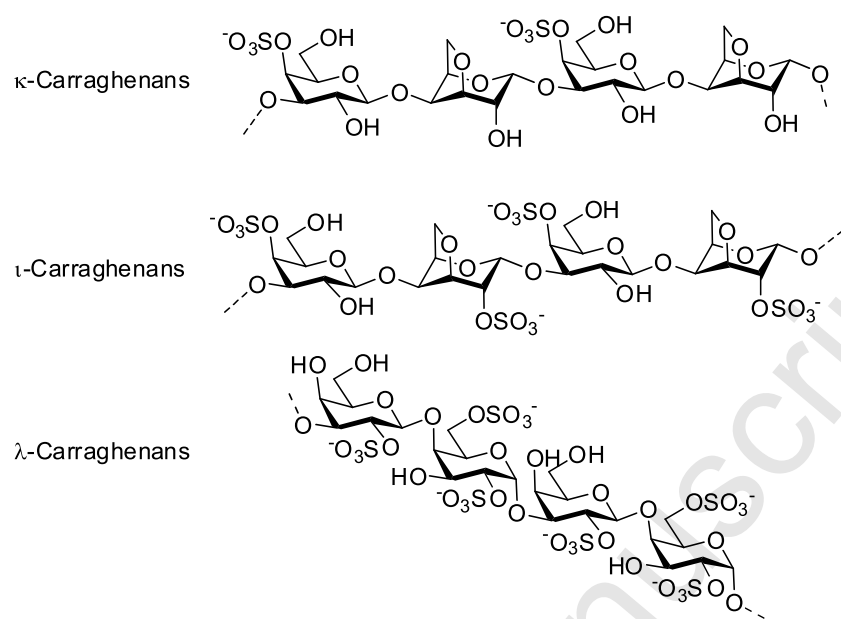
Accepted Manuscript



398

399 **Fig. 2.** (A)  $^{31}\text{P}$  NMR monitoring and (B) High Resolution Mass Spectrometry analysis of the  
 400 degradation of NBPT at pH 5.5.

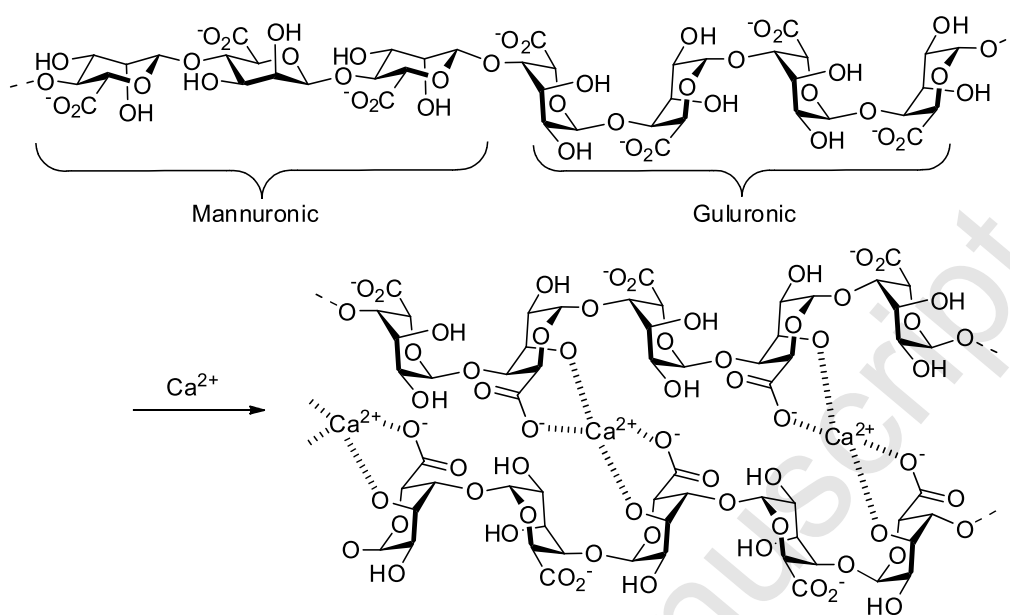
401



401

402 **Fig. 3.** Primary structures of  $\kappa$ -,  $\iota$ -, and  $\lambda$ -carrageenans.

403

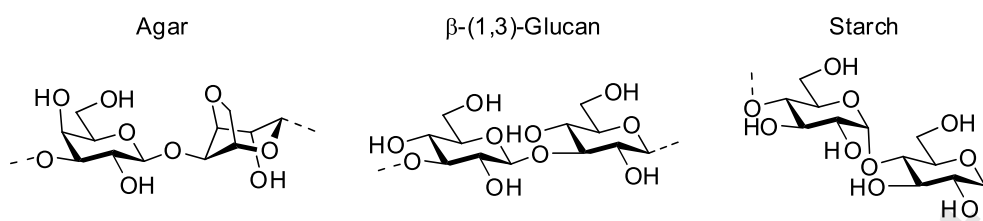


403

404 **Fig. 4.** A conformational model for alginates.

405



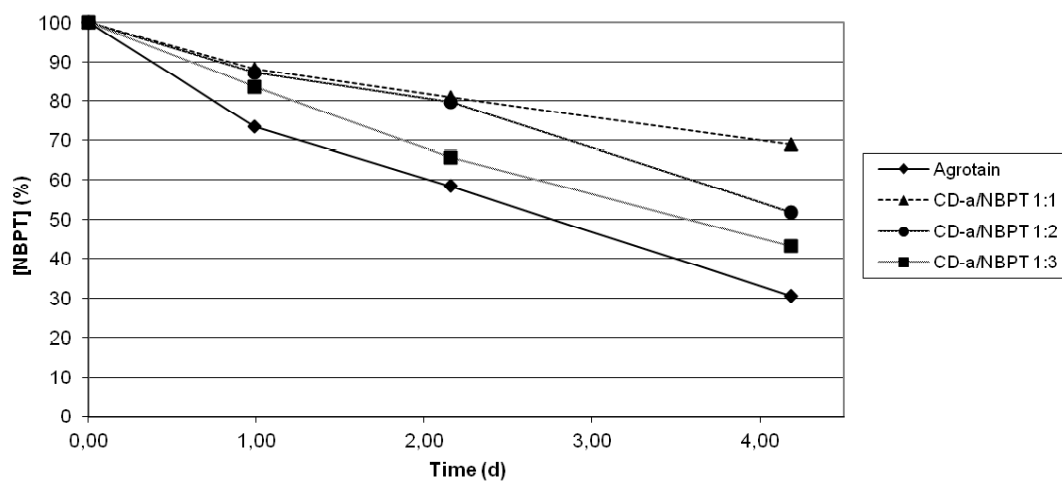


405

406 **Fig. 5.** Main skeleton for agar,  $\beta$ -(1,3)-glucans and starch.

407

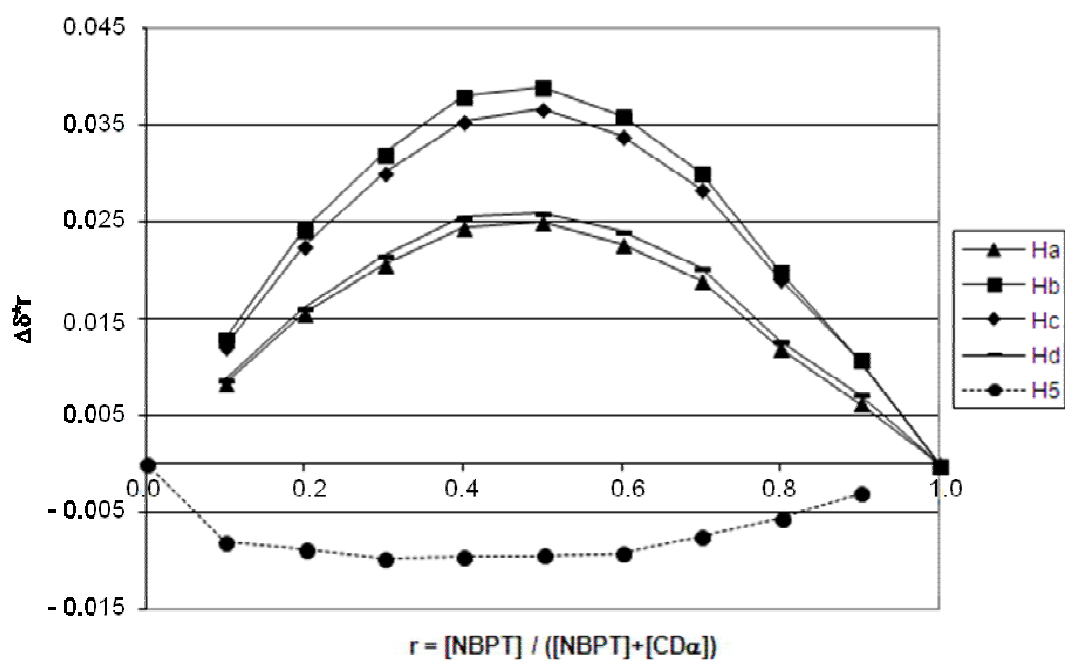
Accepted Manuscript



407

408 **Fig. 6.** Stabilization of NBPT according to the molar ratio CD- $\alpha$ /NBPT.

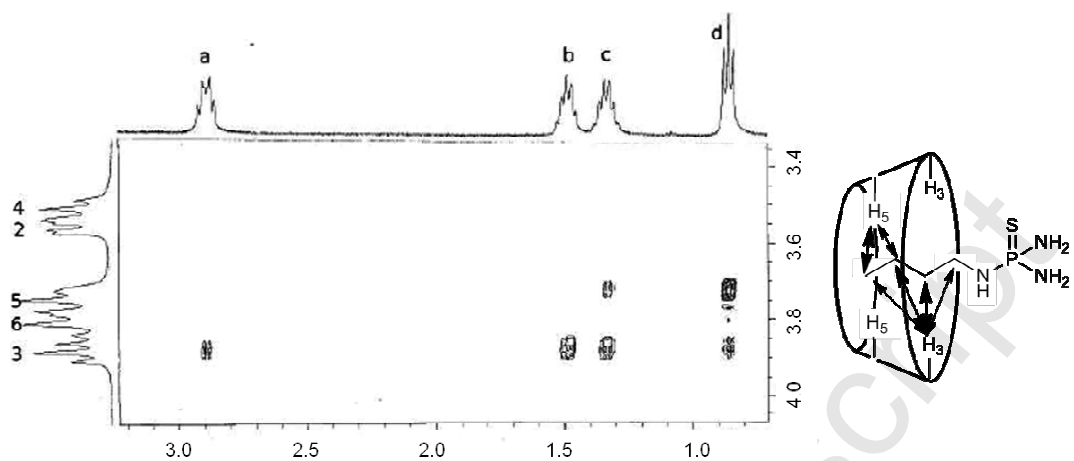
409



409

410 **Fig. 7.** Determination of the  $CD\alpha/NBPT$  according to the Job's plot method (Marçon,  
 411 Mathiron, Pilard, Lemaire-Hurtel, Dubaele & Djedaini-Pilard, 2009). Ha-Hd are for the alkyl  
 412 chain of NBPT and H5 for the  $CD\alpha$ .

413



413

414 **Fig. 8.** Focus on NRM T-ROESY spectrum of the inclusion complex CD $\alpha$ /Nzz

415

416