

Journal Article

The interfacial, emulsification and encapsulation properties of hydrophobically modified inulin

Kokubun, S., Ratcliffe, I. and Williams, P

This article is published by Elsevier. The definitive version of this article is available at:
<https://www.sciencedirect.com/science/article/pii/S0144861718303989>

Recommended citation:

Kokubun, S., Ratcliffe, I. and Williams, P (2018) 'The interfacial, emulsification and encapsulation properties of hydrophobically modified inulin', *Carbohydrate Polymers*, vol 194, pp.18-23. doi: 10.1016/j.carbpol.2018.04.018.

1 **The interfacial, emulsification and encapsulation properties of hydrophobically**
2 **modified inulin**

3

4 **S. Kokubun, I. Ratcliffe and P.A. Williams**

5

6 Centre for Water Soluble Polymers, Wrexham Glyndwr University, Plas Coch, Mold Road,
7 Wrexham, LL11 2AW, United Kingdom

8

9

10

11 Corresponding author: Professor Peter A. Williams, Centre for Water Soluble Polymers,
12 Glyndwr University, Plas Coch, Mold Road, Wrexham, LL11 2AW, United Kingdom

13 Telephone: +44 1978 293083

14 Email: williamspa@glyndwr.ac.uk

15

16

17 **Key words:**

18 inulin, alkenyl succinic anhydrides, critical aggregation concentration, interfacial properties,
19 emulsion stabilisation, encapsulation

20

21

22

23

24

25

26

27

28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66

ABSTRACT

Octenyl- and dodecenyl succinic anhydride derivatives (OSA- and DDSA-) of inulin have been synthesised and their solution and interfacial properties have been determined and compared to a commercially available alkylated inulin, Inutec SP1. All samples formed micellar aggregates in solution above a critical concentration (critical aggregation concentration) and were able to 'dissolve' a hydrophobic dye. They were also able to form stable oil-in-water (O/W) emulsions as assessed by measurements of their droplet size as a function of time. DDSA-inulin with a high degree of substitution was found to be effective at encapsulating beta carotene using the solvent evaporation method which yielded a solid which dissolved readily in simulated gastric fluid. The results confirm the potential application of these materials in a number of areas including, drug delivery, pharmaceuticals, nutraceuticals, cosmetics and personal care.

67

68 INTRODUCTION

69

70 Inulin is a polyfructan and is obtained commercially from chicory. It consists of β 2,1 fructose
71 chains, with degrees of polymerisation ranging between 2 and 60, which terminate with a
72 glucose residue. It is classed as a type of dietary fibre because it is not absorbed in the
73 stomach or small intestine but is degraded by bacteria in the colon to form short-chain fatty
74 acids which have health benefits. There has been considerable interest in recent years in the
75 derivatisation of inulin to form a range of speciality chemicals (Stevens, Merigii & Booten
76 2001). Inutec SP1 is a hydrophobically modified inulin derivative which is produced
77 commercially by reaction of inulin with dodecyl isocyanate in an aprotic solvent to yield inulin
78 dodecyl carbamate (Stevens et al., 2001; Exerowa et al., 2007; 2009a, b; Gotchev et al., 2007;
79 Nestor et al., 2007). It has a molar mass of about 5000 g/mol (Exerowa et al., 2009b; Nestor
80 et al., 2005, 2007, 2008) and is used in a variety of industrial sectors for the stabilisation of
81 emulsions and dispersions..

82 A number of other hydrophobic derivatives have been synthesised by reaction of inulin in
83 organic solvents with fatty acid chlorides, methyl esters, alkyl epoxides, and alkyl isocyanates
84 (Stevens, Merigii & Booten, 2001; Exerowa et al., 2009; Khristov & Czarnecki, 2010; Gochev
85 et al., 2011). A 'green' approach to modification has been developed by Morros et al. (2010,
86 2011), Kokubun, Ratcliffe & Williams (2013; 2015) and Han, Ratcliffe and Williams (2015) who
87 have recently reported the modification of inulin using alkenyl succinic anhydrides in water
88 under mild alkaline conditions to produce inulin derivatives with varying alkenyl chain length
89 and varying degrees of substitution. It was confirmed that these surfactants adsorbed at the
90 air-water interface and that they formed micellar-like aggregates in solution above a critical
91 concentration.

92 The ability of hydrophobically modified inulin derivatives to form micellar aggregates has
93 attracted much interest in recent years. Muley et al. (2016), for example, used Inutec SP1 for
94 the encapsulation and controlled release of the anti-cancer drug, paclitaxel. Encapsulation
95 was achieved using both the 'thin film hydration' and 'solvent evaporation' methods and they
96 demonstrated through dynamic light scattering and transmission electron microscopy studies
97 that near spherical drug-loaded micellar aggregates of ~250nm were produced. Other groups
98 have also used hydrophobic derivatives for encapsulation of active compounds within micellar-
99 like structures. For example, Di Prima et al. (2017) synthesised an amine derivative which was
100 further modified to incorporate retinoic acid to yield mucoadhesive micelles with enhanced
101 transcorneal permeation properties while Mandracchia et al. (2017) produced derivatives
102 containing both vitamin E and biotin capable of forming micelles for potential application as
103 long-circulating carriers for receptor-mediated targeted drug delivery. In another approach,

104 Lopez-Molina et al. (2015) synthesised a cinnamoylated inulin derivative by reaction with
105 cinnamic acid chloride in pyridine and produced microspheres for the targeted delivery of
106 drugs to the colon.

107 The purpose of the present study was to synthesise octenyl and dodecenyl succinic anhydride
108 derivatives of inulin and to investigate their solution and interfacial properties in comparison
109 with Inutec SP1 and to evaluate their ability to encapsulate water insoluble beta carotene. It is
110 our hypothesis that encapsulation using the anionic succinylated derivatives could have
111 significant benefits in the controlled release of the beta carotene compared to the commercial
112 non-ionic Inutec SP1.

113

114

115 **MATERIALS AND METHODS**

116

117 ***Materials***

118

119 Inulin coded Fibruline® DS2 was supplied by Cosucra and was dried at 70 °C for 24 hours
120 before use. It was found to have a weight average and number average molar mass of 3,760
121 and 3,000 g/mol respectively (Kokubun, Ratcliffe & Williams, 2013). Inutec SP1 was obtained
122 by Beneo Biobased Chemicals and was used as supplied.

123 2-octen-1-yl-succinic anhydride (OSA) and 2-dodecen-1-yl-succinic anhydride (DDSA) were
124 obtained from Aldrich Chemical Co. and were used as received. Medium Chain Triglyceride
125 (MCT) gold oil was obtained from Trec Nutrition UK and was used as supplied. Sudan IV was
126 obtained from the Eastman Kodak Company. Beta carotene Type I synthetic ≥ 93 % (UV)
127 powder was obtained from Sigma-Aldrich Chemie GmbH., and was used as supplied.

128

129

130 **Methods**

131

132 *Synthesis of hydrophobically modified inulin*

133 Hydrophobically modified inulin samples were synthesised in aqueous solution under alkaline
134 conditions using OSA and DDSA and were characterised by nuclear magnetic resonance
135 (NMR) spectroscopy as previously reported (Kokubun, Ratcliffe & Williams, 2013). The
136 samples obtained, namely OSA(1), OSA(2) and DDSA(1) had approximately 1 – 2 alkenyl
137 chains per molecule and a further sample, DDSA(2), had ~5 alkenyl chains per molecule.

138

139 *Critical aggregation concentration*

140 The CAC was determined by the dye solubilisation technique using Sudan IV. 10mg of the
141 dye was added to 10 mL of the OSA-, DDSA- inulins or Inutec SP1 at varying concentrations
142 in deionised water. The samples were mixed at 40 °C overnight and filtered using a Millex-GP
143 0.22 µm filter (Millipore Ireland Ltd.) into disposable UV-grade 10 mm path length cuvettes
144 (CXA-110-0053 from Fisher Scientific Ltd.). The absorbance of the solutions was measured
145 at 510 nm using a Lambda 25 UV/vis Spectrometer PerkinElmer. The CAC was determined
146 as the point at which the absorbance increased.

147

148 *Surface and interfacial tension*

149 The surface tension at the air / water interface and the interfacial tension at ASA-inulin or
150 Inutec SP1 aqueous solution / MCT oil interface were measured at varying concentration at
151 25 °C ± 1 °C using the Du Nouy ring method with a Tensiometer K8 and a 4 cm circumference
152 platinum ring RI 01 from Krüss GmbH. The equilibrium surface and interfacial tensions were
153 plotted as a function of the sample concentration and the CAC was estimated from the change
154 in slope of the plots.

155

156 *Zeta potential*

157 The zeta potential of inulin-coated emulsion droplets was determined at various pH at 25 °C
158 using a Zetasizer Nano ZS (Malvern Instrument Lab, Malvern, UK) equipped with a 5 mw He-
159 Ne laser (λ_0 633 nm) and a digital correlator. Measurements were carried out using a folded
160 capillary cell DTS1060 (Malvern Instrument Lab, Malvern, UK). The cell was washed with
161 ethanol and deionised water several times and dried before measurements. Oil-in-water (O/W)
162 emulsions were prepared by mixing 1.5 g MCT oil with 8.5 g of 2.5% OSA-, DDSA- inulin or
163 Inutec SP1 solution for 3 minutes at 24 000 rpm, using an IKA T25 digital Ultra-Turrax mixer.
164 Two drops of the emulsion were added into 10mL 0.01M NaCl which was filtered with a type
165 GN 0.2 µm filter (Millipore Ireland Ltd) before use. The system was mixed for 30 seconds and
166 the pH was adjusted using 0.1M HCl and 0.1M NaOH. Ten runs were performed for each
167 sample. The data was analysed using the Zetasizer Software 6.20 © 2002-2010 from Malvern
168 Instruments Ltd and the zeta potential was determined from the electrophoretic mobility using
169 the Smoluchowski equation.

170

171

172 *Emulsification properties*

173 O/W emulsions were prepared as above and droplet size measurements were made
174 immediately after emulsion preparation and over a period of 21 days for samples stored at
175 room temperature (25 °C) and at 50 °C using the Mastersizer 2000 (Malvern Panalytical Ltd
176 Malvern, UK). Before measuring the samples, background readings for the instrument were

177 carried out to subtract the ambient light signals from the total scattering received from
178 samples. Two or three drops of the sample were introduced into the dispersion unit containing
179 distilled water. The dispersion unit pump speed was 2000 rpm. The obscuration was between
180 10% and 30%. The refractive index of the dispersing medium and the dispersed particles were
181 1.33 and 1.45 respectively. Measurements were performed in duplicate.

182

183 *Encapsulation*

184 Encapsulation of beta carotene using hydrophobically modified inulin was facilitated using the
185 solvent evaporation method. Approximately 1.0 g of the beta carotene and 5.0 g of the ASA-
186 inulin or Inutec SP1 were added to 70 mL of chloroform and the system was stirred with a
187 magnetic stirrer and then left overnight at room temperature inside a fume cupboard to enable
188 the chloroform to evaporate completely. The solubility of the beta carotene in the resulting
189 solid matrix was determined by preparing a number of samples containing 0.02g of the solid
190 in 10 ml deionised water or simulated gastric fluid and mixing at 37 °C. The simulated gastric
191 fluid was prepared by adding 500 ml 1 M HCl and 10.22 g sodium chloride to 5 L deionised
192 water and stirring with a magnetic stirrer overnight at room temperature to fully dissolve. 3ml
193 of each of the dispersions was taken at various time intervals and filtered using a Millex-GP
194 0.22 µm filter (Millipore Ireland Ltd.) into disposable UV-grade 10 mm path length cuvettes
195 (CXA-110-0053 from Fisher Scientific Ltd.). The absorbance of the solutions was measured
196 at 455 nm using a Lambda 25 UV/vis Spectrometer PerkinElmer.

197

198 .

199

200

201

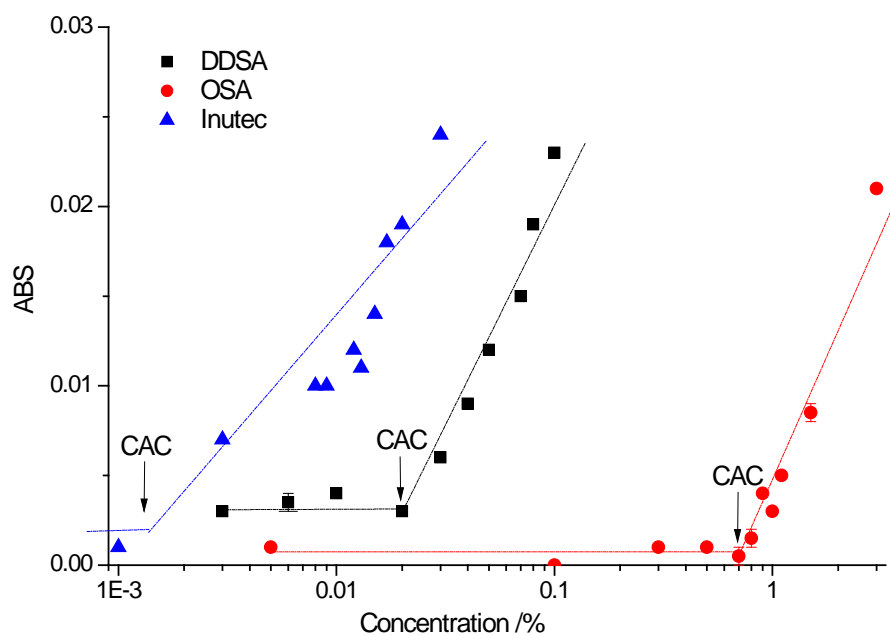
202 **RESULTS AND DISCUSSION**

203

204 *Critical aggregation concentration and interfacial properties*

205 The results obtained for the dye solubilisation studies are presented in Figure 1. It is seen that
206 the absorbance increased at values of 0.70% +/-0.1%, 0.02% +/-005% and 0.002% +/-
207 0.001% for the OSA(1)-inulin, DDSA(1)-inulin and Inutec SP1 respectively.

208



209

210 **Figure 1. Absorbance of OSA(1), DDSA(1)-inulin and Inutec SP1 at varying**
 211 **concentrations in the presence of Sudan IV.**

212

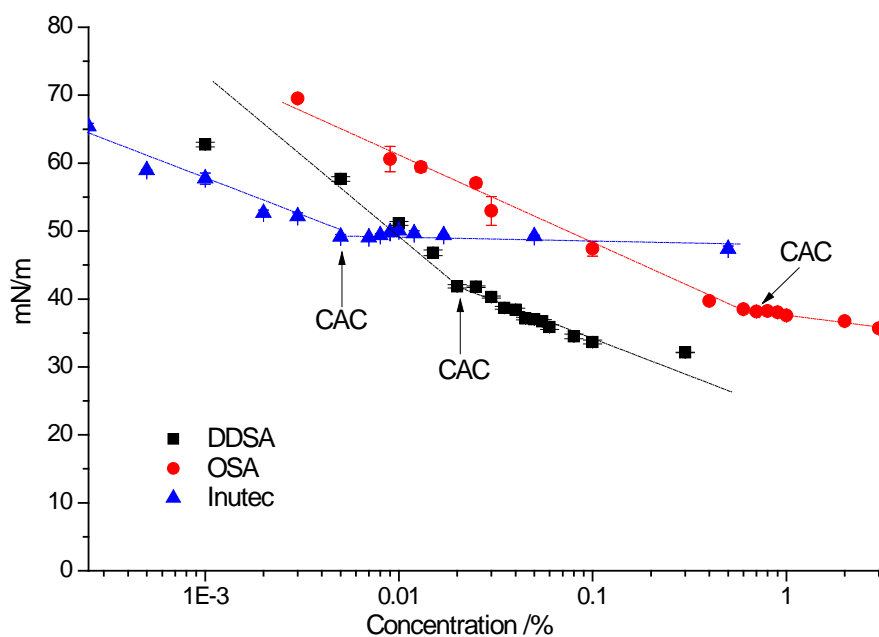
213 The increase is attributed to the formation of micellar-like aggregates through hydrophobic
 214 association of the inulin molecules and the dissolution of the dye in the hydrophobic core as
 215 discussed previously (Kokubun, Ratcliffe & Williams, 2013). The CAC values for the
 216 succinylated samples are expected to be higher than those for Inutec SP1 since the former
 217 have an anionic carboxylate group in the linkage between the alkenyl chains and the inulin
 218 molecule which will tend to inhibit molecular aggregation due to intermolecular electrostatic
 219 repulsions. The CAC is significantly higher for OSA-inulin compared to DDSA-inulin which is
 220 consistent with our previous studies (Kokubun, Ratcliffe and Williams, 2013; 2015; Han,
 221 Ratcliffe and Williams (2015)) and the work of van Kempen et al. (2013a; 2013b; 2014) who
 222 studied the CAC of a series of inulin fatty acid esters with alkyl chain lengths ranging from C8-
 223 C16.

224

225 The surface tension of OSA-inulin, DDSA-inulin and Inutec SP1 samples are plotted as a
 226 function of concentration in Figure 2. The surface tension was found to decrease with
 227 increasing concentration and an inflexion was observed at 0.70% +/-0.08%, 0.020% +/-
 228 0.0025% and 0.005% +/-0.001% respectively for the OSA-inulin, DDSA-inulin and Inutec SP1
 229 and these values closely correspond to the CAC values reported above obtained by dye
 230 solubilisation.

231

232



233 **Figure 2. Surface tension of OSA(1), DDSA(1) -inulins and Inutec SP1 as a function of**
 234 **concentration.**
 235

236
 237
 238 Our studies have shown that the surface tension was 38 mN/m, 42 mN/m and 49 mN/m at the
 239 CAC for the OSA-inulin, DDSA-inulin and Inutec samples respectively. Nestor et al. (2005)
 240 have also determined the surface tension of Inutec SP1 and found that it decreased from ~ 68
 241 to ~45 mN/m with increasing concentration and observed an inflexion at $7 \times 10^{-7} \text{ mol} \cdot \text{dm}^{-3}$ which
 242 is equivalent to 0.00035% assuming an Mw of 5000g/mol. These workers also determined the
 243 CAC by static light scattering and observed an inflexion in the light scattering intensity at a
 244 concentration of $5 \times 10^{-6} \text{ mol} \cdot \text{dm}^{-3}$ (equivalent to 0.0025%) which is in agreement with our
 245 findings. Srinarong et al (2010) also determined the CAC of Inutec SP1 by surface tension
 246 measurements and showed that the surface tension decreased to ~55 mN/m at a
 247 concentration of 0.009% which corresponded to the CAC.

248 The surface excess, $\Gamma / \text{molm}^{-2}$, was calculated from the gradient of the plot of surface tension
 249 as a function of the logarithm of the concentration determined at a concentration just below
 250 the CAC.

251
 252 The area/molecule, A, was calculated using equation (1)
 253

$$\Gamma = -\frac{c}{2RT} \frac{d\gamma}{dc} = -\frac{1}{2RT} \frac{d\gamma}{d \ln c} \quad (1)$$

254
 255
 256 The surface excess and the area per molecule for OSA-, DDSA-inulins and Inutec SP1 are
 257 presented in Table 1.

258
259
260

Table 1. The surface excess and the area/molecule for OSA-, DDSA- inulins and Inutec SP1

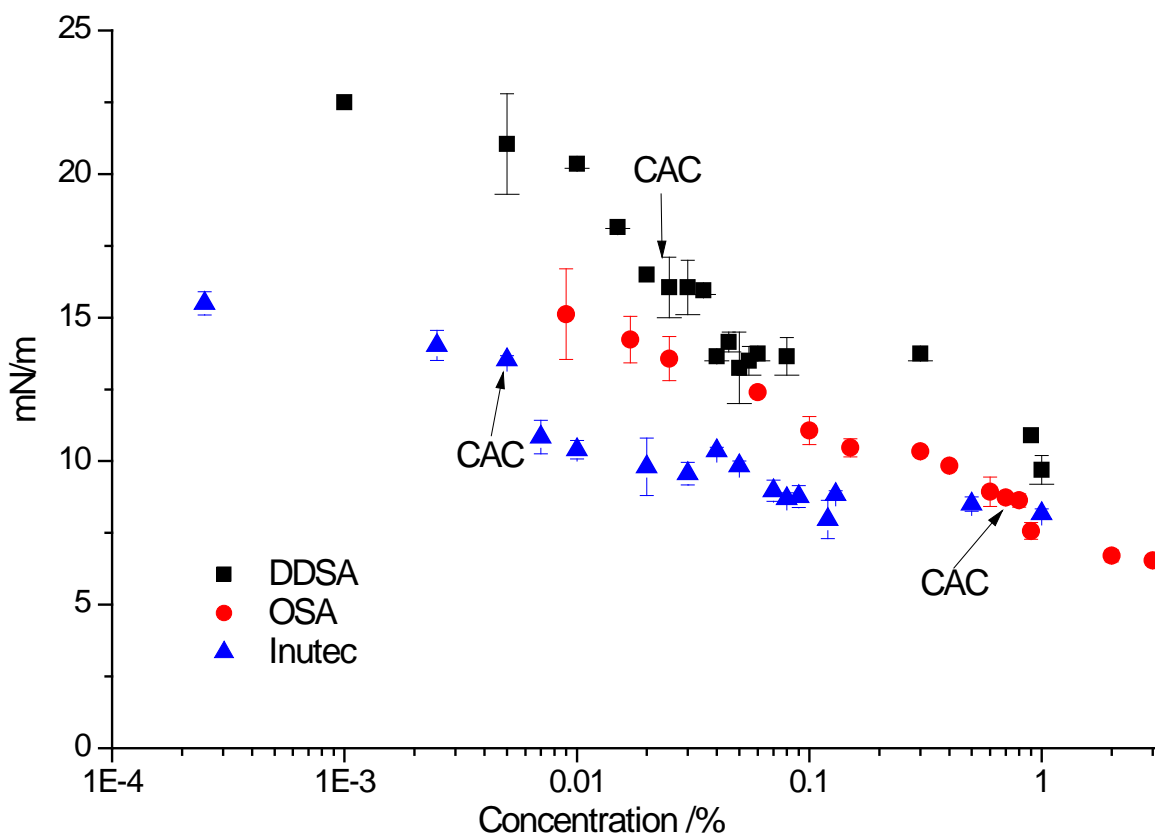
Sample name	$dy/d\ln c/Nm^{-1}$	$\Gamma/molm^{-2}$	$\Gamma^{-1}/ m^2molecule^{-1}$	$\Gamma^{-1}/ nm^2molecule^{-1}$
Surface tension				
OSA-inulin	-0.0132	1.16×10^{-6}	1.44×10^{-18}	1.44
DDSA-inulin	-0.0255	2.23×10^{-6}	7.43×10^{-19}	0.74
Inutec SP1	-0.0108	1.89×10^{-6}	8.78×10^{-6}	0.87

268

269 The value of A from surface tension measurements at the air-water interface was found to be
270 1.44, 0.74 and 0.87nm² for OSA-inulin, DDSA-inulin and Inutec SP1 respectively. Stevens et
271 al. (2001) have reported values of 0.9 nm² for octyl inulin carbamate at the air-water interface.
272 The values for A are significantly larger than those reported for simple sugar-based surfactants
273 based on one or two sugar residues as might be expected due to the higher molar mass of
274 inulin. Soutani et al. (2003) reported values of 0.05 – 0.2 nm² for hydrophobically modified
275 fructose and sucrose surfactants while Garofalakis et al. (2000) reported values of 0.29 – 0.68
276 nm² for surfactants based on xylose, galactose, sucrose and lactose. It is evident that A for
277 the modified inulins will depend on the number of the hydrophobic groups attached to the inulin
278 molecules and to their location along the chain.

279

280 The interfacial tension at the interface between aqueous solutions of OSA-inulin, DDSA-inulin
281 or Inutec SP1 and MCT oil are plotted as a function of concentration in Figure 3 and was found



282 **Figure 3. Interfacial tension of OSA(1), DDSA(1) -inulins and Inutec SP1 at the oil / water**
 283 **interface as a function of concentration.**
 284
 285

286 to decrease as the concentration increased but there was no clear inflexion corresponding to
 287 the CAC values noted above. This is likely to be due to the very heterogeneous nature of the
 288 modified inulin samples. The interfacial tension was found to be 8 mN/m, 16 mN/m and 13
 289 mN/m at the CAC for the OSA-inulin, DDSA-inulin and Inutec SP1 respectively. Stevens et al.
 290 (2001) measured the interfacial tension for octyl inulin carbamate at the IsoparM oil / water
 291 interface and reported an interfacial tension of 6.8mN/m at the CAC.

292
 293 *Emulsification properties*

294 The zeta potential of droplets for OW emulsions prepared using OSA- and, DDSA -inulins
 295 and Inutec SP1 are plotted as a function of pH in Figure 4. It is noted that the zeta potential
 296 increased with increasing pH from -4.8 mV at pH 1.9 to -60.8 mV at pH 9.7 for OSA-inulin and
 297 from -2.2 mV at pH 1.8 to -55.5 mV at pH 10.2 for DDSA-inulin.

298

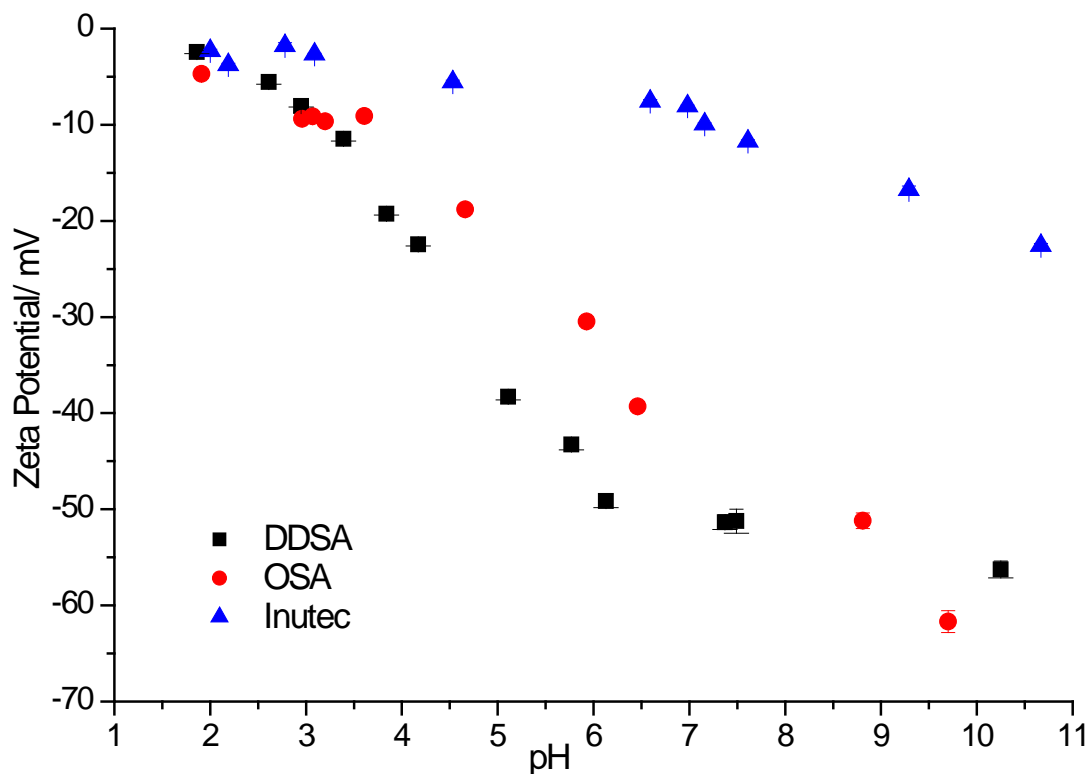


Figure 4. Zeta potential of OSA(1), DDSA(1) -inulins and Inutec SP1 as a function of pH.

299
300
301

302 The increase in zeta potential is due to the fact that OSA-, DDSA- inulins have a carboxylic
303 acid group present in the linkage between the inulin and alkenyl moieties arising from the
304 alkylene succinic anhydride and this dissociates as the pH increases to form the carboxylate
305 ion. Inutec SP1 does not contain ionic groups (Nestor et al., 2005) and hence does not show
306 this trend. The slight increase in the zeta potential observed for Inutec SP1 is likely to be due
307 the adsorption of hydroxide ions at the O/W interface and/or ionisation of hydroxyl ions of the
308 inulin and/or MCT oil (Xin et al., 2013; Liu et al., 2006).

309

310 The droplet sizes for emulsions prepared using 2.5% OSA- and DDSA -inulins and Inutec SP1
311 over time at room temperature and 50 °C are presented in Figures 5.

312

313

314

315

316

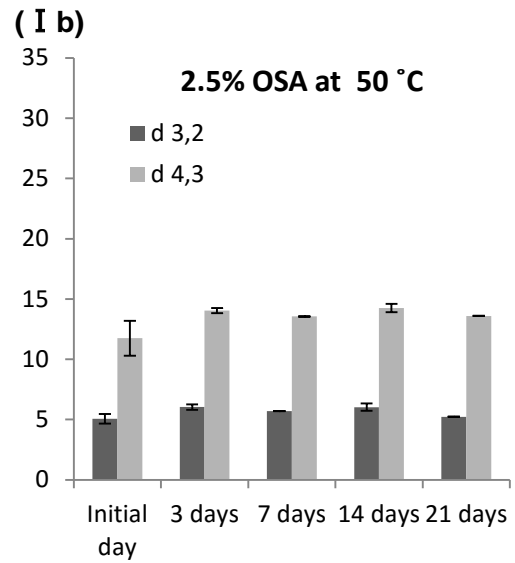
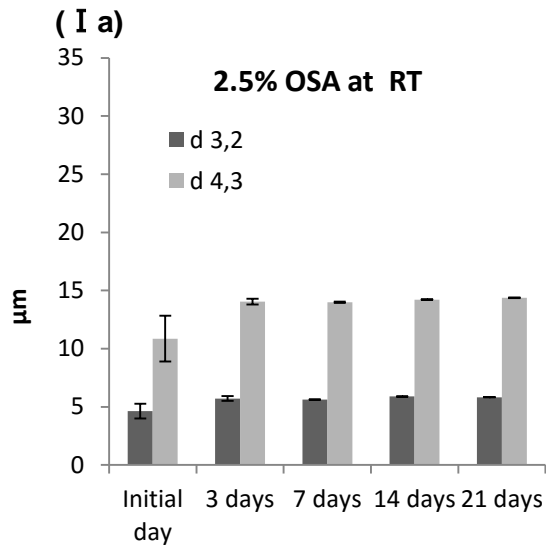
317

318

319

320

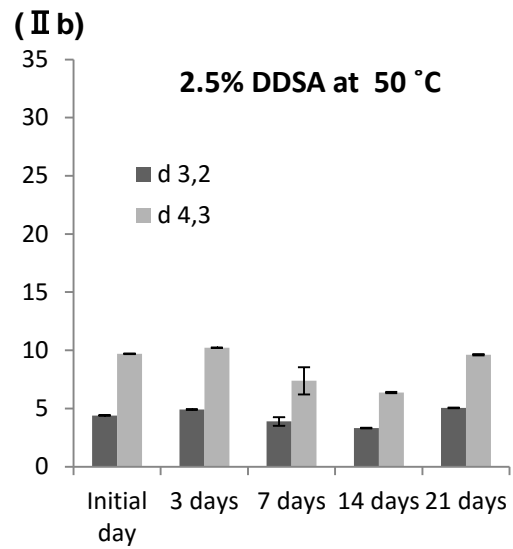
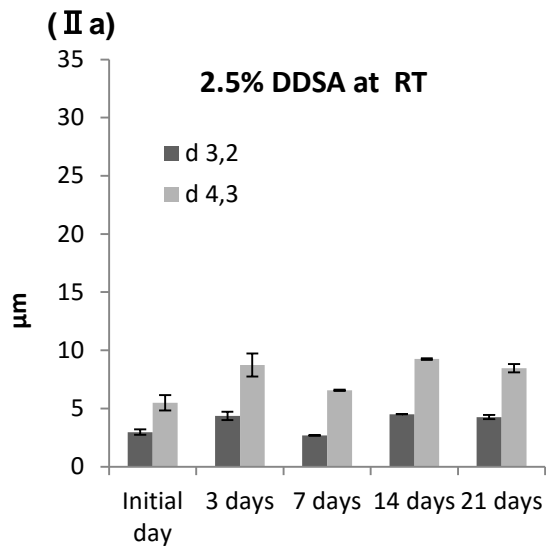
321



322

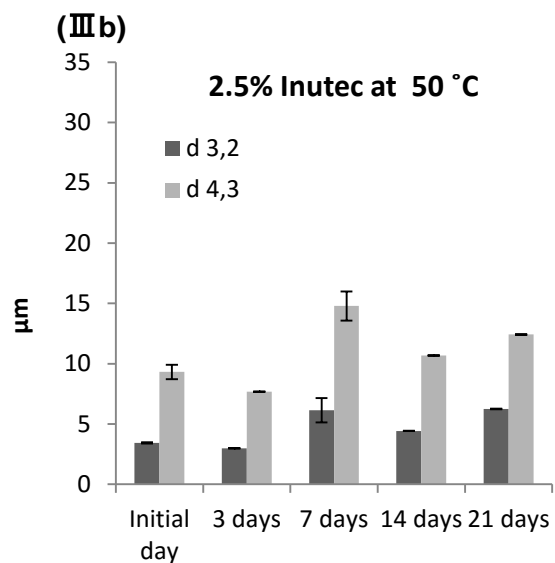
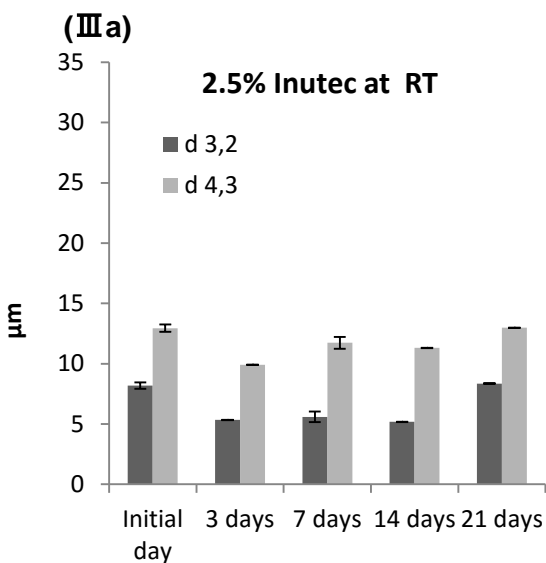
323

324



325

326



327

328

329

330

Figure 5. Surface weighted mean ($d_{3,2}$) and volume weighted mean ($d_{4,3}$) diameters of O/W emulsions using 2.5% OSA (9%)-(I), DDSA (12%)-inulin(II) and Inutec (III) over 21 days (a) at room temperature and (b) 50 °C.

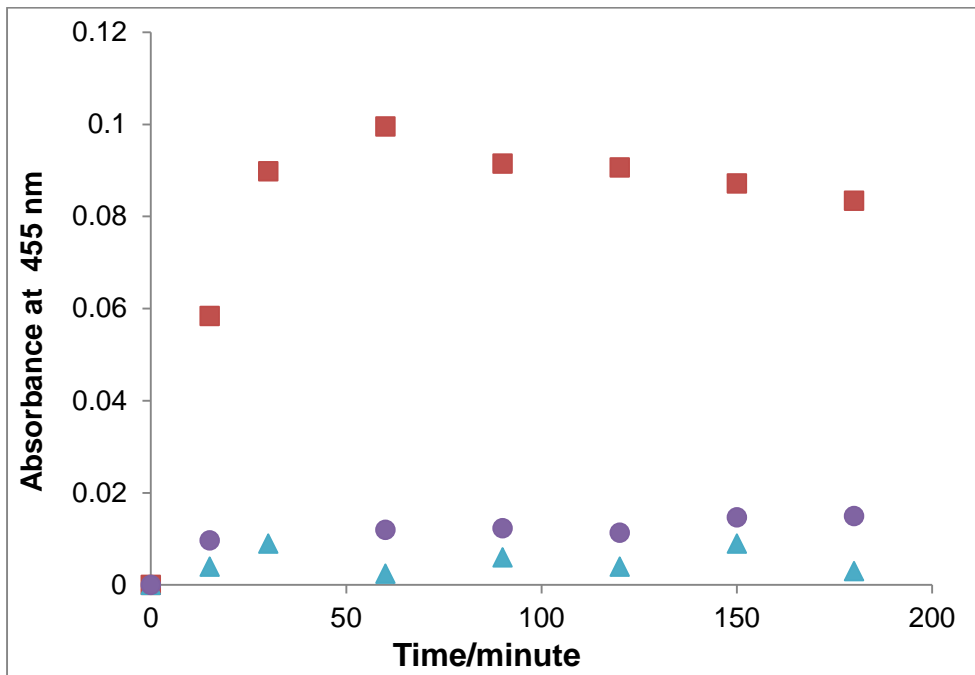
331
332
333
334
335
336
337
338
339
340
341
342
343
344
345
346
347
348
349
350
351
352
353
354
355
356
357
358
359
360
361
362
363
364
365
366
367

The DDSA - inulin sample was found to have the greatest emulsification capacity producing droplets with a smaller size compared to OSA-inulin and Inutec SP1 stabilised emulsions. The surface weighted mean ($d_{3,2}$) and the volume weighted mean ($d_{4,3}$) diameters for all samples remained relatively constant over 21 days at room temperature and 50 °C. This is consistent with the work of Tadros et al. (2004) who prepared 50/50 (v/v) Isopar/water emulsions containing 2% Inutec SP1 (w/v). They demonstrated that emulsion droplets were stable and there was no oil separation over a one year period. It is assumed that the hydrophobic chains covalently attached to the modified inulins facilitate the adsorption of the molecules onto the surface of the oil droplets and that the carbohydrate residues protrude into the aqueous phase. According to Gochev et al.(2011) and Khristov et al. (2010) the inulin molecules form loops at the interface and that the size of the loops will depend on the number of alkyl chains attached. It is evident for Inutec SP1 that droplet aggregation is prevented through steric repulsive forces arising from the interaction of the carbohydrate moieties (Nestor et al., 2005; Stevens et al., 2001). For the OSA- and DDSA -inulin samples, which have a significantly shorter inulin chain compared to Inutec, stabilisation will be achieved by electrostatic repulsive forces due to the presence of the carboxylate ions in the head-group (Kokubun, Ratcliffe & Williams (2015)). This is supported by the zeta potential measurements reported above which show that the droplets acquire a significant negative charge as the pH is increased.

Encapsulation

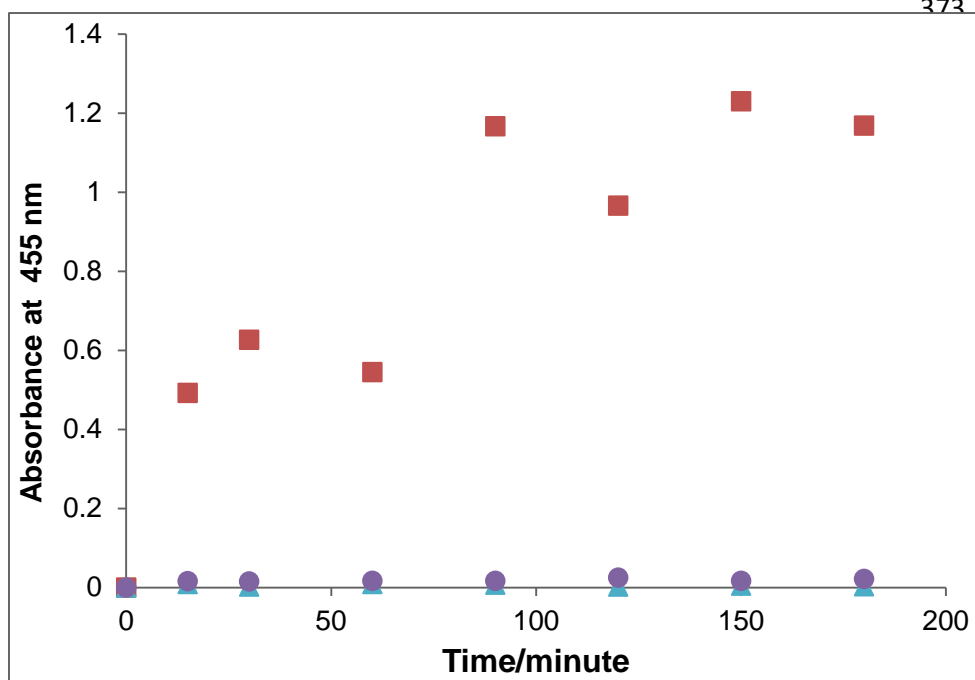
OSA-, DDSA- inulin and Inutec SP1 solid dispersions were formed by the solvent evaporation method and their ability to disperse in water and in simulated gastric fluid was determined by measuring the absorbance of the solution as a function of time. The results are reported in Figures 6a and 6b. The absorbance of the filtered solutions for the DDSA(2) sample was found to increase to a maximum value of 0.1 after ~30 minutes in water but increased to significantly higher values in the gastric fluid. The increase in absorbance is evidence of the presence of micellar aggregates in which the beta carotene is dissolved in the hydrophobic core. Only very small increases in absorbance were observed for Inutec SP1 and the other less substituted OSA-, DDSA- inulin samples.

368 (a)



369
370 (b)

371
372



373
394 **Figure 6 Absorbance of dispersions of beta carotene and OSA(2) [triangles], DDS(2)-**
395 **inulin [squares] and Inutec SP1 [circles] as a function of time dispersed in (a) water (b)**
396 **simulated gastric fluid.**

397

398

399

400 **Conclusions**

401 This study has shown that OSA-, DDSA- inulin and Inutec SP1 form micellar aggregates in
402 solution above a critical concentration which are able to dissolve hydrophobic compounds. In
403 addition, they are effective at reducing the interfacial tension at the air-water and oil-water
404 interface and can stabilise O/W emulsions. The DDSA(2) sample with a higher degree of
405 modification proved more effective than the OSA-inulin and Inutec SP1 to encapsulate and
406 release beta carotene when the solid dispersion was dispersed in water and simulated gastric
407 fluid. These materials have considerable potential for application in the encapsulation of active
408 compounds, such as drugs, vitamins, antimicrobials and aromas for use in, for example,
409 pharmaceutical, nutraceutical, personal care and cosmetic products.

410

411

412

413 **References**

414

415 Di Prima, G., Saladino, S., Bongiovi, F., Adamo, G., Pitarresi, G., and Giammona, G. (2017)
416 'Novel inulin-based mucoadhesives micelles loaded with corticosteroids as potential
417 transcorneal permeation enhancers' *Eur. J. Pharmaceutics and Biopharmaceutics* 117 385-
418 399

419 Exerowa, D., Gotchev, G., Kolarov, T., Khristov, K., Levecke, B. & Tadros, Th. F. (2007)
420 'Interaction Forces in Thin Liquid Films Stabilized by Hydrophobically Modified Inulin
421 Polymeric Surfactant. 2. Emulsion Films', *Langmuir*, 23, 4, 1711-1715.

422 Exerowa, D., Gotchev, G., Kolarov, T., Kristov, K., Levecke, B. & Tadros, Th. F. (2009a)
423 'Comparison of oil-in-water emulsion films produced using ABA or ABn copolymers', *Colloids
424 and Surfaces A: Physicochemical and Engineering Aspects*, 35, 1-3, 50-54.

425 Exerowa, D., Gotchev, G., Kolarov, T., Kristov, K., Levecke, B. & Tadros, Th. F. (2009b) 'Oil-
426 in-water emulsion films stabilized by polymeric surfactants based on inulin with different
427 degree of hydrophobic modification', *Colloids and Surfaces A: Physicochemical and
428 Engineering Aspects*, 334, 1-3, 87-91.

429 Garofalakis, G., Murray, B.S. & Sarney, D.B. (2000) 'Surface Activity and Critical Aggregation
430 Concentration of Pure Sugar Esters with Different Sugar Headgroups', *Journal of Colloid and
431 Interface Science*, 229, 2, 391-398.

432

433 Gotchev, G., Kolarov, T., Levecke, B.T.T., Khristov, K. & Exerowa, D. (2007) 'Interaction forces
434 in thin liquid films stabilized by hydrophobically modified inulin polymeric surfactant. 3.
435 Influence of electrolyte type on emulsion films', *Langmuir*, 23, 11, 6091-6094.

436 Gotchev, G., Petkova, H., Kolarov, T., Khristov, K., Levecke, B., Tadros, Th. F. & Exerowa, D.
437 (2011) 'Effect of the degree of grafting in hydrophobically modified inulin polymeric surfactants
438 on the steric forces in foam and oil-in-water emulsion films ', *Colloids and Surfaces A:
439 Physicochemical and Engineering Aspects*, 391, 1-3, 101-104.

440

441 Han, Lingyu, Ratcliffe, I., Williams, P.A., (2015) 'Self-assembly and emulsification properties of
442 hydrophobically modified inulin' *J Agricultural and Food Chemistry* 63 3709-3715

443

444 Khristov, K. & Czarnecki, J. (2010) 'Emulsion films stabilized by natural and polymeric
445 surfactants', *Current Opinion in Colloid & Interface Science*, 15, 5, 324-329.
446

447 Kokubun, S., Ratcliffe, I. & Williams, P.A. (2013) 'Synthesis, Characterization and Self-
448 Assembly of Biosurfactants Based on Hydrophobically Modified Inulins', *Biomacromolecules*,
449 14, 8 2830-2836.

450

451 Kokubun, S., Ratcliffe, I. and Williams, P.A. (2015) 'The emulsification properties of octenyl-
452 and dodecenyl- succinylated inulins' *Food Hydrocolloids* 50 145-149
453

454 Liu, W., Sun, D., Li, C., Liu, Q. & Xu, J. (2006) 'Formation and stability of paraffin oil-in-water
455 nano-emulsions prepared by the emulsion inversion point method', *Journal of Colloid and*
456 *Interface Science*, 303, 2, 557-563.

457 Lopez-Molina, D., Chazarra, S., How, C.W., Pruidze, N., Navarro-Peran, E., Garcia-Canovas,
458 F., Garcia-Ruiz, P. A., Rojas-Melgarejo, F. and Rodriguez-Lopez, J. N. (2015) 'Cinnamate of
459 inulin as a vehicle for delivery of colonic drugs' *Int. J. Pharmaceutics* 479 96-102

460 Mandracchia, D., Rosato, A., Trapni, A., Chlapanidas, T., Montagner, I. S., Perteghella, S.,
461 DiFranco, C., Torre, M.L., Trapni, G. and Tripodo, G. (2017) '*Nanomedicine: Nanotechnology,*
462 *biology and medicine* 13 1245-1254

463 Morros, J., Levecke, B. & Infante, M.R. (2010) 'Chemical hydrophobic modification of inulin in
464 aqueous media: Synthesis of β -hydroxyalkyl ethers of inulin', *Carbohydrate Polymers*, 81, 3,
465 681-686.

466 Morros, J., Levecke, B. & Infante, M.R. (2011) 'Hydrophobically modified inulin from alkenyl
467 succinic anhydride in aqueous media', *Carbohydrate Polymers*, 84, 3,1110-1116.

468 Muley, P, Kumar, S., El Kourati, F., Kecharwani, S.S. and Tummala, H., (2016)
469 'Hydrophobically modified inulin as an amphiphilic carbohydrate polymer for micellar delivery
470 of paclitaxel for intravenous injection' *Int. J. Pharmaceutics* 500 32-41

471 Nestor, J., Esquena, J., Solans, C., Levecke, B., Booten, K. & Tadros, T.F. (2005) 'Emulsion
472 polymerization of styrene and methyl methacrylate using a hydrophobically modified inulin and
473 comparison with other surfactants', *Langmuir*, 21, 11, 4837-4841.

474 Nestor, J., Esquena, J., Solans, C., Levecke, B., Booten, K. & Tadros, T.F. (2008) 'Emulsion
475 polymerization of styrene using mixtures of hydrophobically modified inulin (polyfructose)
476 polymeric surfactant and nonionic surfactants', *Journal of Applied Polymer Science*, 108, 2,
477 811-815.

478 Nestor, J., Esquena, J., Solans, C., Luckham, P.F., Musoke, M., Levecke, B., Booten, K. &
479 Tadros, T.F. (2007) 'Interaction forces between particles stabilized by a hydrophobically
480 modified inulin surfactant.', *Journal of Colloid and Interface Science*, 311, 2, 430-437.

481 Sagis, L.M.C., Boeriu, C.G., Frissen, G.E., Schols, H.A. & Wierenga, P.A. (2008) 'Highly
482 Stable Foams from Block Oligomers Synthesized by Enzymatic Reactions', *Langmuir*, 24, 2,
483 359-361.

484 Soutani, S., Ognier, S., Engasser, J.M. & Ghouil, M. (2003) 'Comparative study of some
485 surface active properties of fructose esters and commercial sucrose esters', *Colloids and*
486 *Surfaces A: Physicochemical and Engineering Aspects*, 227, 1-3, 35-44.
487

488 Srinarong, P., Hamalainen, S., Visser, M. R., Hinrichs, W. L. J., Ketolainen, J. and Frijlink,
489 H.W., (2010) 'Surface active derivative of Inulin (Inutec SP1) is a superior carrier for solid
490 dispersions with a high drug load' *J. Pharmaceutical Sciences* 100 6 2333-2342.
491
492 Stevens, C.V., Merigii, A. & Booten, K. (2001) 'Chemical modification of inulin, a valuable
493 renewable resource, and its industrial applications.', *Biomacromolecules*, 2, 1, 1-16.
494
495 Stevens, C.V., Meriggi, A., Peristeropoulou, M., Christov, P.P., Booten, K., Levecke, B.,
496 Vandamme, A., Pittevels, N. & Tadros, T.F. (2001) 'Polymeric surfactants based on inulin, a
497 polysaccharide extracted from chicory. 1. Synthesis and interfacial properties',
498 *Biomacromolecules*, 2, 4, 1256-1259.

499 Tadros, T.F., Vandamme, A., Booten, K., Levecke, B. & Stevens.CV. (2004) 'Stabilisation of
500 emulsions using hydrophobically modified inulin (polyfructose)', *Colloids and Surfaces A:
501 Physicochemical and Engineering Aspects*, 250, 1, 133-140.

502 Van Kempen, S.E.H.J., Maas, K., Schols, H.A., Linden, E.V.D. & Sagis, L.M.C. (2013a)
503 'Interfacial properties of air/water interfaces stabilized by oligofructose palmitic acid esters in
504 the presence of whey protein isolate', *Food Hydrocolloids*, 32, 1, 162-171.

505 Van Kempen, S.E.H.J., Boeriu, C.G., Schols, H.A., Waard, P.D., Linden, E.V.D. & Sagis,
506 L.M.C. (2013b) 'Novel surface-active oligofructose fatty acid mono-esters by enzymatic
507 esterification', *Food Chemistry*, 138, 2-3, 1884-1891.

508 Van Kempen, S.E.H.J., Schols, H.A., Linden, E.V.D. & Sagis, L.M.C. (2014) 'Effect of
509 variations in the fatty acid chain on functional properties of oligofructose fatty acid esters',
510 *Food Hydrocolloids*, 40, 22-29.
511

512 Xin, X., Zhang, H., Xu, G., Tan, Y., Zhang, J. & Lv, X. (2013) 'Influence of CTAB and SDS on
513 the properties of oil-in-water nano-emulsion with paraffin and span 20/Tween 20', *Colloids and
514 Surfaces A: Physicochemical and Engineering Aspects*, 418, 5., 60-67.
515
516
517
518
519
520
521