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1 **ENZYMATIC HYDROLYSIS AT HIGH DRY MATTER CONTENT: THE**
2 **INFLUENCE OF THE SUBSTRATES' PHYSICAL PROPERTIES AND OF**
3 **LOADING STRATEGIES ON MIXING AND ENERGETIC CONSUMPTION**

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9 **ABSTRACT**

10 The present work investigates the impact of the physical properties and loading
11 strategies of wheat straw and miscanthus on enzymatic hydrolysis at high DM
12 concentration. Three parameters have been chosen to evaluate the enzymatic hydrolysis
13 performance: (i) the mixing time, (ii) the energetic mixing consumption and (iii) the
14 glucose concentration. It was demonstrated that the hydrolysis of miscanthus is easy to
15 perform and has low viscosity. On the contrary, the higher porosity grade of wheat
16 straw than miscanthus (73% against 52%) contributed to have a very high viscosity at
17 20% *w/w* DM. The development of a fed-batch strategy allowed the reduction of
18 viscosity inducing the energetic consumption lowering from 30 kJ to 10 kJ. It has been
19 also proven that the miscanthus addition in wheat straw achieved to decrease mixing
20 energy consumption at 5-8 kJ, when it represented more than 30% of the total mass of
21 the reaction medium.

22 **KEYWORDS:** Bioethanol; High Dry Matter; Mixing; Enzymatic hydrolysis; Energy
23 consumption; Lignocellulosic materials

24 **1. INTRODUCTION**

25 The global warming, due to the increase of the greenhouse gas (GHG) emissions and
26 the simultaneous depletion of fossil fuels, have encouraged the research of alternative
27 and clean energy sources for the anthropic activities. In particular, the bioethanol
28 industry boomed in the last decades (Battista et al., 2016a). Bioethanol production
29 usually starts from simple sugars derived from cane and corn (first generation biofuels),
30 whose fermentation has very good efficiency. Nevertheless, this production is expensive
31 and non-sustainable because of the competitive use of these substrates with food
32 industry (Clomburg and Gonzalez, 2013). Agro-food residues (second generation
33 biofuels) are becoming important substrates for bioethanol production, limiting the use
34 of fields for non-food production. Wheat straw and miscanthus are common second
35 generation substrates for the bioethanol production. Wheat straw is a waste material
36 from agricultural production and miscanthus is a grass family crop with a high energetic
37 yield by its beneficial chemical composition (low content of lignin) (Lewandowska et
38 al., 2016).

39 Bioethanol production involves four steps: (i) the pretreatments of the substrates, (ii) the
40 hydrolysis to convert ligno-cellulosic material into glucose, (iii) the fermentation of
41 glucose in ethanol and (iv) the distillation. The pretreatments of straw and miscanthus
42 are necessary to optimize the glucose concentration during the hydrolysis and to reduce
43 the viscosity of the reaction medium (Battista et al., 2016b). The pretreatment stage is
44 followed by the hydrolysis, often conducted by purified enzymes able to degrade
45 hemicellulose and cellulose into soluble sugars (Zhou et al., 2008). The enzymatic

46 hydrolysis has currently high yields (75-85%) and improvements are still projected
47 (85-95%) (Balat, 2011).

48 The last phase of the bioethanol production is represented by the distillation. It has been
49 evaluated that to be economically advantageous the distillation requires a minimum
50 ethanol concentration of 4% *w/w*, which means a minimum glucose concentration of 8%
51 *w/w* and an associate ligno-cellulose loading of at least 15% *w/w* DM content during the
52 enzymatic hydrolysis (McIntosh et al., 2016). Working at high DM concentration also
53 permits to reduce the volume of the reactor and consequentially to have lower economic
54 and energetic costs of the process (Larsen et al., 2008).

55 Typical enzymatic hydrolysis of lignocellulosic materials is conducted at low DM
56 concentration (maximum 5% *w/w*) to ensure a good contact between enzymes and
57 substrates (Boussaid and Saddler, 1999), (Xue et al., 2012). There are few studies
58 regarding the enzymatic hydrolysis at high DM concentration. Kristensen et al. (2009)
59 and Jorgensen et al. (2007) have demonstrated that the conversions of cellulose into
60 glucose decreases by the increasing of DM concentration. In addition, Cara et al. (2007)
61 and Battista et al. (2016c) have underlined that at high DM content, the complexity of
62 the lignocellulosic polymers, causes an increase of the reaction medium viscosity and
63 consequentially bad mixing within the bioreactor. The mechanism by which cellulases
64 permit the hydrolysis of cellulose follows three steps: (i) external mass transfer of
65 enzyme, (ii) diffusion/adsorption of the enzyme on the substrate surface and (iii)
66 cellulase catalytic action. The overall reaction rate is determined by the rates of these
67 three events occurring in sequence. If the external mass transfer is neglected (at low DM
68 content), the overall reaction rate will be controlled by the second step (internal
69 diffusion). At high DM content, the mixing is not efficient: the external mass transfer

70 controls the overall reaction rate (Corre et al., 2016) and the hydrolysis efficiency is
71 20% lower than observing at 5% *w/w* DM concentration (Xue et al., 2012).
72 The aim of this work is the improvement of the enzymatic hydrolysis of wheat straw
73 and miscanthus at high DM concentration (20% *w/w*), reducing the reaction medium
74 viscosity. The physical properties influence on viscosity has been observed and
75 different loading strategies of batch and fed-batch have been tested on straw, on
76 miscanthus and on a combination of both substrates. The performances of the tests have
77 been evaluated taking into account the most important factors affecting the
78 bioprocesses: (i) mixing time, (ii) mixing energetic consumption and (iii) the glucose
79 concentration contained in the reaction medium at the beginning and at the end of the
80 hydrolysis phase.

81 **2. MATERIALS AND METHODS**

82 **2.1 Substrates, enzymatic cocktail characteristic and description of the tests**

83 The substrates used for the tests were wheat straw and miscanthus, pretreated at
84 appropriate operative conditions (data not shown). Table 1 summarises the physical and
85 chemical features of the pretreated wheat straw and the pretreated miscanthus. The
86 features of raw substrates were not available. Zhang et al. (2012) founded that soil and
87 climate conditions influence the raw substrates porosity, which can vary in a very range:
88 45-85%. This demonstrates that the results obtained by this work are not dependent on
89 the substrates conditions (raw or pretreated). The content of lignin, hemicellulose and
90 cellulose of both substrates have been determined by an external company which
91 supplied the substrates (Table 1).

92 <Table 1>

93 Cellic CTec-2 (Novozymes) cellulase blend was used for all enzymatic hydrolysis tests
94 and loadings were quoted as FPU (Filter Paper Units)/g glucan. The amount of the
95 enzymatic cocktail has been determined following the methods by McIntosh et al, 2016.
96 Batch and fed-batch tests have been realised using wheat straw, miscanthus and wheat
97 straw-miscanthus mixture as substrates in order to see the rheological behavior and the
98 conversion of the substrates into glucose. All tests, described in Table 2, have been
99 prepared in order to reach the DM concentration of 20% *w/w* and have conducted in
100 triplicate to ensure their repeatability. The duration of each test has been established at 5
101 hours, when was proved that a stable torque trend was reached. This time was not
102 sufficient to guarantee a complete cellulose conversion in glucose. But this aspect was
103 not relevant in this work which had the aim to investigate the correlation between the
104 substrates feature and the apparent viscosity within the reactor.

105 <Table 2>

106 S-B test has been prepared loading the reactor with 2.4 kg of wheat straw-water mixture
107 (0.9 kg of wheat straw), while M-B test loading 2.4 kg miscanthus-water mixture (1 kg
108 of miscanthus). Fed batch tests (S-FB65, S-FB50, S-FB35, M-FB65, M-FB50 and M-
109 FB35, Table 2) consisted a first loading of the 65%, the 50% and 35% of the 2.4 kg
110 reaction medium at the beginning of the tests. The rest of the loading has been gradually
111 added in equal parts after 10, 30, 60, 105 and 120 minutes after the beginning of each
112 test. These fed batch tests had the aim to improve the rheological performance into the
113 reactor and to reduce the power consumption without decreasing the yield from
114 cellulose to glucose. Batch tests have been also conducted on wheat straw-miscanthus-
115 water mixtures (SM-80:20, SM-70:30, SM-50:50, SM-30:70) according the ratios
116 reported in Table 2.

117 The enzymatic hydrolysis of all the tests have been conducted at optimal operative
118 conditions that are at 50°C, 50 rpm and a pH range of 5.0 – 5.5.

119 **2.2 The equipment**

120 The bioethanol production from wheat straw and miscanthus have been conducted in a
121 3L reactor (Figure 1) equipped with a torque meter Kistler 4503A measuring torque till
122 a value of 2 Nm and with a data detection frequency variable from 1 to 10 Hz. Data
123 were recollected by LEIRI software reporting them in an Excel file. The reactor was
124 also equipped with a water-heater and with temperature and pH control sensors. The
125 mixing system was an helicoidal impeller properly designed to deal with high DM
126 concentration and high viscosity medium. The helicoidal impeller (Figure 1) had a
127 diameter of 130 mm and is located at 30 mm from the bottom of the reactor.

128 **2.3 Analytical methods**

129 DM of the wheat straw and miscanthus have been determined according to standard
130 methods described in literature (APHA/AWWA/WEB, 1998). DM represented the
131 content of solids present in the substrates, including the inert materials and the
132 degradable ones (Battista et al., 2016b). The apparent density was determined by the use
133 of Archimedes' principle (Zhao et al., 2016).

134 The apparent viscosity of the wheat straw-water and of miscanthus–water mixtures have
135 been determined at 10 and 20% DM *w/w* before the beginning of the enzymatic
136 hydrolysis. The equipment used was the viscometer DV-II-PRO by Brookfield provided
137 with a cross rotating spindle working at 50 rpm.

138 The glucose concentration has been quantified by an enzymatic reaction using the
139 GLUCOSTAT YSI2700 at the beginning and at the end of the tests.

140 Porosity of the substrates was a very important parameter that was directly linked to the
141 absorption capacity of water: obviously, a major grade of porosity favored the
142 absorption of water molecules by substrates. By this way, the amount of water available
143 for the dispersion of the substrates particles decrease, affecting the viscosity of the
144 reaction medium. The grade of porosity and the average volume pore for macroporosity,
145 mesoporosity and microporosity have been evaluated by N₂ adsorption isotherms
146 method. Initially the sample was degassed at 60 °C for 48 h. The average pore volume
147 was obtained using the Horvath-Kawazoe approximation (Horvath and Kawazoe, 1983).
148 The absorption capacity of wheat straw and miscanthus has been evaluated in
149 qualitative way by a simple experiment: 50 g of dry straw and 50 g dry of miscanthus
150 have been located in two different separatory funnels. 100 mL of distilled water have
151 been poured into the funnels at t = 0. The time of the beginning of water percolation
152 from the outlet of the separatory funnels has been measured in order to have qualitative
153 evaluation of the different grade of porosity of both substrates. Also, at the end of
154 percolation, the amount of the recollected water from the funnels has been weighted in
155 order to have an estimation of the adsorption capacity of straw and miscanthus. The
156 average equivalent diameter of the particles of both substrates has been determined by
157 light scattering with a particles size analyzer in a 10 nm–2 mm range.

158 **2.4 Definition of the parameters used for the evaluation of the tests**

159 The evaluation of the performances of the different tests has been realised by three
160 different parameters taking into account the factors affecting all the bio-technological
161 processes. First, a good fluid-dynamic within the reactor was important to ensure
162 sufficient mass and heat transfer and a good contact between the substrates and the
163 enzymes, avoiding inhibition with too high mechanical shear stress of the impeller. The

164 second factor was mixing energy consumption calculated from torque measurement.
165 Finally, the cellulose conversion was the last factor to evaluate the bioprocess
166 performances. The three parameters used to express these three factors are respectively
167 the mixing time, the energy consumption and the glucose concentration at the beginning
168 and at the end of the enzymatic hydrolysis.

169 **2.4.1 The Mixing Time**

170 Mixing time (t_m) is the characteristic parameter used to investigate the performance of
171 stirred tank reactors. Mixing time is defined as the period of time necessary to achieve
172 the desired level of homogeneity in a given vessel (Jafari et al., 2005) and it is often
173 used as an indication of impeller effectiveness. The shorter the mixing time the more
174 effective the blending (Gumienna et al., 2011). The mixing time was determined by the
175 pH pulse method (Tan et al., 2011), (Correa et al., 2016). 10 mL of NaOH (2 N)
176 solution will be put in the reaction medium. Mixing time was estimated as the time
177 required for the pH to reach 95 % of its final value. The determination of the mixing
178 time, has been conducted at the beginning of the tests, when the adjustment of the acid
179 reaction medium is necessary to reach the operative pH value of 5.5, required by the
180 enzymatic hydrolysis. Mixing time has been also evaluated at the end of the hydrolysis,
181 before the discharging of the reactor.

182 **2.4.2 Power input required by the mixing system**

183 The power consumption was determined by means of a torque meter mounted on the
184 shaft of each impeller. Due to the friction factor, the torque generated by the motor
185 (M_m) is not fully transmitted by the impeller to the reaction medium (Wang et al.,
186 2012). The corrected torque value M_c was calculated by subtracting the residual torque
187 from each measurement:

188 $M_c \text{ (Nm)} = M_m - M_r$ /1/

189 where M_m is the measured torque and M_r is the residual torque, in Nm, respectively.

190 M_r is determined by measuring the torque at 50 rpm. The values of M_m were recorded
191 each second by the torque-meter for all the duration of the test (5 h). An average value
192 of M_c has been calculated each 15 minutes (Δt) and used for the following calculation
193 of the power (P) and mixing energy consumptions (E):

194 $P \text{ (W)} = M_c 2\pi N$ /2/

195 Where N is the rotational speed of the helicoidal impeller, fixed to 50 rpm for all the
196 tests. Finally, the mixing energy consumption is given by the equation:

197 $E \text{ (J)} = \sum P_i \Delta t_i$ /3/

198 Where P_i is the power consumption for the i -th time range Δt_i of 15 minutes (900 s).

199 **2.4.3 Conversion of ligno-cellulosic materials**

200 In order to evaluate if the best operative conditions, obtained by the tests, are adequate
201 for the degradation activity of the enzymes, the conversion of the ligno-cellulosic
202 compounds into glucose has been also considered. Thus, the glucose concentration in
203 the reaction medium has been also measured at the beginning and at end of the tests.

204 **3. RESULTS AND DISCUSSIONS**

205 **3.1 Different viscosity between wheat straw and miscanthus**

206 <Figure 2>

207 <Figure 3>

208 The tests demonstrated that the enzymatic hydrolysis depends on the substrates used to
209 feed the reactor (Figure 2 and Figure 3): the torque (Mc) was higher for wheat straw
210 than for miscanthus. In addition, the wheat straw has recorded a considerable decreasing
211 of the torque values between the beginning and the end of the tests. On the one hand,
212 the required torque for the reaction medium mixing at 50 rpm dropped from 0.64 Nm to
213 0.22 Nm for the S-B test and to 0.09 Nm for the S-FB50 and S-FB35 tests (Figure 2).
214 On the other hand, the torque in the case of miscanthus tests had a lower reduction: it
215 passed from 0.09 to 0.045 Nm (Figure 3). These different values can be explained by
216 the viscosity. The reaction medium composed by 20% w/w DM of wheat straw particles
217 was very viscous, having an apparent viscosity of 200.1 ± 1.7 cP at 10% w/w DM and of
218 420.1 ± 3.1 cP at 20% w/w DM. The miscanthus presented a gentle fluid-dynamic
219 behavior with low viscosity values of 43.81 ± 4.49 cP and 79.40 ± 4.05 cP at
220 respectively 10% and 20% w/w DM. The torque values for miscanthus were only 5-10
221 times higher than torque required by water (about 0.01 Nm) at 50 rpm (Figure 3). The
222 difference in viscosity had an immediate effect on mixing time (Table 3). Mixing time
223 was higher than 50s for the wheat straw and only of 17s for the miscanthus. The high
224 values of DM and the complex polymerization of the lignocellulosic substrates allowed
225 to define the reaction medium as pseudoplastic fluids, whose behavior can be described
226 by models such as power law, Bingham, Cason and Herschel-Bulkley models
227 (Sotaniemi et al., 2016). The remarkable difference between wheat straw and
228 miscanthus viscosity could be due to a different physical structure of the two substrates.
229 Table 1 shows that wheat straw had a higher degree of porosity than miscanthus (73%
230 and 52% respectively) and a higher average diameter value of pores (about 43,100 nm
231 and 16,400 nm respectively). This porosity determined also a different water absorption,

232 higher for wheat straw than for miscanthus particles. This theory has been confirmed by
233 the experimental results obtained from the measurement of the beginning time of
234 percolation and the amount of the water adsorption: 25 s and 45 mL for the wheat straw
235 and 49 s and 29 mL for the miscanthus. The higher water absorption of straw caused a
236 lower amount of liquid in the reaction medium and consequentially an increase of the
237 viscosity. Therefore, there was a reduction of the dispersion and of the homogenization
238 of wheat straw particles within the reactor. Mondebach and Nokes (2013) explained that
239 water reduces the viscosity of the slurry by increasing the lubricity of the particles. It
240 permits to decrease the required shear stress and consequentially the power input for
241 mixing. The water absorption was mainly due to macroporosity which is twice bigger
242 for wheat straw than for miscanthus (Table 1) (Ros et al., 2013). It is also interesting to
243 observe that the total porosity of the substrates was not given by microporosity and
244 mesoporosity (which was almost 0 mL/g). The different porosity degree also permits to
245 explain the apparent density (Table 1), which was about 430 kg/m³ for wheat straw and
246 520 kg/m³ for miscanthus. It was coherent with the density measured at 0.2 MPa: 0.7
247 and 0.93 g/mL for wheat straw and miscanthus, respectively.

248 The analysis for the determination of the average diameter value of the particle, reported
249 in Table 1, permitted to verify that the wheat straw particles are slightly bigger than
250 miscanthus, contributing to the further increasing of the reaction medium's viscosity for
251 the wheat straw.

252 Finally, the higher viscosity of straw was also due by a different distribution of the three
253 major lignocellulosic components (lignin, hemicellulose and cellulose) (Table 1). In
254 fact, Lewandowska et al., 2016 have reported that miscanthus has a higher content of
255 hemicellulose, the most easily degradable and flexible compounds between ligno-

256 cellulosic materials, and a lower concentration of lignin which gives the property of
257 rigidity to ligno-cellulosic polymers (Table 1).

258 **3.2 Batch and fed-batch tests**

259 The effects of the enzymatic hydrolysis have been summarized in Table 3. All the tests
260 have recorded the reduction of the mixing time. It moved from about 50 s to 40 s for the
261 wheat straw, which means a reduction of about 20%. While, the mixing time values
262 declined from 17 s to 10.5 s for miscanthus, with a reduction of more than 35%.

263 <Table 3>

264 The mixing time reduction was clearly imputable to the decreasing of the reaction
265 medium by the effect of the enzymatic hydrolysis. The enzymes attacked the cellulose
266 permitting a significant structural change in terms of the crystallinity and
267 polymerization degrees (Adani et al., 2011). Consequentially, the mixing inside the
268 reactor was improved with a reduction of the torque transmitted by the motor to the
269 impeller.

270 Figure 3 reports the torque values during time for batch and fed-batch tests with
271 miscanthus substrate. All the tests have followed almost the same decreasing evolution
272 of torque during time, recovering almost the same values, from 0.07 Nm at the
273 beginning of the test (average value for all the miscanthus tests) to 0.045 Nm at the end
274 of the hydrolysis. On the contrary, strong difference in the torque values have been
275 recorded for the wheat straw, where the loading reactor strategy had a great impact
276 (Figure 2). The higher values of torque belonged to the S-B test with an initial value of
277 0.65 Nm. The tests S-FB65, S-FB50 and S-FB35 had an initial torque more and more
278 inferior (0.45, 0.19 and 0.12 Nm respectively, Figure 2) due to the minor mass loaded at

279 the beginning of the test. During the first additions, the benefic effects of hydrolysis
280 were not enough efficient and the viscosity remained high, so that a considerable
281 increasing of the torque has been recorded. By the time, the action of the enzymes
282 allowed a sufficient denaturation of the ligno-cellulosic materials (Adani et al., 2011)
283 and the new substrates additions have been quickly homogenized in the reaction
284 medium. Figure 2 also shows that the reduction of the torque was more efficient for the
285 S-FB50 and S-FB35, whose final values of the torque were around 0.09 Nm, inferior
286 than the final values of torque of about 0.23 Nm for the S-FB65. It suggests that a
287 gradual addition of the substrates had a beneficial effect on the denaturation of the
288 ligno-cellulosic materials, probably due to the high concentration of enzymes (which are
289 fed at the beginning of the test) for mass of substrates initially charged. In general, it has
290 been demonstrated that fed-batch offers advantages in the enzymatic hydrolysis over the
291 batch mode: the initial substrates quantity fed into the reactor is lower, so diffusion and
292 mixing limitations can be minimized. In addition, fed-batch strategy permitted to the
293 enzymes to better liquefy the recalcitrant lignocellulosic materials before additional
294 solids addition (Mondebach and Nokes, 2013).

295 As reported in the previous part, torque is strictly linked to the power demand of the
296 mixing system and to the energy consumption for the reaction medium agitation. For
297 this reason, the lower torque of S-FB50 and S-FB35 implied also energetic and
298 economic advantages. Table 3 reported the energy consumption during the tests. It was
299 evident that a gradual addition of the feeding permitted a considerable saving of
300 electrical energy: the S-B test required over 32.5 kJ, while S-FB35 test required only 9.5
301 kJ, which means an energy reduction of about 60%. Also, all the tests having
302 miscanthus as substrate required between 7 and almost 5 kJ, with a slightly energetic

303 reduction for M-FB50 and M-FB35 tests which required 4.8 kJ against the 7 kJ of the
304 M-B and M-FB65. This little difference for the miscanthus tests can be easily explained
305 by considering the lower viscosity of this substrate for the reasons previously discussed.

306 Regarding the cellulose conversion into glucose, Table 3 reported glucose concentration
307 in the reaction medium at the beginning and at the end of the tests. There is no
308 difference between the tests conducted with the wheat straw and the miscanthus. About
309 19.00 - 19.50 g/L of glucose have been found in wheat straw tests after the hydrolysis
310 stage. A slightly higher concentration of 20.00 – 21.00 g/L has been obtained from
311 miscanthus. It is probably due to the different distribution of the three ligno-cellulosic
312 (lignin, cellulose and hemicellulose) between wheat straw and miscanthus, reported in
313 Table 1. Wheat straw had a major concentration of cellulose, which is the main
314 precursor of glucose production. Miscanthus had a minor lignin which limits the access
315 to cellulose to the enzymes, by its more external position between all the lignocellulosic
316 polymers and by its strong covalent bonds (Elgharbawy et al., 2016). The work of
317 Adani et al. (2011) confirmed that the access of cellulase enzymes to crystalline
318 cellulose was greatly reduced by the presence of some compounds, in particular lignin
319 and other structural proteins. Anyway, as previously reported, a short hydrolysis time of
320 5 h allowed to achieve only a partial conversion of the substrates, and longer times are
321 necessary to complete the cellulose conversion into glucose. Finally, if the fed-batch
322 permitted to have benefic effects on the mixing and consequentially a strong reduction
323 in the energetic consumption, it was irrelevant for the glucose concentration. This result
324 was coherent with the review work of Modenbach and Nokel (2013) which has
325 concluded their analysis asserting that the fed-batch mode has given unclear results in
326 the cellulose conversion into glucose.

327 **3.3 Batch tests with straw-miscanthus mixture**

328 Batch tests (Table 2) have been conducted using a mixture of wheat straw and
329 miscanthus at different concentrations in order to observe when the effect of wheat
330 straw on the viscosity begins to decline. Figure 4 reports the torque values of these
331 batch tests and, for comparisons, the ones of S-B and M-B tests. It has been confirmed
332 that mixing time, torque and energetic consumption of SM-80:20 were still very
333 influenced by the presence of wheat straw, like SB Test. However, when the ratio of
334 miscanthus in the reaction medium reached the 30% *w/w* (SM-70:30), the viscosity
335 dropped down and its behavior was almost the same of M-B test. It means that the
336 content of water absorbed into the internal porosity of the wheat straw is not sufficient
337 to compromise an adequate lubrication of the particles, allowing a good mixing of the
338 reaction medium.

339 **4. CONCLUSIONS**

340 The physical properties influence on the reaction medium viscosity at high DM
341 concentration has been studied. Batch test with straw was characterized by bad mixing
342 and high energy consumption. It was due to the high porosity and to high water
343 absorption of straw which caused an increase of the reaction medium viscosity. The
344 problem can be solved or by the fed-batch mode, which permitted to reduce diffusion
345 and mixing limitations, or preparing a mixture of wheat straw-miscanthus with a
346 minimal ratio of miscanthus of 30% *w/w*. By these ways, it was possible to reduce the
347 mixing time and the energy consumption from 30 to 5 kJ.

348 **References**

- 349 1. Adani, F., Papa, G., Schievano, A., Cardinale, G., D'Imporzano, G.,
350 Tambone, F., 2011. Nanoscale structure of the cell wall protecting cellulose
351 from enzyme attack. *Environmental Science & Technology* 45 (3), 1107-
352 1113.
- 353 2. APHA/AWWA/WEF., 1998. *Standards Methods for the Examination of*
354 *Water and Wastewater*. United Book Press Inc. Baltimore. Maryland.
- 355 3. Balat, M., 2011. Production of bioethanol from lignocellulosic materials via
356 the biochemical pathway: A review. *Energy conversion and management* 52,
357 858-875.
- 358 4. Battista, F., Fino, D., Mancini, G., 2016b. Optimization of the biogas
359 production from coffee production waste. *Bioresource Technology* 200, 884-
360 890.
- 361 5. Battista, F., Fino, D., Mancini, G., Ruggeri, B., 2016c. Mixing in digesters
362 used to treat high viscosity substrates: The case of olive oil production
363 wastes. *Journal of Environmental Chemical Engineering* 4, 915-923.
- 364 6. Battista, F., Mancini, G., Ruggeri, B., Fino, D., 2016a. Selection of the best
365 pretreatment for hydrogen and bioethanol production from olive oil waste
366 products. *Renewable Energy* 88, 401-407.
- 367 7. Boussaid, A., Saddler, J. N., 1999. Adsorption and activity profiles of
368 cellulases during the hydrolysis of two Douglas fir pulps. *Enzyme and*
369 *Microbial Technology* 24, 138 –143.
- 370 8. Cara, C., Moya, M., Ballesteros, I., Negro, M.J., González, A., Ruiz, E.,
371 2007. Influence of solid loading on enzymatic hydrolysis of steam exploded

- 372 or liquid hot water pretreated olive tree biomass. *Process Biochemistry*, 42,
373 1003-1009.
- 374 9. Clomburg, J.M., Gonzalez, R., 2013. Anaerobic fermentation of glycerol: a
375 platform for renewable fuels and chemicals. *Trends Biotechnol.* 31 (1), 20-
376 28.
- 377 10. Corre, L.J., Colli Badino, A., Gonc, A.J., Cruz, A., 2016. Mixing design for
378 enzymatic hydrolysis of sugarcane bagasse: methodology for selection of
379 impeller configuration. *Bioprocess Biosyst. Eng.* 39, 285–294.
- 380 11. Elgharbawy, A.A., Alam, M.Z., Moniruzzaman, M., Goto, M., 2016. Ionic
381 liquid pretreatment as emerging approaches for enhanced enzymatic
382 hydrolysis of lignocellulosic biomass. *Biochemical Engineering Journal* 109,
383 252–267.
- 384 12. Gumienna, M., Lasik, M., Szambelan, K., Czarneck, Z., 2011. Reduction of
385 water consumption in bioethanol production from triticale by recycling the
386 stillage liquid phase. *Acta Sci. Pol. Technol. Aliment.* 10 (4), 467-474
- 387 13. Horvath, G., Kawazoe, K., 1983. Method for calculation of effective pore
388 size distribution in molecular sieve carbon, *J. Chem. Eng. Jpn.* 16, 470.
- 389 14. Jafari, M., Soltan Mohammadzadeh, J.S., 2005. Mixing time,
390 homogenization energy and residence time distribution in a gas-induced
391 contactor. *Chemical Engineering Research and Design.* 83 (A5), 452–459.
- 392 15. Jorgensen, H., Vibe-Pedersen, J., Larsen, J., Felby, C., 2007. Liquefaction of
393 Lignocellulose at High-Solids Concentrations. *Biotechnology and*
394 *Bioengineering.* 96 (5), 862-870.

- 395 16. Kristensen, J.B., Felby, C., Jørgensen, H., 2009. Yield-determining factors in
396 high-solids enzymatic hydrolysis of lignocellulose. *Biotechnology for*
397 *Biofuels* 2, 11 -21.
- 398 17. Larsen, J., Ostergaard Petersen, M., Thirup, L., Wen Li, H., Krogh Iversen,
399 F., 2008. The IBUS process of lignocellulosi bioethanol close to a
400 commercial reality. *Chem. Eng. Technol.* 31, 765-722.
- 401 18. Lewandowska, M., Szymanka, K., Kordala, N., Dabrowska, A., Bednarski,
402 W., Juszczuk, A., 2016. Evaluation of *mucor indicus* and *Saccharomyces*
403 *cerevisiae* capability to ferment hydrolysates of rape straw and *Miscanthus*
404 *giganteus* as affected by the pretreatment method. *Bioresource Technology*
405 212, 262-270.
- 406 19. McIntosh, S., Zhang, Z., Palmer, J., Wong, H., Doherty, W.O.S., Vancov, T.,
407 2016. Pilot-scale cellulosic ethanol production using eucalyptus biomass pre-
408 treated by dilute acid and steam explosion. *Biofuels, bioproducts and*
409 *biorefining* 10 (4), 346-358.
- 410 20. Mondebach, A.A., Nokel, S.E., 2013. Enzymatic hydrolysis of biomass at
411 high-solids loadings – A Review. *Biomass and Bioenergy* 56, 526-544.
- 412 21. Ros, A.B., Filho, J.T., Barbosa, G.M.C., 2013. Soil physical properties and
413 growth of sweet potato under different soil managements. *Revista Brasileira*
414 *de Ciencia do Solo* 37, 242-250.
- 415 22. Sotaniemi, V.H., Taskila, S., Ojamo, H., Tanskanen, J., 2016. Controlled
416 feeding of lignocellulosic substrates enhances the performance of fed-batch
417 enzymatic hydrolysis in a stirred tank. *Biomass and Bioenergy* 91, 271-277.

- 418 23. Tan, R.K., Eberhard, W., Buchs, J., 2011. Measurement and characterization
419 of mixing time in shake flasks. *Chemical Engineering Science* 66, 440–447.
- 420 24. Wang, X., Fradette, L., Takenaka, K., Tanguy, P., 2012. Effect of Operating
421 Parameters on the Mixing Performance of the Superblend Coaxial Mixer.
422 *Industrial & Engineering Chemistry Research* 51, 1826–1833.
- 423 25. Xue, Y., Jameel, H., Phillips, R., Chang, H., 2012. Split addition of enzymes
424 in enzymatic hydrolysis at high solids concentration to increase sugar
425 concentration for bioethanol production. *Journal of Industrial and*
426 *Engineering Chemistry* 18, 707–714.
- 427 26. Zhang, Y., Ghaly, A.E., Li, B., 2012. Physical properties of wheat straw
428 varieties cultivated under different climatic and soil conditions in three
429 continents. *American Journal of Engineering and Applied Sciences*, 5 (2),
430 98-106.
- 431 27. Zhao, Z., Fred Cannon, S., Nieto-Delgado, C., Pena, L., 2016.
432 Lignin/collagen hybrid biomaterials as binder substitute for specialty
433 graphites and electrodes. *Carbon* 108, 303-317.
- 434 28. Zhou, J., Wang, Y.H., Chu, J., Zhuang, Y.P., Zhang, S.L., Yin, P., 2008.
435 Identification and purification of the main components of cellulases from a
436 mutant strain of *Trichoderma viride* T 100-14. *Bioresour Technol* 99, 6826–
437 6833.
- 438

439 **CAPTIONS**

440 **Figures**

441 Figure 1. The reactor and the helicoidal impeller used for the enzymatic hydrolysis of
442 wheat straw and miscanthus.

443 Figure 2. Torque values *vs* time for batch and fed-batch tests having wheat straw as
444 substrate.

445 Figure 3. Torque values *vs* time for batch and fed-batch tests having miscanthus as
446 substrate.

447 Figure 4. Torque values *vs* time for batch tests having wheat straw and miscanthus as
448 substrates.

449 **Tables**

450 Table 1. Chemical and physical characteristics of wheat straw and miscanthus.

451 Table 2. Abbreviation and description of the tests.

452 Table 3. Mixing time, energy consumption and glucose concentration of the tests.

Figure 1

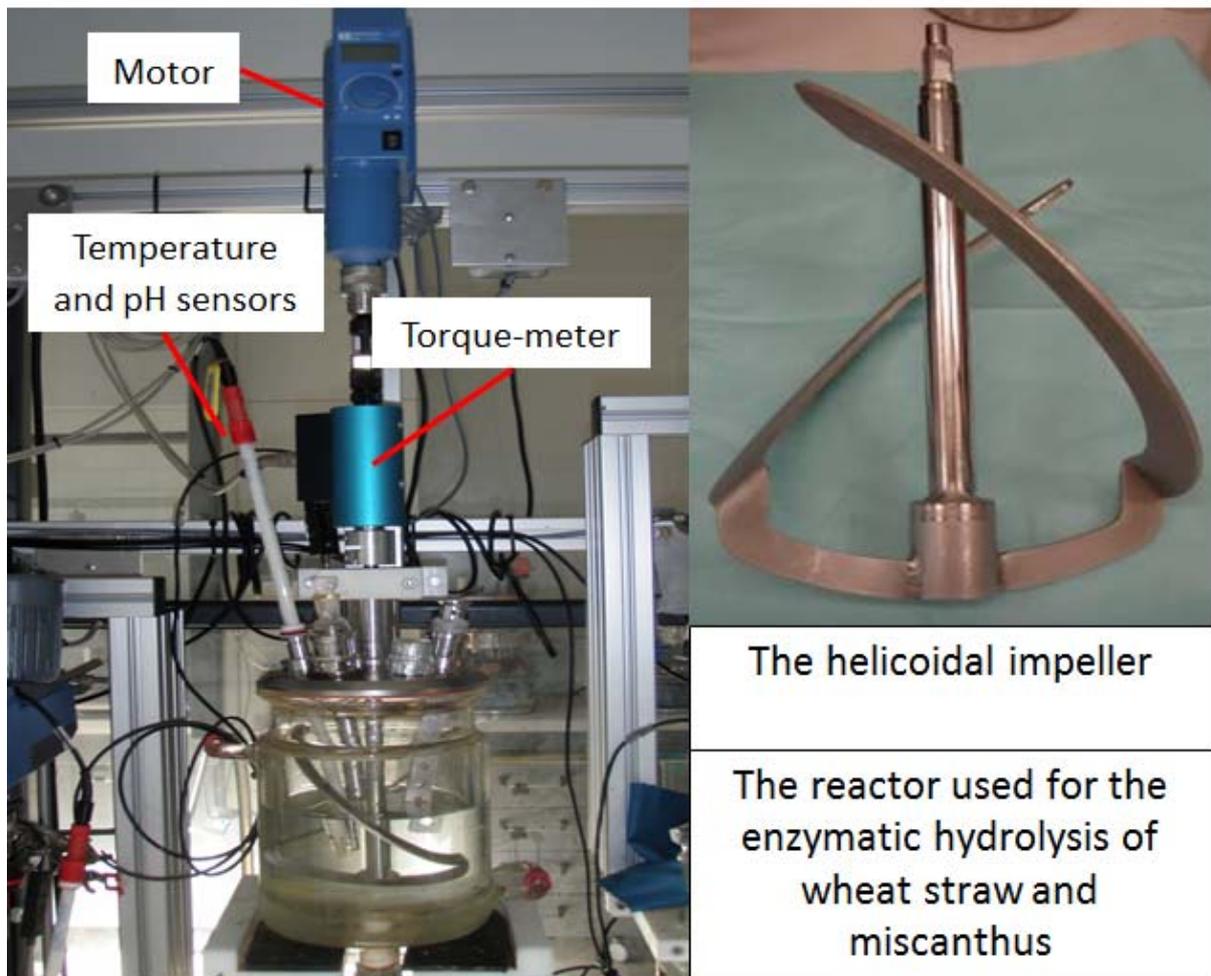


Figure 2

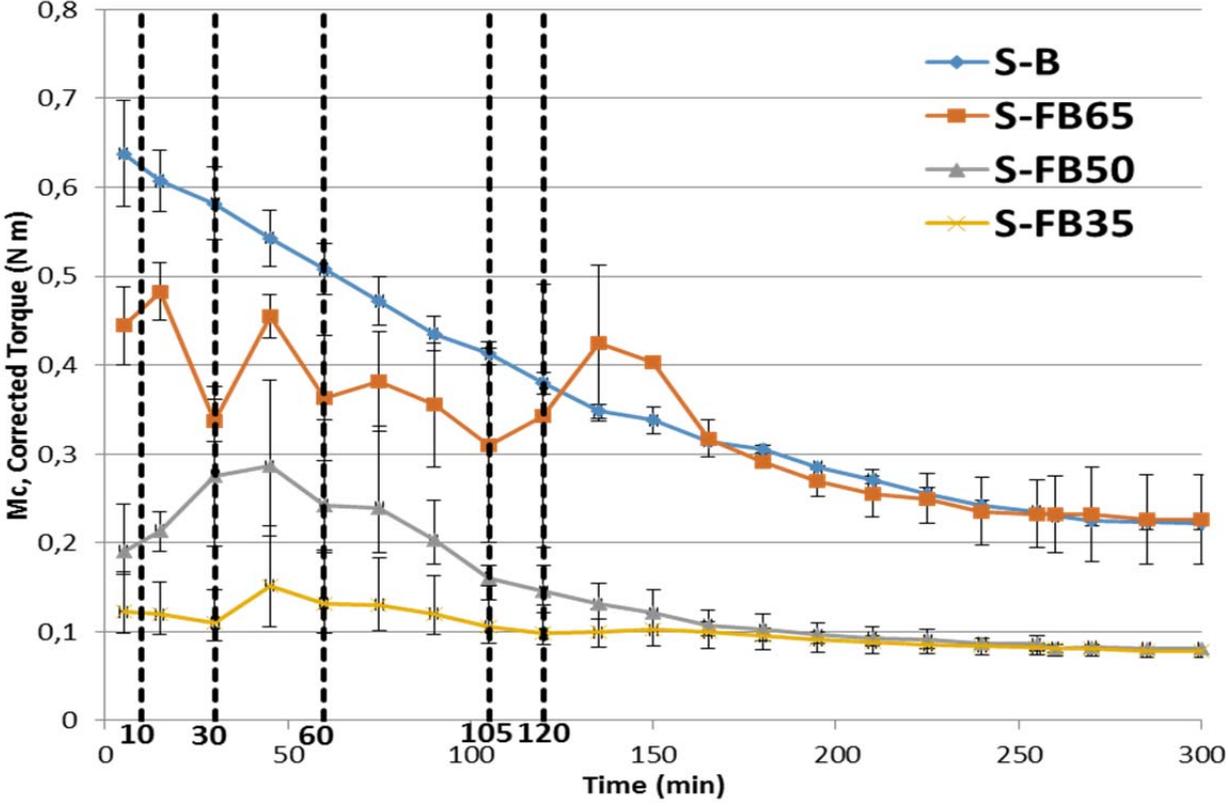


Figure 3

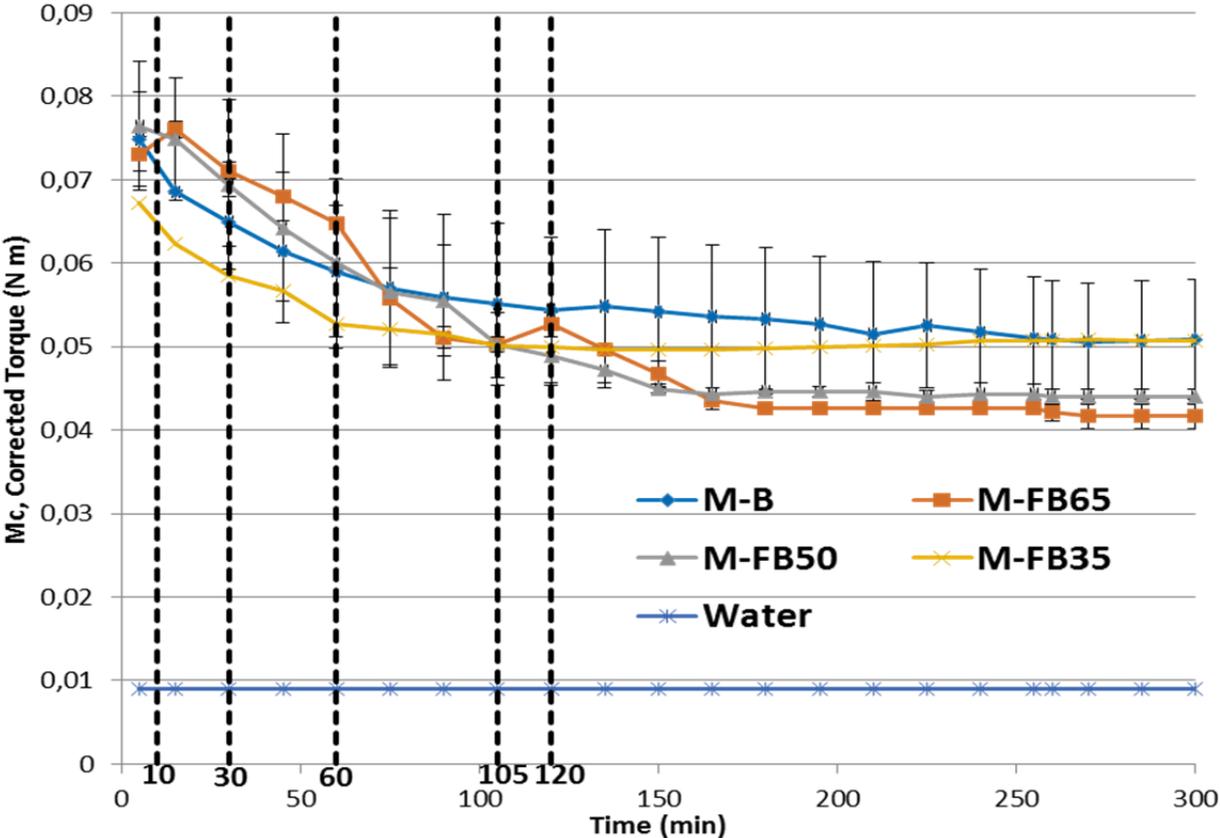


Figure 4

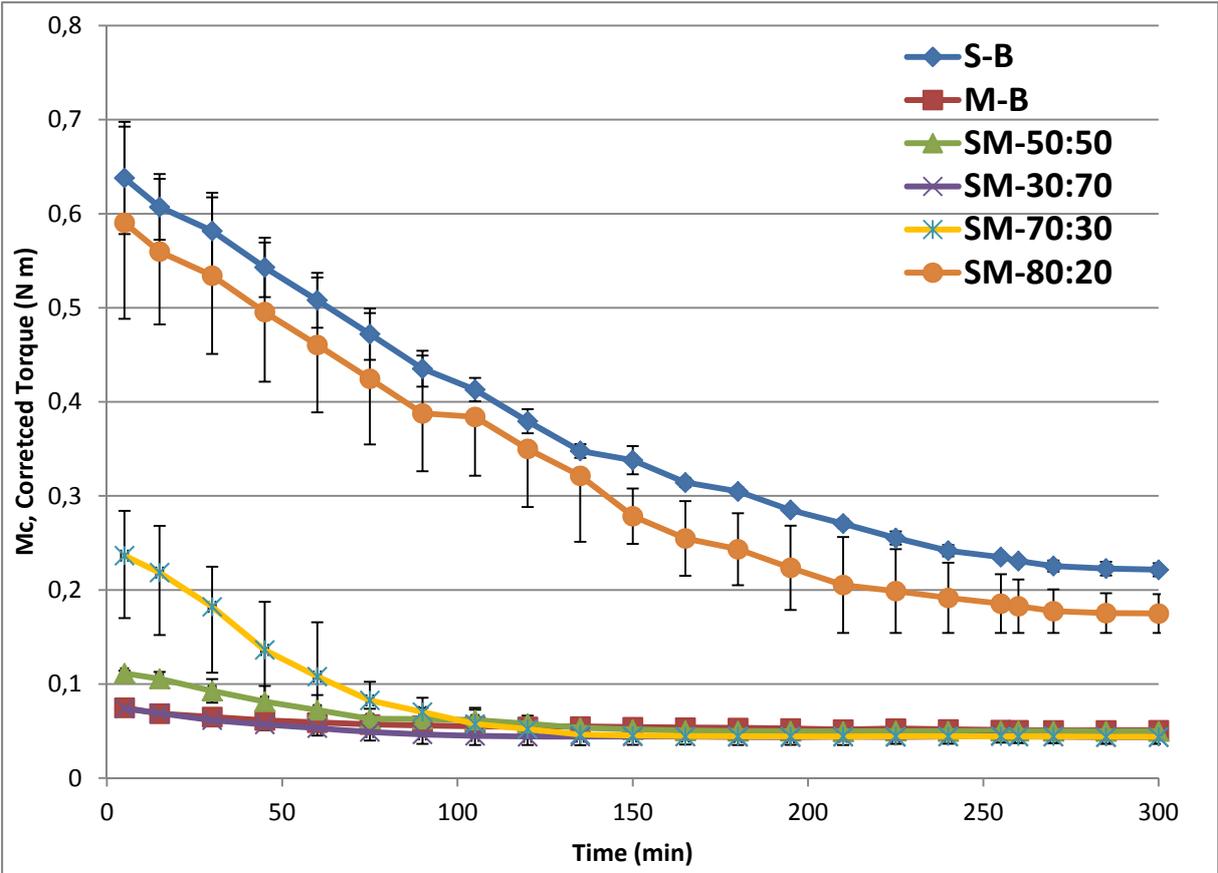


Table 1

	Miscanthus	Wheat Straw
DM content (% w/w)	73.35 ± 1.01	70.79 ± 1.29
Cellulose content (%w/w)	45.30 ± 2.35	49.20 ± 2.07
Hemicellulose content (% w/w)	27.10 ± 1.23	12.20 ± 1.91
Lignin content (% w/w)	9.80 ± 0.14	14.90 ± 1.41
Apparent density (kg/m³)	516.10 ± 8.67	433.90 ± 13.40
Density a 0.212 MPa (g/mL)	0.93 ± 0.05	0.70 ± 0.04
Porosity (%)	52.00 ± 2.60	73.00 ± 3.65
Volume of macroporosity (mL/g)	0.34 ± 0.03	0.65 ± 0.07
Volume of mesoporosity (mL/g)	0.02 ± 0.00	0.02 ± 0.00
Volume of microporosity (mL/g)	0.00 ± 0.00	0.00 ± 0.00
Average diameter of the pores (nm³)	16461.10 ± 823.06	43128.40 ± 2156.42
d (0.1) μm	158	175
d (0.5) μm	516	551
d (0.9) μm	1210	1340

Table 2

Labels	Description of the tests
S-B	Batch test with wheat straw
S-FB65	Fed batch test with 65% of the total mass of wheat straw loaded at the beginning of the experiment
S-FB50	Fed batch test with 50% of the total mass of wheat straw loaded at the beginning of the experiment
S-FB35	Fed batch test with 35% of the total mass of wheat straw loaded at the beginning of the experiment
M-B	Batch test with miscanthus
M-FB65	Fed batch test with 65% of the total mass of miscanthus loaded at the beginning of the experiment
M-FB50	Fed batch test with 50% of the total mass of miscanthus loaded at the beginning of the experiment
M-FB35	Fed batch test with 35% of the total mass of miscanthus loaded at the beginning of the experiment
SM-80:20	Batch test with a mixture composed by 80% of wheat straw and 20% of miscanthus
SM-70:30	Batch test with a mixture composed by 70% of wheat straw and 30% of miscanthus
SM-50:50	Batch test with a mixture composed by 50% of wheat straw and 50% of miscanthus
SM-30:70	Batch test with a mixture composed by 30% of wheat straw and 70% of miscanthus

Table 3

	Mixing Time (s)	Energy Consumption (J)	Glucose concentration (g/L)
Water	3.33 ± 0.44	847.12 ± 9.42	xxxxxxxxxxx
Wheat Straw at t = 0	53.27 ± 2.10	xxxxxxxxxxxxx	4.11 ± 0.15
S-B	41.28 ± 1.81	32,623.21 ± 272.94	18.42 ± 1.23
S-FB65	42.57 ± 1.50	34,105.87 ± 797.05	19.96 ± 0.83
S-FB50	41.20 ± 1.64	13,028.88 ± 1010.21	19.54 ± 1.26
S-FB35	39.20 ± 1.68	9,567.57 ± 1442.52	19.67 ± 1.21
Miscanthus at t = 0	17.20 ± 1.26	xxxxxxxxxxxxx	3.51 ± 0.18
M-B	11.26 ± 0.84	6,814.98 ± 635.90	21.85 ± 0.25
M-FB65	10.00 ± 2.17	7,287.02 ± 150.41	20.10 ± 1.15
M-FB50	10.42 ± 0.85	4,788.05 ± 263.05	20.11 ± 0.74
M-FB35	10.16 ± 0.57	4,888.74 ± 128.19	20.25 ± 0.85
SM-80:20	38.57 ± 2.37	30,548 ± 542.34	20.21 ± 0.85
SM-70:30	36.50 ± 1.42	7,946.21 ± 124.91	19.81 ± 0.63
SM-50:50	24.50 ± 3.53	5,661.82 ± 476.88	20.87 ± 1.35
SM-30:70	15.50 ± 2.12	4,492.21 ± 85.43	20.57 ± 1.01