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**Acidification with sulfur of the separated solid fraction of raw and co-digested pig slurry: effect on greenhouse gas and ammonia emissions during storage**

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39 2000), perlite and lightweight expanded clay aggregate (Leca<sup>®</sup>) (Berg *et al.* 2006), wooden lids and  
40 chopped straw placed on the slurry surface (Amon, 2006).

41 A strategy widely used in Denmark to reduce NH<sub>3</sub> volatilization consists in slurry acidification  
42 (Eriksen *et al.* 2008). Ammonia volatilization can indeed be reduced by lowering slurry pH,  
43 whereby the NH<sub>3</sub>/NH<sub>4</sub><sup>+</sup> equilibrium shifts towards NH<sub>4</sub><sup>+</sup> concentration. Acidification is also known  
44 to positively affect GHG emission (Fangueiro *et al.* 2014; Dai & Blanes-Vidal, 2013; Kai *et al.*  
45 2008; Jensen, 2002; Frost *et al.* 1990; Stevens *et al.* 1989).

46 Nevertheless, acidification is commonly performed by using strong acids, mainly concentrated  
47 sulfuric acid. Some limitations to their use, such as their hazards to human health, are important  
48 issues that need to be overcome. Furthermore, at present, solutions to acidify solid manures (e.g.  
49 farmyard manure and slurry separated solid fraction) are lacking.

50 The paper presents the results of a laboratory study performed to assess: i) the feasibility to acidify  
51 the separated solid fraction of raw and co-digested pig slurry by using a powdery sulfur-based  
52 product and ii) the effect of this acidification method on greenhouse gases (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O) and  
53 NH<sub>3</sub> emissions during manure storage.

54

## 55 **Materials and methods**

### 56 *Manure sampling*

57 Samples of raw (RS) and co-digested slurry (DS) were sampled at two farms located in Piedmont  
58 (northwest Italy).

59 Raw slurry was collected from a pig-breeding farm, where 2500 sows and 2300 fattening pigs were  
60 bred on slatted floors. The pigs' diet was mainly represented by corn mash, and to lesser degrees, of  
61 barley, soybean, wheat, and bran.

62 Co-digested slurry was collected in the same period from a CSTR (Continuous Stirred Tank  
63 Reactor) biogas plant with an installed electric power of 500 kW. The mesophilic plant (40° C) has  
64 a hydraulic retention time (HRT) of 40 days and is fed with (w/w) 70% pig slurry, 12% maize  
65 silage, 7% sorghum silage and 4% cattle manure.

66 Raw slurry and co-digestate were transported in 30 litres barrels to the laboratory and placed in a  
67 refrigerated room at +4° C until separation tests.

### 68 *Mechanical separation*

69 Separation tests were performed at the Waste Management Group laboratory of the Department of  
70 Agriculture, Forest and Food Sciences (DISAFA) - University of Turin, Italy. Raw slurry and co-  
71 digested slurry were mechanically separated by a lab-scale screw press device normally used to  
72 produce tomato sauce (Popovic *et al.* 2014). The machinery has a maximum working rate of 200 kg  
73 h<sup>-1</sup> of tomato, an auger rotation of 180 rpm and a 1 mm diameter mesh size. Screen openings of  
74 commercial mechanical separators vary, ranging from 0.1 to 3.0 mm, according to separator type  
75 and particularly to the total solids content of the input manure (Hjorth *et al.* 2010). For screw press,  
76 studies conducted in Italy by Balsari *et al.* (2006) and Dinuccio *et al.* (2014) reported screen

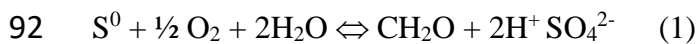
77 openings ranging from 0.75 to 1.5 mm, with smaller openings typically used for pig slurry and  
78 larger for dairy cattle.

### 79 *Solid fraction acidification and chemical analysis*

80 The efficiency of acidification on emission abatement depends on the additive, manure type, step in  
81 the slurry management chain, and contact between additive and manure (Ndegwa *et al.* 2008).  
82 Several studies have confirmed that NH<sub>3</sub> emissions are directly related to the final pH of the slurry  
83 reached after the addition of the amendment (Fangueiro *et al.* 2014): by achieving pH values of 5.5  
84 – 6 the NH<sub>3</sub> (Kai *et al.* 2008; Jensen, 2002; Frost *et al.* 1990; Stevens *et al.* 1989) and CH<sub>4</sub> (Ottosen  
85 *et al.* 2009) emissions can be reduced by 70 - 90%. Thus, we fixed the value 5.5 as pH target below  
86 which emission were expected to be decreased.

87 The obtained undigested (raw) and co-digested solid fractions were acidified by the addition of a  
88 powdery sulfur-based product (Microthiol® Disperss®, 80% micronized wettable elemental sulfur)  
89 widely used in crop protection as a fungicide.

90 The rationale behind acidification with elemental sulfur relies on the chemical reaction described in  
91 equation (1):



93 It has been well documented (e-g., Fukumoto *et al.* 2003) that manure that is stored solid allows  
94 oxygen diffusion into the manure pile, and therefore, there will likely be the opportunity reaction of  
95 equation 1 to occur.

96 Sulfur was added to both co-digested and raw separated solid fractions at three rates: 0.5%, 1 % and  
97 2% (w/w) calculated on wet basis (WB). Solid fraction after sulfur addition was thoroughly mixed  
98 manually to evenly distribute the powdery product. Unacidified raw and co-digested solid fractions  
99 were used as control. Prior to and after acidification, samples of all treatments were collected, and  
100 stored at 4°C prior to chemical characterization. Dry matter (DM) content was measured after  
101 drying (24h at 105 °C) the fresh samples to constant weight. The volatile solids content (VS) was  
102 calculated as weight loss upon ignition at 550 °C for 5h (VDI 4630, 2006). Samples were weighted  
103 using a four digits trusted balance (Kern®, mod. ABS 220-4). pH of the solid fractions prior and  
104 during the experiment were measured by a glass electrode for semi solid-biomasses (Hanna  
105 instruments® electrode HI 1053B). At the end of the trials pH was measured after solid fraction  
106 dilution in deionized water, followed by 45 min of shaking, and then 15 min of settling (Jorgensen  
107 & Jensen, 2009). Total N (N<sub>tot</sub>) and total ammonia nitrogen (N-NH<sub>3</sub>) were measured according to  
108 the Kjeldahl standard method (AOAC, 1990).

### 109 *Measurement of gaseous emission*

110 Emission tests were performed by filling 2000cm<sup>3</sup> jars with 1000cm<sup>3</sup> of unacidified and acidified  
111 solid fractions with three replicates per treatment. The bulk density of the tested raw and co-  
112 digested solid fraction samples was estimated to be 500g/1000cm<sup>3</sup>. Gaseous (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O and  
113 NH<sub>3</sub>) emissions were measured by a ventilated chamber system and using an infrared photo  
114 acoustic detector (IPD) (1412 Multi-gas Monitor, Innova® Air Tech Instruments, Ballerup,  
115 Denmark) as described by Dinuccio *et al.* (2008). The IPD was calibrated before the beginning of

116 the experiment by the manufacturer and was run with corrections from cross interferences between  
117 CO<sub>2</sub>-water vapor and measured target gases, and cross compensation (Huszár *et al.* 2008; Tirol-  
118 Padre *et al.* 2014). Before emission measurements, each jar was closed with an airtight lid provided  
119 with two ports for air inlet and outlet. The air inlet port was connected in an airtight way with a  
120 flow meter and a pump. The headspace between the solid-fraction surface and the lid was then  
121 ventilated to guarantee a complete air change per minute. Gaseous emission were monitored every  
122 24h for the first 2 weeks of trial and three times per week thereafter. The operative steps followed  
123 for emission measurement was carried out according to Dinuccio *et al.* (2008). Specifically, an air  
124 flow of 1000 cm<sup>3</sup>/min across the headspace was established for at least 20 min before gas sampling  
125 to reach a steady state and then emissions were measured over a period of 16 min. Trials were  
126 stopped when all (GHG and NH<sub>3</sub>) gaseous emission dropped to zero for three consecutive days.  
127 Specifically, the tests lasted 30 and 60 days for raw and co-digested solid fraction respectively. The  
128 cumulative net gaseous emissions were determined according to Dinuccio *et al.* (2008). Data were  
129 tested by one-way ANOVA and the Tukey tests ( $\alpha = 0.05$ ). Measured gaseous losses were  
130 converted into CO<sub>2</sub>eq by using the IPCC (2013) Global Warming Potential (GWP) values. Along  
131 the experiment, the environmental temperature at the laboratory was recorded by means of two  
132 Onset® Hobo U12 data loggers.

## 133 **Results and discussion**

### 134 *Raw and co-digested solid fractions chemical characteristics*

135 Chemical characteristics of raw and co-digested solid fraction samples measured at the beginning of  
136 the experiments are shown in Table 1. Despite a similar DM content, VS concentration in the co-  
137 digested solid fraction was significantly ( $p < 0.05$ ) lower than that in raw solid fraction, as a  
138 consequence of organic matter degradation during the anaerobic digestion process. The initial pH  
139 were 8.00 and 8.51 for the raw and co-digested solid fraction respectively. Also total nitrogen  
140 concentration was similar for the two biomasses, whereas a higher ammonia nitrogen content was  
141 found for the co-digested solid fraction, due to N mineralization occurring during anaerobic  
142 digestion.

143 At the end of the experiment, the DM content of both raw and co-digested solid fraction were found  
144 to be higher compared to the initial values (Table 2) as a consequence of water evaporation during  
145 the experiments (Table 3). The evolution of solid fractions pHs along the experiments are shown in  
146 Fig. 1. With respect to unacidified solid fraction from mechanical separation of raw slurry, pH  
147 remained above 6.5 for the whole experimental period. Acidified fractions showed decreasing pH  
148 values already after 24hrs from sulfur addition, as a result of H<sup>+</sup> formation and S oxidation (Roig *et al.*  
149 *et al.* 2004). Sample RS 2 reached the pH target (5.5) at day 7, RS 1 at day 9 and RS 0.5 after 14 days  
150 from S addition. The minimum pH values (2.47) was reached by RS2 at day 23. With co-digested  
151 solid fractions, sulfur addition took longer to affect solid fraction pHs. The latter started indeed to  
152 drop after three days from acidification. This might be due to the higher buffer capacity of the  
153 material when compared to non-digested solid fraction. DS 1 and DS 2 needed about a week to  
154 reach the pH target, whereas pH of DS 0.5 treatment dropped below 5.5 after approximately 30  
155 days. The minimum pH value (2.87) was reached by DS2 treatment at day 56.

156 Environmental temperature is well known to strongly affect NH<sub>3</sub> and CH<sub>4</sub> emissions (Dinuccio *et al.* 2008, Wang *et al.* 2014). Furthermore, Jaggi *et al.* (1999) found a strong influence of  
157 temperature on the rate of S oxidations. Recorded temperatures were similar along the two  
158 experiments. Average, minimum and maximum values are reported in Table 3.  
159

#### 160 *NH<sub>3</sub> emissions*

161 NH<sub>3</sub> emissions from raw-slurry separated solid fraction started to drop already at day 3 when pH  
162 approached 5.5 (Fig. 2a). All treatments were effective, regardless of S application rate. Fig. 3  
163 shows the total NH<sub>3</sub> emission quantified along the trial. The control (RS) lost as ammonia  
164 approximately 6% of its initial total nitrogen content (Table 4). This value is consistent with that  
165 (5.6%) measured by Dinuccio *et al.* (2008). Acidified samples lost 1.93% to 3.20% of their initial  
166 total nitrogen (Table 4). Depending on the amount of added S, NH<sub>3</sub> emissions from RS 0.5, RS 1  
167 and RS 2 acidified fractions were respectively 49%, 65% and 70% lower than those of the control  
168 treatment. Specifically, the higher the S application rate, the higher the abatement efficacy. These  
169 findings are consistent with measurement performed on raw slurry by Pain *et al.* (1990), Kai *et al.*  
170 (2008) and Dai & Blanes-Vidal (2013) by using sulfuric acid as acidifying agent. The NH<sub>3</sub>  
171 emissions from co-digested solid fraction were twofold higher when compared to those of raw  
172 separated solid fraction. This was probably due the higher initial N-NH<sub>3</sub> concentration (Table 1)  
173 (Chadwick *et al.* 2011). All acidification treatments significantly reduced ammonia emissions by  
174 approximately 65% with respect to untreated solid fraction. NH<sub>3</sub> emissions from acidified fractions  
175 started to drop at day 7 (Fig. 2b), when pH approached 5.5 (Fig. 1b). The control (DS) lost on  
176 average 19% of total initial nitrogen as ammonia, whereas from acidified solid fractions 6-7% of the  
177 initial nitrogen was lost as ammonia (Table 4).

#### 178 *GHG emissions*

179 The effect of S addition on GHG emissions from the storage of raw slurry and co-digested solid  
180 fractions is displayed in Fig. 4. Although the two tests had different duration (30 and 60 days for  
181 RSs and DSs respectively) total GHG emission from control samples (RS, DS) were in the range of  
182 6 kg CO<sub>2</sub>eq m<sup>-2</sup>. N<sub>2</sub>O was the most relevant GHG in both experiments. Acidification showed to be  
183 more effective when applied on raw (non-digested) solid fractions. The highest emission reduction  
184 (%) was obtained with 2% S addition, but this value was found to be not significantly ( $p > 0.05$ )  
185 different from that (%) recorded for RS 1. A 0.5% S application rate was able to reduce by 44%  
186 GHG emission when compared to control. The same S application rate (treatment DS 0.5) increased  
187 CO<sub>2</sub>eq. emission by 44% when applied to co-digested solid fraction, due to high (+55%) N<sub>2</sub>O  
188 emissions. Nevertheless, DS 0.5 reached the target pH very late (after 30 days from S addition),  
189 thus suggesting this rate to be too low for this kind of animal waste, being characterized by a high  
190 initial pH and buffer capacity. N<sub>2</sub>O emissions increasing were probably due to an enhanced  
191 microbial activity with S as a growing factor (Sierra-Alvarez *et al.* 2007). Biogas obtained by  
192 digesting pig slurry generally contains approximately 3000-8000 ppm hydrogen sulfide (H<sub>2</sub>S) (Wei-  
193 Chin Lin *et al.* 2012). Hydrogen sulfide have damaging effects on the engine components and  
194 equipment and it is therefore removed before combustion in combined heat and power units. The  
195 most common method for H<sub>2</sub>S removal from biogas is based on the addition of a small amount of  
196 oxygen or air (3-5% v/v) directly into the digester (Ramos & Fdz-Polanco, 2014). In this way it  
197 takes place the biological aerobic oxidation of H<sub>2</sub>S to elemental sulfur and sulphates by a

198 consortium of sulphur-oxidising microorganisms (e.g., Thiobacillus bacteria). This process can  
199 results in the accumulation of elemental sulfur and sulphates in the digester. It is assumed that in  
200 the co-digested slurry are present nitrifying prokaryotes that could have an affinity with sulfur.  
201 Therefore a higher sulfur dose might be necessary to inhibit the nitrification/denitrification  
202 biological activity of these bacteria that could be otherwise promoted by a lower S application rate.

203 Higher S application rates (DS 1 and DS 2) significantly reduced CO<sub>2</sub>eq. losses (by 39% and 55%  
204 respectively). With special regards to methane, by applying 2% sulfur a 54% losses reduction was  
205 observed.

## 206 **Conclusions**

207 The addition of elemental S to solid fractions showed to be a reliable and effective method to  
208 acidify raw and digested solid fractions. Thus, it can be considered as an alternative method to the  
209 common sulfuric acid utilization. Sulfur addition led to significant reduction of gaseous losses (NH<sub>3</sub>  
210 and GHG) during the solid fractions storage. The most evident outcome is represented by the  
211 significant reduction of NH<sub>3</sub> emissions rate for both the tested biomasses with abatement of up to  
212 70% in raw slurry solid fraction and 65% for the digested one.

213 GHG emissions were respectively reduced from 44% to 78% according to the amount of S added to  
214 non-digested solid fraction. The lower S rate significantly increased GHG emission from the  
215 digested solid fraction only with special regards to increased N<sub>2</sub>O losses.

216 The experimental results allow a first positive evaluation on the possibility to decrease the pH and  
217 gaseous emissions by adding sulfur to solid manures, thus enabling an effective pollution reduction  
218 without using strong acids. The latter aspect is indeed one of the main concerns and a major limit to  
219 the diffusion of manure acidification at a European level.

220 According to our preliminary results 1% S might be considered as the best application rate,  
221 allowing an emission reduction in line with the present acidification technology performances  
222 (Fangueiro *et al.* 2014). However, according to the current market price of powdery sulfur for crop  
223 protection purpose (1€/kg) the former application rate would cost around 5€ per ton of treated solid  
224 fraction. This cost is five times higher than that of slurry acidification by H<sub>2</sub>SO<sub>4</sub>. Nevertheless, it  
225 must be considered that besides the commercial powdery sulfur (normally used for crop protection),  
226 sulfur is a byproduct of the oil refining process. The latter is considered as a waste and thus its reuse  
227 in the animal waste management sector might considerably reduce the cost of slurry acidification.  
228 Appropriate procedures for safely using a powdery acidifying product are already under study by  
229 our research group. Moreover, the DISAFA-Waste Management Group is currently investigating  
230 the feasibility to lower solid fraction pH by S addition to slurry prior to mechanical separation, with  
231 the aim to i) reduce the S application rates and, ii) acidify both solid and liquid fractions with a  
232 single treatment.

233

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- 334

335 **Table captions**

336 Table 1. Average chemical characteristics of raw and co-digested solid fractions at the beginning of  
 337 the experiments (n=3). Values of Standard deviation in brackets.

338 Table 2. Average chemical characteristics of the solid fraction at the end of the test (n=3). Values of  
 339 Standard deviation in brackets.

340 Table 3. Average, maximum and minimum temperatures measured during the tests.

341 Table 4. Percentage of ammonia nitrogen emitted from raw slurry SF and digested solid fractions,  
 342 values with same letters are not significantly different, (n=3). Values of Standard deviation in  
 343 brackets.

344

345

346 Table 1.

<b>Biomass</b>	<b>DM (%)</b>	<b>VS (% DM)</b>	<b>pH</b>	<b>N<sub>tot</sub> (%w/w )</b>	<b>N-NH<sub>3</sub> (%N<sub>tot</sub> )</b>
Pig slurry	15.4 (0.16)	88.0 (0.14)	8.00 (0.01)	0.32 (0.09)	27.0 (0.07)
Co-digested	14.2 (0.32)	83.7 (0.33)	8.51 (0.02)	0.30 (0.10)	36.0 (0.11)

347 DM: dry matter, VS: volatile solids, N<sub>tot</sub>: total nitrogen, N-NH<sub>3</sub>: ammonia nitrogen

348

349 Table 2.

<b>Sample</b>	<b>DM (%)</b>	<b>VS (% DM)</b>	<b>pH</b>	<b>N<sub>tot</sub> (%w/w)</b>	<b>N-NH<sub>3</sub> (%N<sub>tot</sub> )</b>
RS	23.4 (1.20)	85.2 (0.42)	7.14 (0.02)	0.54 (0.12)	1.00 (0.05)
RS 0.5	27.5 (2.70)	84.9 (0.11)	6.18 (0.10)	0.77 (0.06)	45.0 (0.12)
RS 1	28.5 (2.15)	80.6 (0.84)	4.65 (0.35)	0.88 (0.11)	53.0 (0.08)
RS 2	29.7 (2.51)	88.9 (0.51)	3.55 (0.28)	1.32 (0.08)	57.0 (0.12)
DS	26.5 (1.76)	80.0 (0.44)	7.77 (0.11)	0.54 (0.05)	2.00 (0.00)
DS 0.5	30.1 (3.65)	80.1 (0.66)	5.88 (0.18)	0.68 (0.10)	30.0 (0.06)
DS 1	33.8 (3.64)	80.7 (0.49)	4.63 (0.36)	0.85 (0.14)	51.0 (0.03)
DS 2	36.1 (2.19)	81.1 (0.44)	3.51 (0.23)	0.92 (0.10)	55.0 (0.13)

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Table 3.

<b>Origin of solid fraction</b>	<b>Average (°C)</b>	<b>Max (°C)</b>	<b>Min (°C)</b>
Pig slurry	20.5	24.1	15.5
Co-digested slurry	21.3	26.5	15.5

353

354 Table 4.

Trial	N_NH <sub>3</sub> emitted (%N <sub>tot</sub> )
RS	6.34 (0.94) b
RS 0.5	3.20 (0.29) a
RS 1	2.24 (0.05) a
RS 2	1.93 (0.40) a
DS	19.2 (1.08) b
DS 0.5	7.27 (0.84) a
DS 1	6.09 (0.55) a
DS 2	6.30 (0.78) a

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357 **Figures captions**

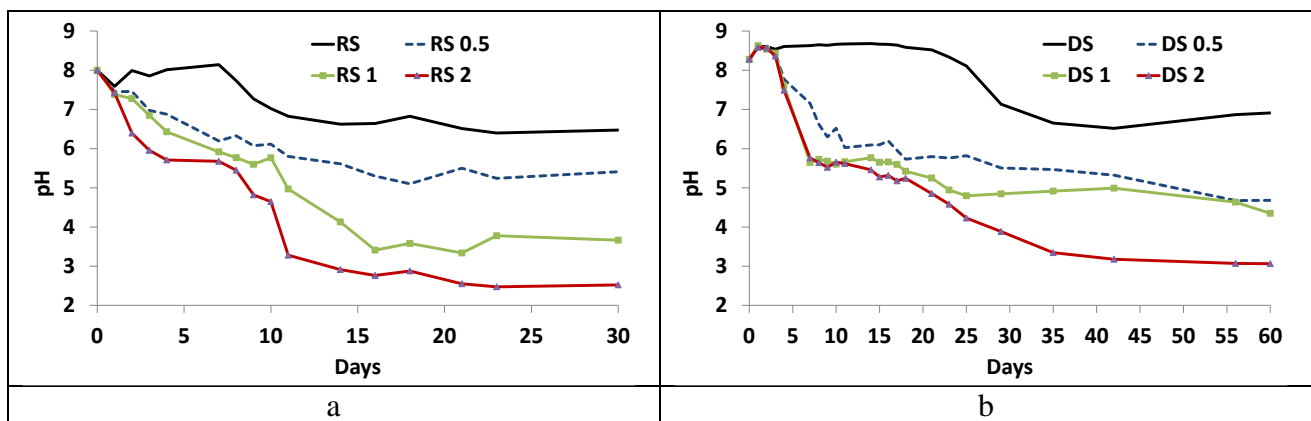
358 Fig. 1. Average pH values pattern of (a) raw slurry solid fraction and (b) co-digested solid fraction  
359 samples along the experiment

360 Fig. 2. Emission fluxes of ammonia (NH<sub>3</sub>) during storage of (a) raw slurry solid fraction and (b) co-  
361 digested solid fraction. Error bars indicate standard deviation (number of observations=3)

362 Fig. 3. Total net ammonia emission from (a) raw slurry solid fraction and (b) digested solid fraction  
363 (values with same letters are not significantly different)

364 Fig. 4. Total GHG emissions during a) raw pig slurry solid fractions and b) co-digested solid  
365 fractions storage (values with the same letters are not significantly different, n=3)

366

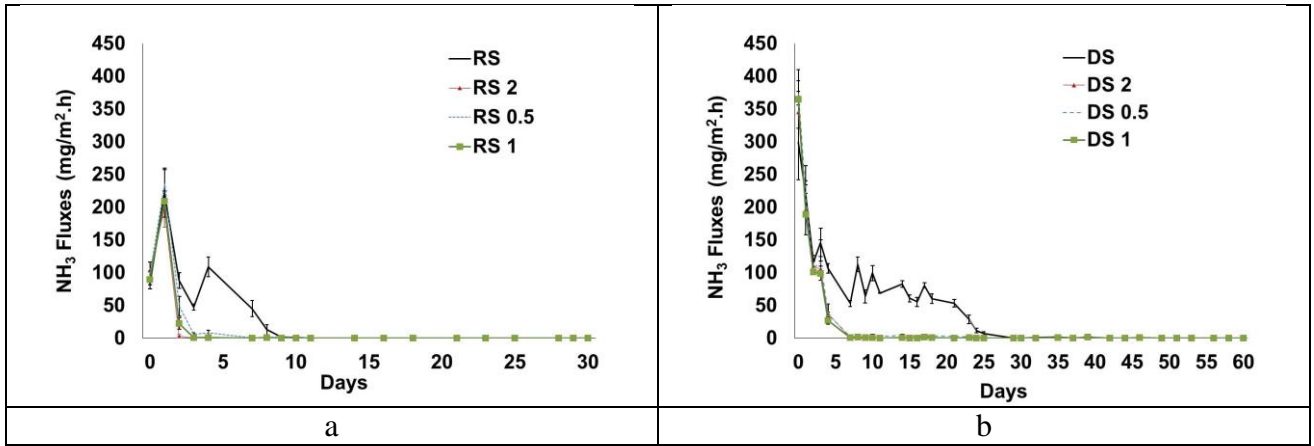


367 Fig. 1.

368

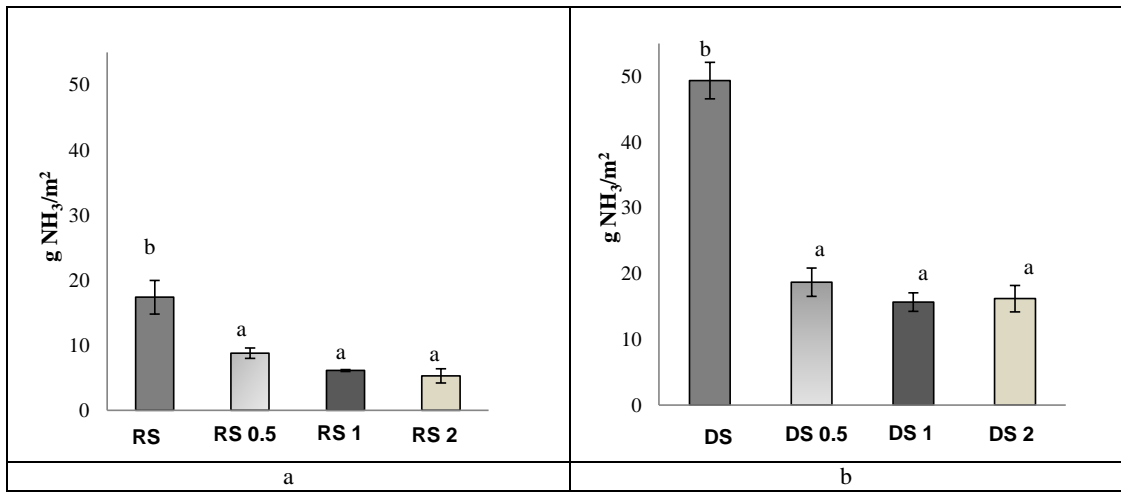
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371 Fig. 2.

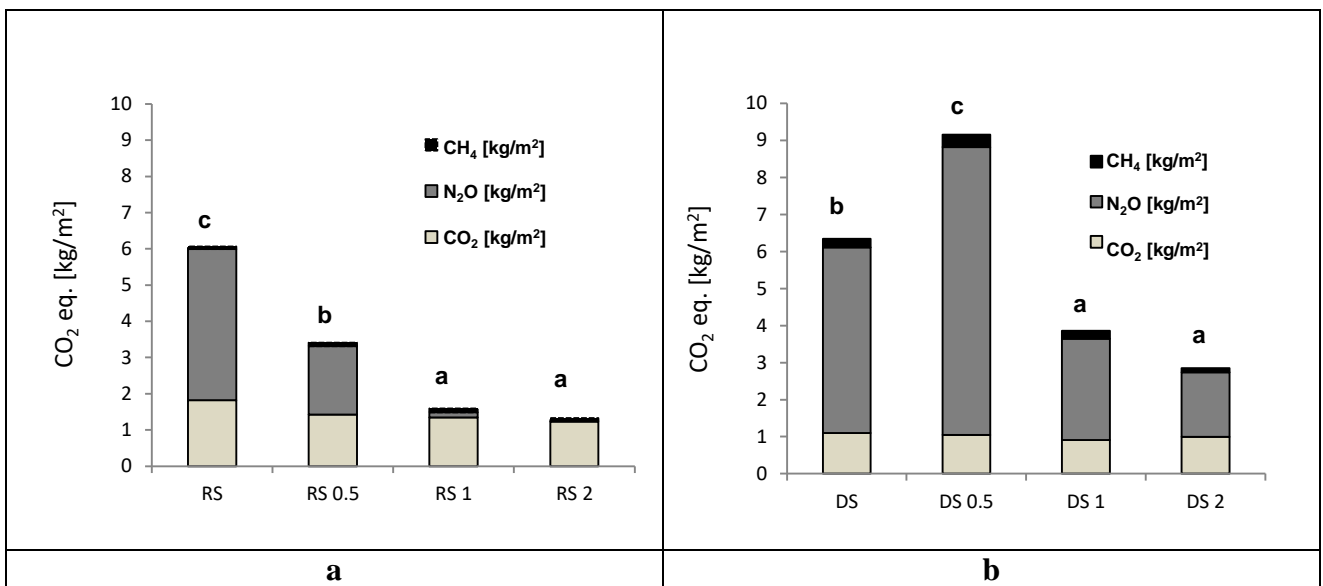
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373 Figure 3.

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375



376 Fig. 4.