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1 **Effect of environmental enrichment with wood materials and straw pellets on the metabolic**
2 **status of sows during gestation**

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9

10 **Abstract**

11

12 Environmental enrichment is a recognized strategy to improve sow welfare. Providing
13 manipulable wood materials and straw pellets to sows during gestation might participate in
14 satisfying their investigative behavior. Sows may also get a benefit from chewing and eating
15 fibers, which can decrease their hunger. Such strategy, however, should not adversely affect
16 metabolic status of sows and newborn piglets. In this study, gestating sows were group-
17 housed in a conventional system on slatted floor (C, n = 26) or in the same system enriched
18 with pieces of oak attached to a chain and straw pellets (CE, n = 30). Straw pellets were
19 provided in the trough at a rate of 200 g/d from 3-30 days of gestation (DG) and 400 g/d from
20 31-104 DG. On DG105, sows were transferred into farrowing pens and housed in identical
21 individual stalls on slatted floor. Sow body weight and backfat thickness were recorded before
22 insemination, on DG105 and at weaning. Plasma concentrations of metabolites and insulin
23 were measured in sows on DG73 and DG102. Blood was also collected from a subset of
24 piglets at birth (n = 6 per litter in 5 C and 8 CE litters) to determine their metabolic and
25 oxidative status. Sow body weight, backfat thickness, and estimated body lipid and protein

26 masses did not differ between treatments during gestation and lactation. Maternal plasma
27 concentrations of glucose, lactate, NEFA, beta-hydroxy-butyrate and insulin did not differ
28 between groups ($P > 0.10$). However, CE sows had lower circulating concentrations of urea
29 ($P < 0.001$) and a greater increase in triglyceride concentrations between DG73 and DG102
30 ($P < 0.05$). Treatment did not influence ($P > 0.10$) piglet birth weight or plasma
31 concentrations of glucose, fructose, lactate and albumin, antioxidant potential and the
32 oxidative stress index in newborns. On the day after farrowing, the milk produced by CE sows
33 contained more minerals ($P < 0.01$) than the milk of C sows but similar contents of protein,
34 fat, lactose, energy and IgA. The proportion of piglets that died at birth and within 12 h of
35 birth was lower in CE than in C litters ($P < 0.05$), but overall mortality (stillbirth +
36 preweaning death) did not differ between the two groups. To conclude, providing manipulable
37 materials and straw pellets to sows during gestation had little impact on sow metabolic status
38 but improved early neonatal survival.

39

40 **Highlights**

41

- 42 • Manipulable materials and straw pellets were provided to sows during gestation.
- 43 • Pieces of wood and straw pellets had no negative effect on sow metabolic status.
- 44 • Pieces of wood and straw pellets had no effect on piglet birth weight.

45

46 **Keywords:** straw; sow; gestation; metabolic status; welfare

47

48 **1. Introduction**

49

50 Improving the sustainability of pig farms requires numerous adaptations of present
51 systems, among which increasing the welfare of the sows and reducing the neonatal mortality
52 of their piglets. This goal might be achieved in environmentally friendly systems for gestating
53 sows. Compared with a group-housing system on a slatted floor with low space allowed per
54 sow (a conventional system in many countries), a housing system enriched with deep straw
55 bedding and offering more space was associated with reduced maternal stress, mild positive
56 effects on piglet maturity at birth and less neonatal mortality (Merlot et al., 2017; 2019;
57 Quesnel et al., 2019). Nevertheless, because rebuilding farms according to most welfare-
58 friendly standards is not always possible in the short term, temporary alternative strategies
59 should be developed. Wood materials can be manipulated and chewed, thus keeping the
60 gestating sows occupied while they are fed restrictively. Straw pellets offer a number of
61 benefits as manipulable and chewable materials and they may also participate in reducing sow
62 hunger via the satiating and swelling effects of insoluble dietary fibers contained in the straw.
63 Enriching the conventional gestation system with wood objects in the pen and straw pellets
64 distributed at the end of the meal may thus improve sow welfare, as illustrated by less
65 stereotypies, more activities of investigation, and lower saliva concentrations of cortisol
66 observed in these sows (Quesnel et al., 2018). However, the fibrous components contained in
67 wheat straw may also influence the absorption pattern of nutrients (Noblet et al., 1989;
68 Ramonet et al., 2000). In line with this effect, feeding pregnant sows with diets rich in dietary
69 fiber influenced their metabolic status and body reserves (Quesnel et al., 2009; Loisel et al.,
70 2013). The impacts however vary with the nature of dietary fiber (Ramonet et al., 2000). We
71 hypothesized that providing wood materials and straw pellets to sows during gestation may
72 influence their metabolic status, with potential effect on nutrient partitioning and
73 consequences on the metabolic status of piglets at birth. This study aimed at testing these
74 hypotheses.

75

76 **2. Animals, materials and methods**

77

78 *2.1. Animals and experimental design*

79

80 The experiment was carried out in the experimental farm of the Chambre Régionale
81 d'Agriculture de Bretagne (CRAB) at Crécom (Saint-Nicolas du Pélem, France). The
82 experimental protocol was approved by the local Ethics Committee in Animal Experiment of
83 Rennes, France, and by the French Ministry of Higher Education and Research.

84 Two group-housing gestating pens were used. Pens were designed for 12 females
85 **maximum** each. They were divided into an open loafing area, where sows had space to move
86 and have social interactions, and a row of free-access individual stalls equipped with feeding
87 troughs. Pens were on a concrete slatted floor and offered 2.4 m² of space per sow. Two metal
88 chains were provided in each pen as a minimal recommended enrichment material. One pen
89 was used without further enrichment (Conventional system, **C**). The second pen
90 (Conventional Enriched system, **CE**) was enriched by providing pieces of oak attached to a
91 chain (3 per pen) and wheat straw pellets distributed by the animal caregiver in the trough
92 after each meal. Pieces of wood are especially suitable to be bitten and chewed by the sows
93 (EFSA AHAW Panel, 2014).

94 The experiment was carried out in three successive replicates of Landrace x Large White
95 sows of mixed parities (1 to 9). Sows were introduced into the gestating pens a few days
96 before insemination. **Seventy-one** sows were inseminated with semen from Piétrain boars.
97 **Fifteen sows were excluded because they were not pregnant, aborted or had leg problems.** In
98 total, 56 sows had confirmed pregnancies and were raised throughout gestation and lactation
99 (**C**: n = 26, **CE**: n = 30). **At the end of gestation, the number of sows per pen was 8, 10 and 8**

100 C sows in replicates 1, 2 and 3 respectively, and 10 CE sows in each replicate. All sows were
101 transferred to farrowing pens at approximately 105 days of gestation (DG105, DG0 being the
102 day of the first insemination) where they were kept in identical individual crates with slatted
103 floor. Housing and management practices from late pregnancy to weaning were similar for the
104 two groups of sows.

105

106 2.2. Sow and litter management during gestation and lactation

107

108 Sows were fed commercial standard diets during gestation and lactation. Diet composition
109 and levels of feeding are presented in Table 1. During gestation, feed was provided to each
110 sow in the form of soup at 0830 and 1630 h in two equal meals. At the end of each meal,
111 straw pellets (First pellets, Maisonneuve, France) were given to CE sows only, at a rate of 200
112 g/d between DG3 and DG30 and 400 g/d between day DG31 and DG104. This
113 supplementation strategy was based on a pre-trial conducted to determine the amount of
114 pellets that could be fed to sows without reducing their appetite. Various quantities of pellets
115 (200, 400 and 600 g/d) provided in 2 meals to gilts and sows in mid-gestation were tested. No
116 feed or straw refusal was recorded with 200 and 400 g but some straw refusals were observed
117 with 600 g. We therefore decided not to exceed 400 g/d and to adopt a progressive increase
118 (200 then 400 g). Pellets were made of dry chopped straw that took up water when distributed
119 in the trough and disintegrated into wisps of straw. Their nutritional composition is given in
120 Table 1. Any feed or straw pellets left in the trough were recorded daily. In the farrowing
121 rooms, sows were individually fed the same lactation diet through an automatic dispensing
122 system.

123 On DG114, parturition was induced by an intramuscular injection of cloprostenol (2 mL of
124 Planate®, MSD Santé Animale, Beaucauzé, France). Piglets born alive and stillborn were

125 individually weighed within 12 h after birth. Then, piglets received standard care
126 interventions. When a sow had more than 15 piglets 24 h after parturition, the extra-piglets
127 were adopted by a sow with a smaller litter (especially with litter size less than 12). Cross-
128 fostering was limited as much as possible and was done within treatment. Piglets were
129 weaned at 28 days and individually weighed. Sows and piglets had free access to water
130 throughout the experiment. Piglets had also access to creep feed from day 10 of lactation.

131

132 2.3. Measurements and sampling during gestation and lactation

133

134 Sows were weighed a few days before artificial insemination, on DG105 and on the day of
135 weaning. On those same days, their backfat thickness was measured ultrasonically using an
136 IMAGO apparatus (ECM, Angoulême, France), at the level of the last rib on each side, 65
137 mm from the midline (P2 site). Their rectal temperature was recorded on DG105, on the day
138 of parturition and the day after. The numbers of piglets born alive, “stillborn” (piglets that
139 died at birth or within 12 h after birth) and weaned were recorded. Piglet death, date and cause
140 were registered throughout lactation.

141 Blood samples were collected on heparin from all sows on DG73 and DG102, before the
142 morning meal. Milk was collected on the day (24 to 36 h) after farrowing, after an
143 intramuscular injection of 20 IU of oxytocin (Ocytovem, Céva Santé Animale, Libourne,
144 France). Milk samples (60 mL) were immediately filtered through gauze and stored at -20°C.

145 Litters from the last replicate (C: n = 5, CE n = 8) were supervised at farrowing and
146 subjected to specific measurements: sex, weight, crown-rump length, and rectal temperature
147 1 h after birth were recorded for all piglets of these litters. Blood samples were collected from
148 five to six piglets per litter (40 females and 34 males in total) from the umbilical cord

149 immediately after birth, before any consumption of colostrum. All blood samples were
150 immediately centrifuged for 10 min at 2,600 x g at 4°C to collect plasma.

151

152 *2.4. Biological analyses*

153

154 **All analyses were done in duplicate.** Concentrations of metabolites were assayed in
155 maternal plasma samples. Enzymatic methods using an Automatic Analyzer (Konelab20i,
156 Thermo Fisher Scientific, Cergy-Pontoise, France) were used to determine plasma
157 concentrations of glucose, triglycerides, β -hydroxybutyrate, and urea (references 981304,
158 981786, 984325, and 981818, respectively, Thermo Fisher Scientific, Vantaa, Finland),
159 lactate (reference735-10, Trinity Biotech, Bray, Ireland), and NEFA (NEFA HR(2),
160 references 434-91795 and 436-91995, Wako, Neuss, Germany). **The intra-assay CV were 1%**
161 **for glucose, 2% for triglycerides, 4% for β -hydroxybutyrate, 3% for urea, 1% for lactate, and**
162 **3% for NEFA.** Plasma concentrations of insulin were measured using a RIA kit (INSULIN-
163 CT; IBA Molecular, Orangeburg, NY, USA). **This kit uses porcine insulin (unlabeled and**
164 **iodinated) and a primary antibody directed against porcine insulin.** Assay sensitivity was 4.6
165 μ IU/mL. The intra-assay CV was 12.2%. Contents of dry matter, ash, gross energy, crude
166 protein, lipids, lactose and immunoglobulins A (IgA) were assayed in milk as **fully** described
167 by Loisel *et al.* (2013).

168 Piglet metabolic status was assessed by plasma concentrations of glucose, lactate, fructose,
169 and albumin in samples collected at birth. Glucose and lactate were assayed by using the same
170 kits as for sow plasma. Kit references for fructose and albumin were 984302 and 981767,
171 respectively (Thermo Fisher Scientific, Vantaa, Finland). **The intra-assay CV were 1% for**
172 **fructose and albumin. As previously described (Buchet et al., 2017), oxidative status was**
173 **assessed by the concentration of hydroperoxides (H₂O₂) and the total antioxidant capacity of**

174 plasma, which were analysed using commercial kits (dROM and BAP tests, Diacron Labs
175 S.R.L., Grosseto, Italy) adapted to an automated analyser (Konelab 20i, Thermo Fisher
176 Scientific, Cergy-Pontoise, France). The dROM test measures the concentration of
177 hydroperoxides generated by the peroxidation of lipids, proteins or nucleic acids. The intra-
178 assay CV was 6%. The results of the test are expressed in $\mu\text{g Eq H}_2\text{O}_2/\text{mL}$. The Biological
179 Antioxidant Power (BAP) results from the combined effects of many antioxidants such as uric
180 acid, ascorbic acid, proteins, alpha-tocopherol or bilirubin. The intra-assay CV was 2%. The
181 results are expressed in $\mu\text{mol/L}$ of equivalent vitamin C used as an iron-reducing reference
182 agent.

183

184 *2.5. Calculations and statistical analyses*

185

186 The chemical composition of sows was estimated from their body weight and backfat
187 thickness using the equations proposed by Dourmad et al. (1997) for lipids and proteins: lipid
188 (kg) = $-26.4 + 0.221 \text{ EBW} + 1.331 \text{ P2}$, and protein (kg) = $2.28 + 0.178 \text{ EBW} - 0.333 \text{ P2}$,
189 where EBW (kg) represents the sow empty live weight estimated from body weight (EBW =
190 $0.905 \text{ BW}^{1.013}$), and P2 (mm) the backfat thickness at the level of the last rib. At the end of
191 gestation, sow body weight was calculated by subtracting the estimated weight of uterine
192 contents (UCW) from body weight with UCW (kg) = $0.3 + 1.329 \text{ litter weight at birth (kg)}$
193 (Dourmad et al., 1997).

194 Statistical analyses were performed using SAS (SAS Inst. Inc., Cary, NC). All models
195 included the effect of treatment (C or CE) and replicate (1, 2, or 3). The GENMOD procedure
196 was used to analyze the number of piglets per litter, using a Poisson distribution and a log-
197 transformation as the link function, and to analyze mortality rates and proportion of piglets in
198 classes of birth weight, using a binomial error distribution and a logit-transformation. To

199 calculate rates of mortality per litter, a piglet was considered to belong to the litter in which he
200 was at the time of his death. Other data were analyzed by ANOVA using the MIXED
201 procedure. For sow and litter performance and milk composition, the model included
202 treatment as the main effect and replicate as random effect. For metabolite and insulin
203 concentrations of sows, repeated measures ANOVA with the fixed effect of treatment (the
204 error term being sow within treatment) and day (the residual error being the error term) as
205 well as the treatment x day interaction were in the model. For traits of newborn piglets (with
206 data recorded on several piglets per litter), the model included the effect of treatment and the
207 random effect of sow nested within treatment. Data are expressed as least-squares means and
208 SEM when analysed using the MIXED procedure and as raw data when analysed using the
209 GENMOD procedure. Differences between C and CE systems were considered significant if
210 $P < 0.05$.

211

212 **3. Results**

3.1. Sow body condition and metabolic status

213

214 During gestation, no feed or straw refusal was observed in C or CE groups. The
215 consumption of straw pellets provided on average 34% extra crude fiber daily to CE sows
216 compared with C sows during the first month of gestation and 68% between DG30 and
217 DG104. It provided only 1.1 and 2.1% extra net energy, 2.0 and 4.1% extra nitrogen and 2.3
218 and 4.6% extra fat during the first month of gestation and between DG30 and DG104,
219 respectively. Sow body weight and backfat thickness before insemination, at DG105 and at
220 weaning did not differ between treatment groups (Table 2). Backfat thickness gain during
221 gestation was lower for CE than for C sows ($P < 0.05$), whereas backfat thickness loss during

222 lactation did not differ between the two groups. The estimated mass of body lipids and
223 proteins at the three physiological stages and their variations did not differ significantly
224 between the two groups of sows (Table 2). At DG105, CE sows had greater rectal
225 temperatures than C sows (Table 2) but there were no more differences between treatment
226 groups on the day of farrowing and the day after.

227 Sow metabolic status changed between DG73 and DG102 (Table 3). Except for lactate,
228 plasma concentrations of metabolites were greater at DG102 than at DG73 ($P < 0.05$). For
229 triglycerides, this increase was more accentuated in CE than in C sows. On the opposite,
230 maternal insulin concentrations decreased with gestational age. Lower concentrations of urea
231 ($P < 0.001$) were observed in CE than in C sows at both stages. Plasma concentrations of
232 other metabolites and insulin did not differ between C and CE sows at both gestation stages.

233

234 *3.2. Sow reproductive performance*

235

236 No treatment effect was observed on the total number of piglets (15.4 ± 0.6 and 15.7 ± 0.8
237 for C and CE sows, $P = 0.785$), the number of piglets born alive (13.8 ± 0.5 and 14.7 ± 0.7 for
238 C and CE sows, $P = 0.347$) and weaned piglets (11.7 ± 0.5 and 12.4 ± 0.5 , $P = 0.424$). The
239 number of piglets that died at birth or within 12 h of birth was numerically lower in CE than
240 in C litters (1.1 ± 0.2 and 1.7 ± 0.4 , respectively, $P = 0.077$). Relatively to the total number of
241 piglets per litter, the proportion of these piglets that died at birth or within 12 h of birth was
242 lower in CE than in C litters (6.6 ± 1.2 vs $11.1 \pm 3.0\%$ of total born piglets, $P < 0.05$). In
243 contrast, the rate of piglet mortality during lactation (beyond 12 h postpartum) did not differ
244 between C and CE litters ($P > 0.05$). Overall mortality from birth to weaning (including
245 stillbirth) did not differ between the two treatment groups (23.2 ± 3.5 and $19.1 \pm 2.2\%$ for C
246 and CE litters, respectively, $P = 0.292$). Litter weight and mean piglet weight at birth ($21.0 \pm$

247 0.5 kg and 1.43 ± 0.03 kg, respectively) and at weaning (106.1 ± 3.0 kg and 8.94 ± 0.15 kg,
248 respectively), as well as litter and piglet weight gain during lactation (3.04 ± 0.09 kg/d and
249 264 ± 4 g/d) did not differ between the two treatment groups ($P > 0.05$). **The distribution of**
250 **piglets into classes of birth weight (< 1 kg, 1.0-1.8 kg and > 1.8 kg) did not differ between**
251 **treatments ($P > 0.05$).**

252 On the day after farrowing, CE sows produced a milk that contained more ash, and
253 therefore more minerals, compared to C sows ($P = 0.004$, Table 4). Otherwise, contents of dry
254 matter, lactose, protein, fat, and energy in milk, as well as IgA concentrations, did not differ
255 between treatments (Table 4).

256

257 *3.3. Piglet characteristics at birth*

258

259 Piglet traits at birth were evaluated in the third replicate from 13 litters. Treatment did not
260 influence the length and weight of piglets at birth and their body temperature 1 hour after
261 birth ($P > 0.05$, Table 5). Piglet metabolic status, assessed by plasma concentrations of
262 glucose, lactate, fructose, and albumin did not differ between piglets born from C and CE
263 sows ($P > 0.05$, Table 5). At birth, plasma hydroperoxide concentration was lower in C than
264 in CE piglets ($P < 0.001$, Table 5), but total antioxidant capacity evaluated by BAP and the
265 oxidative stress index were not altered by treatment.

266

267 **4. Discussion**

268

269 The study was part of a project investigating a strategy to improve the welfare of sows by
270 providing manipulable materials to satisfy their investigative behavior and straw pellets to
271 reduce feeding frustration during gestation. Despite the swelling capacity of wheat straw and

272 its nutritional composition providing mostly fibrous ingredients, no feed nor straw refusals
273 were observed **in the troughs** for the sows receiving this treatment during gestation. **Moreover,**
274 **no significant waste of pellets was observed. Nevertheless, because there was no plate under**
275 **the troughs to collect any waste pellets, some waste cannot be ruled out. Peltoniemi *et al.***
276 **(2010) reported that sows fed a high-fiber diet with ad libitum access to the feed wasted on**
277 **average 60 g of feed per sow and per day.** The amount of straw pellets distributed brought
278 extra net energy and nitrogen to CE sows, which represented on average during gestation only
279 1.8% of net energy and 3.4% of nitrogen provided by the conventional diet. Despite this extra
280 intake, CE sows gained less backfat thickness during gestation. This might be due to the
281 depressing effects of dietary fiber on energy and nutrient digestibility (Noblet et al., 1989;
282 Bach Knudsen et al., 1993). Another explanation may be related to the physical activity of CE
283 sows, which spent more time in a standing posture to investigate the manipulable materials
284 available in their pen when compared with C sows (Quesnel et al., 2018).

285 Treatment had minor impact on sow metabolism during gestation. It significantly
286 influenced plasma concentrations of urea, with reduced concentrations in CE sows. This is
287 consistent with the lower preprandial concentrations of plasma urea that have been previously
288 reported in late-gestating sows fed a high-fiber diet compared to sows fed a low-fiber diet
289 (Loisel et al., 2013). Such effect could be linked to a greater nitrogen use by gut microbiota in
290 response to dietary fiber intake. Indeed, blood urea nitrogen is a substantial source of nitrogen
291 for bacteria of the gut and microbial mass may be increased by an increased intake of dietary
292 fiber, especially in response to the soluble fraction of dietary fiber (Bach Knudsen, 2001). In
293 rats, increasing intakes of soluble fermentable fiber or oligosaccharides increased urea flux
294 from blood to cecum and induced a decrease in blood urea concentrations (Levrat et al., 1993;
295 Younes et al., 1995). Alternatively, lower plasma urea concentrations may reflect a lower
296 protein oxidation due to a lower intestinal absorption of protein when sows consumed straw.

297 The present results also indicate changes in sow metabolic status during the third part of
298 gestation, which were consistent with previous findings (Mosnier et al., 2010). Why the
299 increase in triglyceride concentrations between DG73 and DG102 was greater in CE than in C
300 sows remains unclear. Triglycerides in the blood are mainly derived from dietary fat but C
301 and CE sows were fed the same amount of gestating diet. **Although straw pellets provided**
302 **only a small quantity of fat to sows compared with the diets, it cannot be ruled out that this**
303 **extra fat participated, at least in part, in this difference in triglyceride concentration between C**
304 **and CE sows. Another explanation is related to the effect of dietary fiber on gut microbiota.**
305 **Feeding sows high-fiber diets increases the plasma concentrations of short-chain fatty acids**
306 **(Serena et al., 2009). Dietary fiber might also modulate gut microbiota composition, and**
307 **particularly influence species able to transform dietary fiber into short-chain fatty acids,**
308 **subsequently modifying the energy metabolism of the host, as suggested in growing pigs (Yan**
309 **et al., 2013).**

310 The last treatment effect we observed on sows was a greater rectal temperature at the end
311 of the treatment. It can be attributed to straw ingestion as consumption of fibrous feeds
312 induces a greater heat production (Noblet et al., 1989). In line with the present result,
313 Renaudeau et al. (2003) reported that feeding lactating sows a diet containing a high level of
314 dietary fiber increased sow **rectal** temperature by 0.2°C on average.

315 **Although straw enrichment was not prolonged until parturition, we hypothesized that**
316 **changes in sow metabolic status in response to enrichment might have consequences on milk**
317 **at the initiation of lactation. Straw distribution ceased on average 11 days before parturition,**
318 **which is when colostrum synthesis starts (Quesnel and Farmer, 2019). However, treatment**
319 **had little impact on the composition of the milk collected on the day after farrowing. Average**
320 **contents of nutrients, energy and IgA, were very close in the two treatment groups. The only**
321 **difference was in the content of minerals, which may be explained by the fact that wheat**

322 straw contains minerals. Extra supply by straw pellets averaged 10% of mineral supply by
323 feed. It would be interesting to investigate if the consumption of straw pellets increases the
324 concentrations of specific microelements with potential beneficial impacts on piglet health or
325 survival.

326 With regard to piglet survival, treatment had a positive impact by reducing mortality that
327 occurred during farrowing and within 12 h after birth. This effect cannot be related to piglet
328 birth weight or litter heterogeneity, which were not influenced by treatment. In a previous
329 study, piglets born from sow raised on deep straw litter (E system) were found to have a better
330 early survival than piglets born from sow raised on a concrete floor during gestation (C
331 system). In this previous study, the better survival was not due to a beneficial effect of fiber
332 on kinetics of birth since duration of farrowing, average birth interval and rhythm of piglet
333 births did not differ between the 2 housing systems. In contrast, this previous study revealed
334 that piglets from these two origins had some differences in energy metabolism. Especially, the
335 insulin to glucose ratio of the E piglets was lower suggesting that these piglets had a greater
336 insulin responsiveness than the C piglets (Quesnel et al., 2019). We hypothesized that these
337 metabolic differences might partly contribute to the differences of mortality. In the present
338 study, however, the difference in mortality cannot be attributed to traits related to differences
339 in metabolic or oxidative status of newborn piglets, because the only difference between CE
340 and C piglets concerned hydroperoxide concentrations in plasma at birth, which was low and
341 did not alter the oxidative index.

342

343 5. Conclusions

344

345 The distribution of manipulable materials and straw pellets to sows housed in a poor
346 environment during gestation had no negative effect on their body composition and metabolic

347 status at the end of gestation. This enrichment did not influence piglet birth weight and
348 markers of piglet metabolic and oxidative status. However, it reduced piglet mortality at birth
349 and shortly after birth, and increased mineral content of milk produced at the onset of
350 lactation. Therefore, this strategy to improve sow welfare can be recommended in
351 conventional pig farms, where sows are commonly experiencing hunger and scarce positive
352 stimulations during gestation.

353

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355

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360

361 **Conflict of interest**

362

363 The authors declare that they have no competing interests.

364

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366

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432

433 **Table 1**
 434 Composition of the standard gestation and lactation diets.
 435

	Gestation	Lactation
	diet	diet
Ingredients, % (as fed-basis)		
Barley	35.00	20.00
Wheat	24.81	40.50
Wheat bran	10.00	4.00
Soybean meal	-	14.72
Sunflower meal	10.00	4.00
Rapeseed meal	0.63	-
Corn 2015 Std	-	8.63
Oat	5.00	-
Sugar beet pulp	6.45	2.00
Cornstarch	3.23	1.20
Palm oil	1.70	1.34
Calcium carbonate	2.06	1.00
Dicalcium phosphate	-	0.84
Salt	0.42	0.44
L- Lysine 50%	0.29	0.54
Methionine	-	0.04
Vitamin and mineral premix	0.30	0.30
Choline 75 liq	0.053	0.05
Valine 40	-	0.26

L-threonine

0.03

0.114

436

437

438 **Table 2**

439 **Chemical** composition of feed and straw pellets and distribution to sows. The distribution of
440 gestation and lactation diets was similar for C and CE sows, but only CE sows received straw
441 pellets.
442

	Gestation	Lactation	Straw pellets
	diet	diet	
Sows	C and CE	C and CE	CE only
Composition (as fed basis)			
NE, MJ/kg	9.08	9.81	1.47 ¹
Crude protein, %	12.9	16.5	3.9
Lysine, %	0.6	1.0	Not measured
Lipids, %	3.7	3.1	Not measured²
Crude fiber, %	6.9	4.4	35.7
NDF, %	22.2	15.4	71.6
ADF, %	8.5	5.5	41.1
ADL, %	2.0	1.2	5.1
Ash, %	4.1	4.4	5.4
Average distribution per sow, kg/d			
Insemination to day 28	3.0	-	0.2 (from d 3)
Day 29 to 60	2.6	-	0.4
Day 61 to 80	3.0	-	0.4
Day 81 to 104	3.6	-	0.4
Day 105 to term	3.6	-	-

1 st to 3 rd day of lactation	+1 kg daily	-	-
4 th to 28 th day of lactation	-	Adapted to litter size	-

443 ¹ Straw pellets contained 17.29 MJ of gross energy per kg (as analysed) and net energy per kg
444 was estimated with the InraPorc® software.

445 ² Wheat straw contains on average 1.3% of lipids (InraPorc®).

446

447 **Table 3**
 448 Variations in body weight, backfat thickness and estimated chemical composition of sows that
 449 were housed during gestation in a conventional system (C) or a conventional system enriched
 450 with manipulable materials and straw pellets (CE).
 451

	Treatment		<i>P</i> -value ¹
	C	CE	
No. of sows	26	30	
Parity	3.3 ± 0.4	3.7 ± 0.4	0.402
Gestation length, d	114.7 ± 0.2	114.8 ± 0.2	0.749
Body weight, kg			
Before AI	228.0 ± 11.9	246.6 ± 11.1	0.257
At 105 d of gestation	284.6 ± 10.0	298.8 ± 9.5	0.184
At weaning	255.3 ± 10.1	269.8 ± 9.9	0.212
Variation during gestation	56.6 ± 5.1	52.2 ± 4.8	0.534
Variation during lactation	-26.2 ± 4.0	-29.3 ± 3.9	0.983
Backfat thickness, mm			
Before AI	18.8 ± 1.6	20.3 ± 1.6	0.204
At 105 d of gestation	22.2 ± 1.7	21.7 ± 1.6	0.659
At weaning	17.4 ± 1.4	18.1 ± 1.4	0.593
Variation during gestation ²	3.3 ± 0.8	1.4 ± 0.8	0.014
Variation during lactation ³	-4.7 ± 0.4	-3.6 ± 0.4	0.060
Lipid, kg			
Before AI	48.0 ± 4.3	54.0 ± 4.1	0.180

At 105 d of gestation	58.8 ± 4.0	61.1 ± 3.9	0.472
At weaning	51.7 ± 3.5	55.7 ± 3.5	0.220
Variation during gestation	10.7 ± 1.8	7.0 ± 1.6	0.106
Variation during lactation	-7.1 ± 1.5	-5.5 ± 1.5	0.270
Protein, kg			
Before AI	35.8 ± 2.0	38.5 ± 1.8	0.307
At 105 d of gestation	39.8 ± 1.4	42.3 ± 1.3	0.179
At weaning	40.7 ± 1.6	43.0 ± 1.6	0.239
Variation during gestation	3.9 ± 0.9	3.9 ± 0.8	0.983
Variation during lactation	1.1 ± 0.8	0.6 ± 0.7	0.535
Sow rectal temperature, °C			
At 105 d of gestation	37.9 ± 0.1	38.1 ± 0.1	0.037
On the day of farrowing	38.6 ± 0.2	38.4 ± 0.1	0.216
24 h after farrowing	39.0 ± 0.1	39.1 ± 0.1	0.578

452 ¹ Effect of treatment. **Least-squares means ± SEM.**

453 ² With sow body weight before artificial insemination (AI) used as a covariate.

454 ³ With sow body weight at 105 d of gestation used as a covariate.

455

456 **Table 4**

457 Plasma concentrations of metabolites and insulin in sows that were housed during gestation in
 458 a conventional system (C) or a conventional system enriched with manipulable materials and
 459 straw pellets (CE).

460 Blood was collected at 73 and 102 days of gestation (DG).

461

	At DG73		At DG102		<i>P</i> -value ¹		
	Treatment		Treatment				
	C	CE	C	CE	T	D	TxD
Glucose, mM	4.2 ± 0.1	4.1 ± 0.1	4.4 ± 0.1	4.1 ± 0.1	0.086	0.015	0.164
Lactate, mM	2.4 ± 0.1	2.0 ± 0.1	2.1 ± 0.2	1.8 ± 0.1	0.062	0.049	0.361
NEFA, μM	116.8 ± 18.9	103.0 ± 18.3	183.7 ± 19.8	130.3 ± 18.8	0.120	0.005	0.227
Triglycerides, mg/L	319.6 ± 23.0 ^a	305.6 ± 22.3 ^a	447.4 ± 24.1 ^b	531.5 ± 22.9 ^b	0.198	<0.001	0.010
Urea, mg/L	222.3 ± 7.6	195.1 ± 7.4	263.1 ± 8.0	220.4 ± 7.6	<0.001	<0.001	0.189
OH-butyrate, μM	45.1 ± 3.8	39.9 ± 3.7	56.6 ± 4.0	52.5 ± 3.8	0.288	<0.001	0.870
Insulin, μIU/mL	14.4 ± 1.1	15.6 ± 1.1	10.9 ± 0.8	10.1 ± 1.1	0.888	<0.001	0.375
Insulin:glucose, μIU/mL per mM	3.4 ± 2	3.7 ± 0.2	2.5 ± 0.3	2.4 ± 0.2	0.598	<0.001	0.499

462 ¹ Effects of treatment (T), day (D) and the interaction (TxD). **Least-squares means ± SEM.**

463 ^{a, b} Means without a common superscript differ (*P* < 0.05).

464

465

466

467 **Table 5**
 468 Composition of milk collected 1 day after farrowing from sows that were housed during
 469 gestation in a conventional system (C) or a conventional system enriched with manipulable
 470 materials and straw pellets (CE).
 471

Item	Treatment		P-value ¹
	C	CE	
Dry matter ² , %	21.0 ± 0.5	20.9 ± 0.5	0.984
Ash ² , %	0.67 ± 0.02	0.71 ± 0.02	0.004
Lactose ² , %	4.0 ± 0.1	4.0 ± 0.1	0.698
Protein ² , %	8.1 ± 0.4	7.9 ± 0.4	0.668
Fat ² , %	8.8 ± 0.4	8.6 ± 0.4	0.778
Gross energy, kJ/g	5.84 ± 0.17	5.79 ± 0.16	0.843
IgA, mg/mL	8.48 ± 0.87	8.02 ± 0.84	0.703

472 ¹ Effects of treatment. **Least-squares means ± SEM.**

473 ² Grams per 100 g of whole milk.

474

475

476

477 **Table 6**

478 Neonatal traits of piglets born from sows that were housed during gestation in a conventional
 479 system (C) or a conventional system enriched with manipulable materials and straw pellets
 480 (CE).

481

	Treatment		<i>P</i> -value ¹
	C	CE	
No. of litters ²	5	8	
All piglets			
No. of piglets born alive	70	116	
Mean piglet length at birth, cm	24.7 ± 0.5	24.1 ± 0.4	0.398
Mean piglet BW at birth, kg	1.32 ± 0.10	1.37 ± 0.08	0.737
Rectal temperature 1 h after birth, °C	37.4 ± 0.3	37.8 ± 0.2	0.306
Piglets submitted to blood sampling			
No. of piglets	32	42	
Mean piglet length at birth, cm	24.3 ± 0.6	24.7 ± 0.5	0.570
Mean piglet BW at birth, kg	1.38 ± 0.10	1.45 ± 0.08	0.616
Rectal temperature 1 h after birth, °C	37.4 ± 0.2	37.9 ± 0.2	0.158
Metabolite plasma concentrations			
Glucose, mM	3.39 ± 0.15	3.02 ± 0.13	0.087
Lactate, mM	4.23 ± 0.54	3.73 ± 0.43	0.484
Fructose, mM	2.92 ± 0.24	2.61 ± 0.20	0.344
Albumin, g/L	7.04 ± 0.21	6.54 ± 0.25	0.242
Oxidative status³			
BAP, Fe ²⁺ , μM	1624 ± 50	1550 ± 43	0.283

H ₂ O ₂ , µg Eq/mL	158 ± 1	162 ± 1	0.007
OSI ³	0.10 ± 0.01	0.11 ± 0.01	0.173

482 ¹Effect of treatment. **Least-squares means ± SEM.**

483 ²From the third replicate only.

484 ³ Oxidative stress index as the ratio between hydroperoxides (H₂O₂, µg Eq /mL) and BAP
 485 (µM) concentrations.

486