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1 Mitigating greenhouse gas and ammonia emissions
2 from swine manure management: a system analysis

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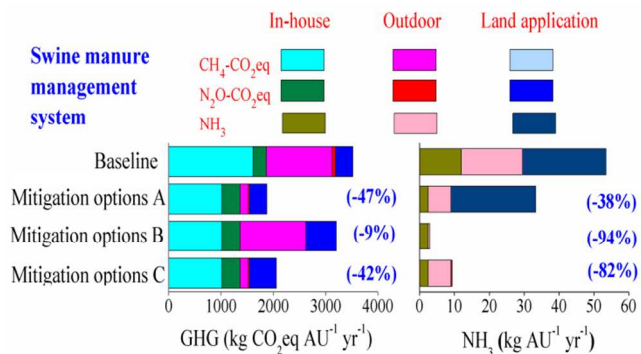
20 KEYWORDS. manure, greenhouse gases, ammonia, mitigation

21

22 ABSTRACT: Gaseous emissions from animal manure are considerable contributor to global
23 ammonia (NH₃) and agriculture greenhouse gas (GHG) emissions. Given the demand to promote
24 mitigation of GHGs while fostering sustainable development of the Paris Agreement, an
25 improvement of management systems is urgently needed to help mitigate climate change and to
26 improve atmospheric air quality. This study presents a meta-analysis and an integrated
27 assessment of gaseous emissions and mitigation potentials for NH₃, methane (CH₄) and nitrous
28 oxide (N₂O) (direct and indirect) losses from four typical swine manure management systems
29 (MMSs). The resultant emission factors and mitigation efficiencies allow GHG and NH₃
30 emissions to be estimated, as well as mitigation potentials for different stages of swine operation.
31 In particular, changing swine manure management from liquid systems to solid-liquid separation
32 systems, coupled with mitigation measures, could simultaneously reduce GHG emissions by
33 65% and NH₃ emissions by 78%. The resultant potential reduction in GHG emissions from
34 China's pig production alone is greater than the entire GHG emissions from agricultural sector of
35 France, Australia, or Germany, while the reduction in NH₃ emissions is equivalent to 40% of the
36 total NH₃ emissions from the European Union. Thus, improved swine manure management could
37 have a significant impact on global environment issues.

38

39 Abstract Art



40

41 1 INTRODUCTION

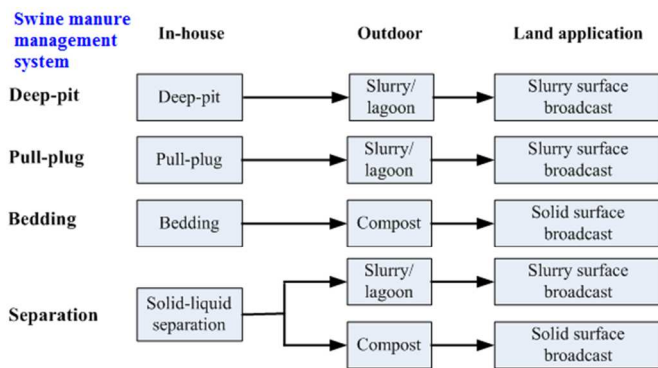
42 Livestock production represents the largest anthropogenic source of methane (CH₄) and
 43 nitrous oxide (N₂O),^{1,2} and contributes a range of critical environmental problems,^{3,4} including
 44 greenhouse gas (GHG) emissions,⁵⁻⁸ ammonia (NH₃) emissions and alteration of nitrogen
 45 cycles⁹⁻¹², land and water use,⁷ and misuse of antibiotics leading to anti-microbial resistance.¹³ In
 46 China, for example, an estimated 42% of the national total chemical oxygen demand (COD) and
 47 22% of the total nitrogen (TN) discharged to the environment arise from livestock production.¹⁴

48 Livestock produce large quantities of manure rich in nitrogen and organic matter that
 49 contribute considerably to global emissions of NH₃ and GHGs.¹⁵ Approximately 40% of the
 50 global anthropogenic NH₃ and N₂O emissions are associated with livestock manures.^{2,9,16} In
 51 China, as much as 78% of the N excreted from the animals are lost to the environment,¹⁷ mainly
 52 through NH₃ emissions which can contribute to odor emanation, water eutrophication, soil
 53 acidification,^{18,19} promote the formation of particulate matter (PM), and also increase climate
 54 change since NH₃ is a precursor of N₂O.^{20,21} Pig manure is particularly important due to the rapid
 55 increase in pig production over recent decades²² and the trend towards intensification of

56 production. Pig manure contributes, respectively, 76%, 32% and 44% of the national CH₄, N₂O,
57 and NH₃ emissions from livestock manures in China.^{23,24}

58 Gaseous emissions from manure management occur in three phases, namely, in-house
59 handling, outdoor storage and treatment, and land application.²⁵ As emissions of NH₃, N₂O and
60 CH₄ result from microbiological, chemical, and physical processes, these emissions are
61 influenced by a multitude of different factors, such as manure characteristics,²⁵ temperature,²⁶ O₂
62 availability,²⁷ tradeoff between emissions of CH₄ and N₂O,²⁸ as well as interactions between N₂O
63 and NH₃.²⁹ Studies have been conducted to address manure-related emissions, and various
64 mitigation measures have been tested and developed. However, most studies have focused either
65 on one specific gas, one individual manure management phase or influencing factor, or
66 mitigation practice.^{1,30,31} Yet it is now recognized that some mitigation measures can cause
67 unintended environmental side effects on other gaseous emissions. For instance, shallow
68 injection, whilst reducing NH₃ emissions from slurry spreading as compared to surface
69 broadcasting, can result in greater N₂O emissions and may also increase the persistence of faecal
70 indicator organisms in soil.^{25,32} Therefore, radical rethinking is imperative to achieve
71 comprehensive reductions in major environmental impacts through an entire manure
72 management system assessment.

73 Four typical manure management systems (MMSs) associated with swine production
74 throughout the world, namely, deep-pit, pull-plug, bedding, and solid-liquid separation, were
75 analyzed in this study (Figure 1).



76

77 **Figure 1.** Representation of the baseline scenarios of four manure management systems.

78 **Deep-pit system.** This is a liquid system, in which manure is collected and stored in the pit
 79 below a slatted floor for several months. Manure is usually thoroughly cleaned out from pit when
 80 a batch of pigs is finished, and the liquid slurry is stored in a lagoon or storage tank until the soil
 81 tillage season when it is land-applied.

82 **Pull-plug system.** This is also a liquid system, but it differs from the deep-pit system in the
 83 length of manure storage period. In pull-plug mode, a shallow pit is used in-house to store slurry
 84 for 2-8 weeks and then drained, by gravity, to an outdoor storage facility, and the slurry is then
 85 land-applied. Liquid systems (including both the deep-pit system and pull-plug system), are
 86 widely used in confined animal feeding operations, accounting for 87%, 92% and 100% of the
 87 swine MMSs in the United States, Germany, and The Netherlands, respectively.³³

88 **Bedding system.** This is a solid manure system, in which the animal's excreta is deposited
 89 onto straw, sawdust or other bedding materials during the in-house phase. Solid manure is then
 90 removed from the pig house and either stockpiled or actively composted, then land-applied.
 91 Given that composting can prevent potential risks of pathogen transfer and reduce viable weed
 92 seeds compared to stockpiling manure, only the composting treatment is included in the analysis

93 of gaseous emissions from the bedding system. Bedding systems are expected to increase in the
94 future due to concerns about animal welfare under other systems.³⁴

95 **Separation system.** This system refers to the separation of solid and liquid manure, in which
96 solids are scraped or manually cleaned out from pig house daily or more frequently, and the
97 liquid is separated. The liquid fraction contains a reduced nutrient burden and flows out of the
98 animal house by gravity to an outdoor storage facility (lagoon or tank). The solid fraction would
99 be composted. Finally, both solid and liquid manure will be land-applied. The separation system
100 is particularly attractive for new facilities, and would be difficult to retrofit to existing buildings.

101 This study represents the first attempt to perform a system-level, comprehensive assessment of
102 GHG and NH₃ emissions from four typical swine MMSs to demonstrate the potential influence
103 of system choices on the magnitude of gaseous emissions. A comprehensive dataset has been
104 collated and developed on CH₄, N₂O and NH₃ emission factors (EFs) for each stage of the
105 MMSs, which included four in-house manure handling practices, three outdoor storage and
106 treatment practices, and seven land application practices. This meta-analysis also quantifies the
107 efficiencies of 17 mitigation strategies, including three in-house, eight outdoor storage and
108 treatment, and six land application mitigation measures. System-level GHG and NH₃ emissions
109 for the four MMSs, with or without mitigation measures were analyzed, and the most effective
110 designs for simultaneous reduction of GHG and NH₃ emissions from each MMS were
111 recommended.

112 2 MATERIALS AND METHODS

113 **2.1 Data sources and selection criterion.** The ISI Web of Knowledge database
114 (www.isiwebofknowledge.com) and the Chinese journal database (www.cnki.net) were used to
115 search all published datasets as of January 2016. Specific search terms were combined and used,

116 depending on animal categories (swine, pig, livestock, animal), manure, in-house manure
117 management (slatted floor, pit, bedding, litter, pull-plug, discharge, scraper, separation), outdoor
118 manure management (lagoon, slurry pond, storage tank, compost, solid storage, stockpile), land
119 application (surface spreading, injection, incorporation, band spreading), gaseous emission (NH_3 ,
120 CH_4 , N_2O , and GHG gas), and mitigation measure (diet, biofilter, biogas, additive, cover, acid,
121 cooling, nitrification inhibition). Literature sources used in this study were selected based on the
122 following criteria: 1) The research object was swine; 2) The study included at least one of the
123 CH_4 , N_2O and NH_3 gases; 3) Gas emission flux or gas emission factor was available; 4) For
124 literature related to mitigation, only studies that reported at least one control group were selected
125 so that emission mitigation efficiency could be calculated.

126 Application of the selection criteria resulted in 142 peer-reviewed papers containing 958
127 effective observations which were used in the meta-analysis. Data were collected from both
128 published tables and text for all the selected research articles, as well as extracted from published
129 figures using the GetData Graph Digitizer software (v. 2.22).³⁵ In addition to the gaseous
130 emission data, related information allowing interpretation of the observations such as swine
131 number, swine weight, area of the lagoon/storage tank, emission flux, and other gas emission
132 relevant information such as study location, seasons, the manure property parameters, and soil
133 properties were recorded (Dataset S1, tabs for raw data). The location and distribution of the data
134 used in this study are summarized in Figure S1. It can be seen that most studies were distributed
135 in Europe, North American and East Asia.

136 **2.2 Data analysis**

137 **2.2.1 Calculation of emission factors (EFs) in the different phases.** To perform statistical
138 analysis, the various units of gas emissions were converted into $\text{kg AU}^{-1} \text{ yr}^{-1}$ (1 AU [animal unit])

139 = 500 kg) using the calculation method presented in Table S1. The NH₃ and N₂O EFs for
140 outdoor manure management (storage and treatment) and land application phases in this paper
141 were calculated as the percentage of total nitrogen (TN), i.e., kg NH₃-N (kg TN)⁻¹ and kg N₂O-N
142 (kg TN)⁻¹. When unit conversion was not possible due to lack of key information, the original
143 emission data were excluded from the statistical analysis. The integrated EFs for each phase of
144 MMS, including the median, mean value, standard error and Interquartile Range (IQR), were
145 calculated with SPSS software (v. 20.0, SPSS Inc., Chicago, IL, USA). Results were not
146 weighted according to sample size; therefore, all of the observations had equal impact on the
147 results. Given the influence of a few measurements with very high values or very low values on
148 the mean values, median values were used instead of means as the basis for subsequent
149 calculations, since median values are quite robust to outliers.³⁶ The 95% confidence interval
150 (95%CI) of the median was calculated using Eq.1.

$$151 \quad 95\%CI = 1.58 \times \frac{IQR}{\sqrt{N}} \quad [1]$$

152 where: N represent the number of observations for each emission factor.

153

154 **2.2.2 Calculation of GHG and NH₃ emissions for the baseline scenarios of four swine**
155 **manure management systems.** Integrated GHG and NH₃ emissions for the baseline scenarios of
156 the four MMSs were calculated, based on the summation method for CH₄ and N mass flow
157 method for NH₃ and N₂O, respectively. The indirect N₂O emissions arising from N deposition
158 and N leaching or runoff were also considered. The detailed calculation process is presented in
159 section 2 of the SI.

160 **2.2.3 Calculation of mitigation efficiency of each measure.** The efficiencies of individual
161 mitigation measures for the corresponding manure management phases were assessed by

162 comparing the result of control and treatment groups sourced from 347 observations, using the
163 following formula:

$$164 \quad E_m = \left(\frac{ER_{trt}}{ER_{ctrl}} - 1 \right) \times 100\% \quad [2]$$

165 where E_m is mitigation efficiency, ER_{trt} is gas emissions in the experimental group with
166 mitigation measures, and ER_{ctrl} is gas emissions in the control group without mitigation
167 measures. Thus, a negative or positive E_m value indicates that the selected measure can reduce or
168 increase gas emissions, respectively. The median E_m values for each measure were calculated
169 using an analytical approach adapted from Benayas et al.³⁷ and Tuomisto et al.³⁸ The normality
170 of the data was tested using the Kolmogorov-Smirnov test. Not all of the E_m s for each mitigation
171 measure were normally distributed; therefore, the Wilcoxon Signed-Rank test was used to
172 determine if the median E_m s were significantly different from zero when there were sufficient
173 results for specific measures. SPSS 20.0 software was used for the statistical analyses.

174 **2.2.4 Calculation of gas emissions under mitigation scenarios for four manure**
175 **management systems.** The integrated mitigation scenarios were set with individual mitigation
176 options included into the corresponding phases of the MMS, and these scenarios are displayed in
177 Table S2. The gas emissions under mitigation scenarios for the four MMSs were the sum of the
178 emissions from each phase, and were based on the numerous calculation schemes described in
179 section 3 of SI. The calculations are presented in Dataset S1 (DeepPitSystem, PullPlugSystem,
180 BeddingSystem, and SeparationSystem tabs; select the dynamic links to other tabs to view the
181 raw data).

182 **2.2.5 Uncertainty Analysis.**

183 Monte Carlo simulations (1000 runs) with R (version 3.3.1) were applied to estimate the
184 uncertainty of the system level emissions. The calculated median values of the gas emission

185 factors, mitigation efficiency factors, as well as their 95% confidence intervals (CI) were
186 included in the uncertainty analysis. The probability density functions (PDF) were assumed as
187 normal distributions for each input data.³⁹

188 As there is a total of 101 designed scenarios for the four systems, quantifying the uncertainty
189 for all the systems would be quite complex, considering the upstream and downstream relations
190 of N. Therefore, a partial uncertainty analysis²² for the four baseline systems and the 12
191 recommended systems was conducted to illustrate the likely uncertainty ranges in the results.

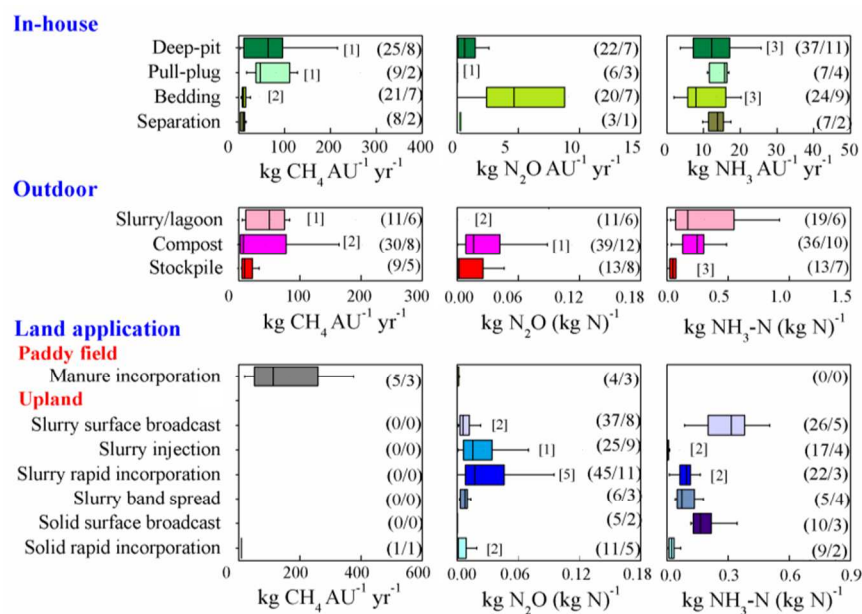
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193 3 RESULTS AND DISCUSSION

194 **3.1 Gaseous emission factors (EFs) for different phases of the swine manure management**
195 **systems.** Emission factors for each phase of the MMSs were assessed from 611 observations by
196 meta-analysis, including four in-house manure handling practices, three outdoor storage and
197 treatment practices, and seven land application practices (detailed description in SI text) (Figure
198 2).

199 **3.1.1 In-house phase.** The results show that different in-house manure collection methods
200 have a significant impact on gas emissions, especially for CH₄ and N₂O. The CH₄ EF is largest
201 for the deep-pit mode (median value of 64.37 kg CH₄ AU⁻¹ yr⁻¹, Table S3), because manure in
202 deep-pits with long storage periods is conducive to generation of CH₄ due to anaerobic
203 conditions. The pull-plug mode with manure regularly removed has the next highest CH₄ EF of
204 47.09 kg CH₄ AU⁻¹ year⁻¹. In comparison, CH₄ emissions for separation mode are much lower
205 with an EF of 10.93 kg CH₄ AU⁻¹ yr⁻¹. The bedding mode has comparatively the lowest CH₄ EF
206 (10.63 kg CH₄ AU⁻¹ yr⁻¹) but the highest N₂O EF (4.70 kg N₂O AU⁻¹ yr⁻¹) due to the nitrification
207 and denitrification processes, which are facilitated by the co-existence of aerobic and anaerobic

208 areas in the continuously accumulating manure on the animal house floor.⁴⁰ The IQR for N₂O EF
 209 of bedding is high at 15.16, with the high variation of the N₂O EF likely due to the complex
 210 emission mechanism of N₂O. For NH₃ emissions, the bedding mode shows the lowest median
 211 value of 8.05 kg NH₃ AU⁻¹ yr⁻¹; whereas for deep-pit, pull-plug and separation modes, the median
 212 NH₃ EFs are higher, in the range of 11.99-14.98 kg NH₃ AU⁻¹ yr⁻¹. There are only three studies
 213 available for separation mode (Table S3), indicating more research is needed.



214
 215 **Figure 2.** Box and whisker plots of the CH₄, N₂O and NH₃ emission factors for the various
 216 manure management practices in three phases (in-house, outdoor and land application) (see
 217 Table S3-S5 for numeric data). The vertical lines of the boxplots represent the median, upper and
 218 lower quartiles. The whiskers show values that extend to 1.5 orders of box length. The numbers
 219 in the square brackets represent the number of outliers (>1.5 orders of box length). Values in
 220 parentheses represent the number of observations on which the statistics were based and the
 221 number of studies from which the observations originated.

222 **3.1.2 Outdoor manure storage and treatment phase.** Slurry/lagoon storage has the largest
223 median CH₄ EF of 50.4 kg CH₄ AU⁻¹ yr⁻¹, which is much greater than that for composted manure
224 (11.1 kg CH₄ AU⁻¹ yr⁻¹) or stockpiled manure (9.4 kg CH₄ AU⁻¹ yr⁻¹), as the liquid slurry storage
225 maintains anaerobic conditions compared to solid manure storage. Slurry/lagoon storage emits
226 almost no N₂O (Figure 2, Table S4), but Harper et al.⁴¹ showed one outlier with an N₂O EF of
227 0.012 kg N₂O-N (kg N)⁻¹. Harper et al.⁴¹ indicated that the NO₃⁻ content in the top 0.5m of
228 lagoon can be 0-34.0 mg N kg⁻¹ which may be supported by the O₂ released from algae in the
229 slurry surface. The N₂O EF for composted manure is 0.017 kg N₂O-N (kg N)⁻¹, compared to
230 0.0017 kg N₂O-N (kg N)⁻¹ for manure that is statically stockpiled. Meanwhile, NH₃ EFs for the
231 slurry/lagoon storage, composted, and stockpiled manure are 0.170, 0.249 and 0.047 kg NH₃-N
232 (kg TN)⁻¹, respectively. Compared with solid stockpile, the consecutive air exchange, in
233 combination with the elevated temperature due to aerobic fermentation, leads to the higher N₂O
234 and NH₃ EFs during active composting.⁴²

235 **3.1.3 Land application phase.** Manure contains a large quantity of C which can be converted
236 to CH₄ when applied to flooded paddy field soils (113.4 kg CH₄ AU⁻¹ yr⁻¹) (Figure 2, Table
237 S5). For upland cropping systems, CH₄ emissions are low and the cropping system is usually seen
238 as a sink for CH₄.⁴³ As such CH₄ emissions during manure upland application are not considered
239 in the following system-level emission calculations.

240 N₂O emission from land application is approximately 0.0058 kg N₂O-N (kg N)⁻¹ for surface
241 broadcast slurry and 0.0001 kg N₂O-N (kg N)⁻¹ for surface broadcast solid manure. Liquid slurry
242 broadcast had a notably higher N₂O EF compared to solid manure. Liquid slurry provides
243 nitrogen, moisture and a source of easily degradable C to the soil, and the increase in
244 heterotrophic activity due to C turnover may provide oxygen-deficient conditions stimulating

245 N₂O emissions for extended periods.⁴⁴ Slurry injection and rapid incorporation increased the
246 N₂O emission factor to 0.0150 and 0.0170 kg N₂O-N (kg N)⁻¹, respectively (Table S5).

247 Compared with N₂O-N, NH₃-N loss is larger from manure land application. Surface broadcast
248 slurry and solid manure results in high NH₃ emission factors of 0.3177 and 0.1800 kg NH₃-N (kg
249 TN)⁻¹, respectively (Figure 2 and Table S5). The usually larger surface area for air contact with
250 slurry may cause higher NH₃ volatilization than solid manure during the land application process.
251 But the NH₃ EF of solid manure land application is lower than that during the solid manure
252 composting process (0.249 kg NH₃-N (kg TN)⁻¹), since a large proportion of TAN is removed
253 during the aerobic fermentation process of compost. The NH₃ emission factors for slurry
254 injection and rapid incorporation were 0.0049 and 0.0955 kg NH₃-N (kg TN)⁻¹, respectively
255 (Figure 2 and Table S5).

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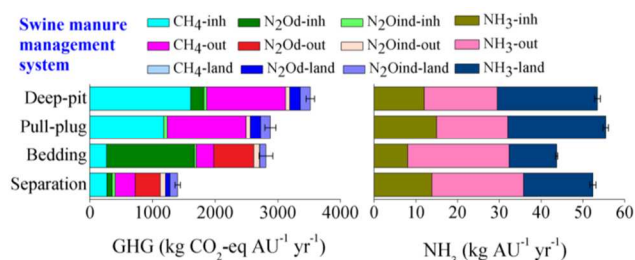
257 **3.2 GHG and NH₃ emissions from baseline scenarios of four manure management**
258 **systems.** Of the four MMSs, the deep-pit system has the greatest GHG emissions, reaching
259 3517±67 (95%CI) kg CO₂-eq AU⁻¹ yr⁻¹, followed by the pull-plug system (2879±88 kg CO₂-eq
260 AU⁻¹ yr⁻¹), and the bedding system (2809±108 kg CO₂-eq AU⁻¹ yr⁻¹). The separation system has
261 the lowest GHG emission of 1400±41 kg CO₂-eq AU⁻¹ yr⁻¹, which is only 40% of the emissions
262 of the deep-pit system (Figure 3. Detailed calculations are presented in section 2 of SI, and
263 results are presented in tab SummBaseEmi of Dataset S1). The results are consistent with the life
264 cycle analysis (LCA) study by De Vries et al.³⁹ which reported that separation reduced GHG
265 emission by 66%-82%. However, the relative uncertainty of the results in this study is
266 comparatively lower than that of De Vries et al.³⁹ The improvement may result from using the

267 computed median value and its 95% CI as the input parameter in this analysis, instead of the use
268 of one point value and the high uncertainty range represented by observed min to max values.

269 The relative contribution of different GHGs are quite different between the four baseline
270 systems, in that CH₄ dominates the GHG emissions of both liquid systems (deep-pit and pull-
271 plug), but accounts for smaller GHG emissions for the pull-plug system. The reason for the
272 lower CH₄ emission of the pull-plug system lies in its less anaerobic environment and a shorter
273 in-house storage period than the deep-pit system. For the bedding system, N₂O is the major GHG
274 contributor due to occurrence of nitrification and denitrification in the solid manure at different
275 phases of the MMS, with N₂O emissions from in-house manure handling and outdoor phases
276 representing 50% and 23% of the total GHG emissions, respectively. For the separation system,
277 the in-house CH₄ and N₂O emissions are both relatively low, because the solid fraction of the
278 manure is removed from the house soon after excretion. Land application represents a relatively
279 small source of the total GHG emissions from MMSs, contributing less than 9% of the whole-
280 system emissions. Since there are no CH₄ emissions during upland manure application process,
281 only N₂O emissions were included in the calculation of GHG emissions. In addition, the lower
282 manure N preserved in the final stage, combined with the low direct N₂O EF factors of 0.0001-
283 0.017 kg N₂O-N (kg N)⁻¹, and the low indirect N₂O EF of 1% for NH₃-N to N₂O-N, as well as
284 0.75% for N leaching/runoff to N₂O-N,²¹ contributed to the low GHG emissions from this land
285 application stage.

286 NH₃ emissions for both liquid systems of deep-pit and pull-plug are comparable at 53.4 ±0.7
287 and 55.4 ±0.7 kg AU⁻¹ yr⁻¹. The bedding system has the lowest NH₃ emission factor of 43.7 ±0.3
288 kg AU⁻¹ yr⁻¹ (Figure 3), because the NH₃ EF for surface broadcasting of solid manure is only half
289 of that for liquid manure (Figure 2). For the two liquid systems, the land application phase

290 dominates the NH_3 emissions for the whole system; whereas for the bedding and separation
 291 systems, the outdoor manure storage and treatment phase contributed the most, as the solid
 292 fraction has a higher NH_3 emission during the composting phase than the land application phase.

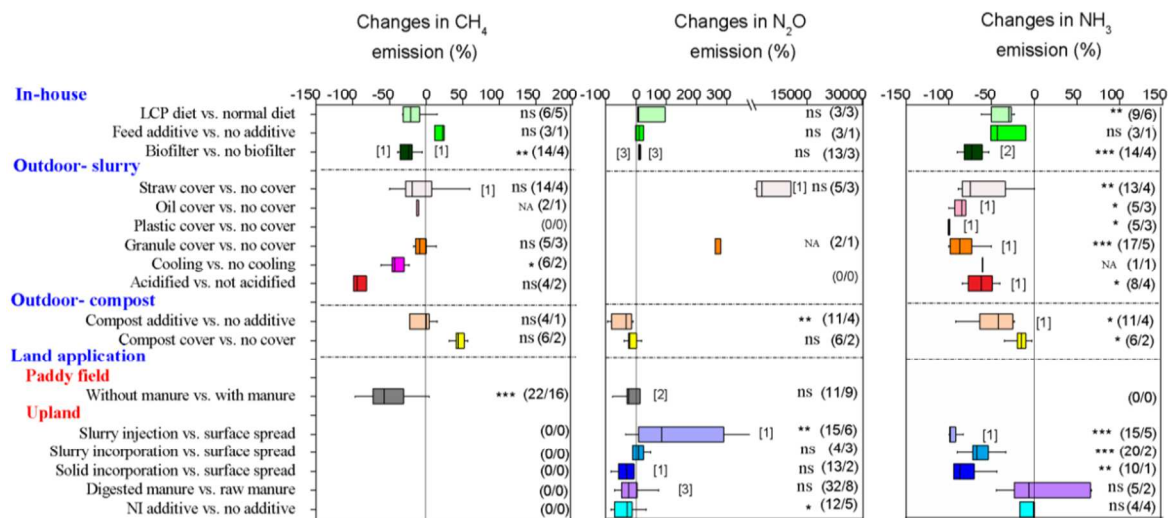


293
 294 **Figure 3.** GHG and NH_3 emissions of baseline scenarios for deep-pit, pull-plug, bedding and
 295 separation systems as defined in Figure 1 (see Tab SummBaseEmi in Dataset S1 for numeric
 296 data). N_2Od =direct N_2O emission; N_2Oind =indirect N_2O emission; in=in-house; out=outdoor;
 297 land=land application; AU=animal unit (1AU= 500kg).

298
 299 **3.3 Effect of mitigation measures.** Various mitigation practices have been developed for
 300 reducing NH_3 and GHG emissions at each phase of MMS; but only practices with available
 301 measurement data on the mitigation effect are included in this analysis. The definitions of each
 302 mitigation measure chosen here are detailed in the SI text. The changes in NH_3 , N_2O and CH_4
 303 emissions under different mitigation practices at each phase are presented in Figure 4.

304

305



306

307 **Figure 4.** Box and whisker plots of the efficiency of mitigation strategies for CH₄, N₂O and NH₃

308 emissions (see Table S6-S8 for numeric data). Vertical lines of the boxplot represent the median,

309 upper and lower quartiles. The whiskers show values that extend to 1.5 orders of box length. The

310 numbers in the square brackets represent the number of outliers (>1.5 orders of box length).

311 Values in parentheses indicate the number of observations for the statistical analysis, and the

312 number of studies from which the observations originated. Wilcoxon Signed Rank test:

313 ***P<0.001; **P<0.01; *P<0.05; ns=not significantly different from zero; NA= not applicable.

314 LCP= low crude protein; NI=nitrification inhibitor.

315

316 **3.3.1 Effect of in-house mitigation measures.** A low crude protein (LCP) diet is highly

317 beneficial as it limits N at source, resulting in lower N content of the excreta (17.0%, Table S9)

318 and thus reduces N-related gaseous emissions during the subsequent manure management

319 phases. This delivers a mitigation potential for NH₃ emissions during the in-house phase (30%,

320 p<0.01) and provides other environmental co-benefits, such as reduced N losses in runoff and

321 eutrophication. Some experiments show that LCP diets may increase manure N₂O emissions,⁴⁵
322 although the amount is not appreciable (Figure 4).

323 The use of biofilters is seen as one of the most effective mitigation measures for limiting NH₃
324 emissions from animal houses (72%, P<0.001) (Figure 4). However, some studies suggest that
325 biofilters may increase N₂O emissions because the absorbed NH₃ from the exhaust air may be
326 nitrified and denitrified, generating N₂O.⁴⁶ Biofilters are also effective at removing CH₄ (24%,
327 P<0.01) via oxidation.⁴⁷

328

329 **3.3.2 Effects of outdoor manure storage and treatment mitigation measures.** For
330 mitigation from slurry storage, almost all types of covers have proven to be effective in reducing
331 NH₃ emissions with median mitigation efficiencies of >75%. Floating plastic cover is the most
332 effective option with a mitigation efficiency of 99.5% (P<0.05), because the plastic covering
333 with secure sealing characteristics could help to avoid gas emissions. Floating straw and granule
334 covers are not recommended since they may increase N₂O emissions by 29 and 2.7 times,
335 respectively, due to nitrification and denitrification processes occurring within the slurry/additive
336 crusts that develop,⁴⁸ although only the effect of straw cover is statistically significant (Figure 4;
337 P<0.05). Petersen et al.⁴⁹ also indicated that cumulative N₂O emission from swine slurry storage
338 can reach 20.6-39.7 g N₂O m⁻² with a straw cover, compared to 0-0.1 g N₂O m⁻² without a straw
339 cover during a 58 day summer measurement period. Meanwhile, a straw cover showed a CH₄
340 mitigation effect with a median value below 0, with the large IQR of 46.50%. Some studies have
341 reported that the decomposition of straw, if used for a prolonged period, may serve as an
342 additional carbon source for methanogens.⁵⁰ Acidification is effective in NH₃ mitigation, with a

343 reduction efficiency of 56% ($P < 0.05$). It also results in a high CH_4 mitigation efficiency (88%,
344 $P = 0.068$) as methanogenesis is inhibited in the acidified slurry.^{51,52}

345 For mitigation of emissions during active composting, additives have proven to be effective in
346 reducing NH_3 (42%, $p < 0.05$) and N_2O (32%, $p < 0.01$) emissions and improving the compost
347 nutrient value. The only outlier that occurred for NH_3 mitigation was for the forsterite compost
348 additive,⁵³ which increased NH_3 emissions by 86%, but delivered a low N_2O emission of 0.65%
349 $\text{kgN}_2\text{O-N (kg N)}^{-1}$ (a 94% reduction of N_2O from control), since forsterite can inhibit the process
350 of conversion of NH_3 to N_2O during composting. Bautista et al.⁵⁴ reported that the $\text{NH}_4^+\text{-N}$ ions
351 of compost with alum and zeolite amendment were three times greater than those of compost
352 without the additives.

353 Biogas recovery and utilization exhibited a high GHG mitigation potential. However,
354 according to 2006 IPCC guideline,²¹ approximately 10% of the CH_4 generated from biogas
355 digesters may subsequently leak to the air. Meanwhile, CH_4 loss from digestate storage is not
356 negligible,⁵⁵ and 5-15% additional biogas yield from digestate storage has been reported.⁵⁶ All of
357 these emissions should be taken into account when assessing the mitigation effect of biogas
358 digesters. Unfortunately, there is no literature reporting a direct comparison of biogas digester vs.
359 the baseline scenario. Therefore, we could not give quantitative data on the mitigation efficiency
360 of biogas digester. A detailed calculation method was developed and presented in section 2.4 of
361 SI.

362
363 **3.3.3 Effects of mitigation measures for land application.** Avoiding manure application to
364 rice paddy fields is an effective GHG mitigation option, with CH_4 and N_2O mitigation efficacy of
365 57% ($p < 0.001$) and 23% ($p = 0.575$), respectively. Emissions from paddy fields, with vs. without

366 manure application, could be 105-353 vs. 31-108 kg ha⁻¹ for CH₄, and 0.44-0.97 vs. 0.31-0.74 kg
367 ha⁻¹ for N₂O.⁵⁷ Compared with pig manure application, use of chemical fertilizers proved to be
368 50% lower in GHG emissions from paddy fields;⁵⁸ thus use of chemical fertilizers instead of
369 animal manure is recommended for paddy fields. But, the emission from manufacture process of
370 chemical fertilizers should be included in future LCA analyses.

371 For manure application to other crops in upland, the specific loss of NH₃-N can be reduced
372 significantly by changing the application method from surface broadcast to injection or
373 incorporation. Mitigation efficiency is usually higher than 70%, and the highest NH₃-N (TN)⁻¹
374 abatement (99%, p<0.001) is observed for slurry injection with a low IQR of 6.90%, meaning a
375 notable agreement between cases available. Reducing NH₃ loss means that more nitrogen is
376 available for crop uptake, with reduced requirement for commercial fertilizers, but the increased
377 soil mineral N pool could potentially cause higher N₂O emissions. Slurry injection may increase
378 N₂O-N (TN)⁻¹ by 84% (p<0.01); nevertheless, the increase of N₂O emission may still be deemed
379 as an acceptable tradeoff for the reduction in NH₃ losses⁴⁴ due to the low N₂O-N loss to TN ratio
380 (median value of 0.7% as indicated in Figure 2). It can be seen that almost all measures used in
381 land application showed a variety of effects on N₂O emission with the IQRs being in the range of
382 49% to 282% (Figure 4). The complex N₂O production processes, the variable manure and soil
383 properties in each study lead to the variability among results for these measures.⁵⁹

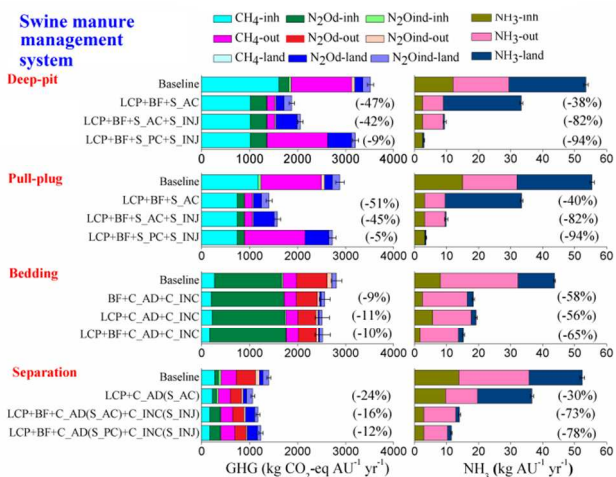
384

385 **3.4 Emissions of four manure management systems under mitigation scenarios.** GHG and
386 NH₃ emissions corresponding to the mitigation scenarios for the four MMSs are shown in Figure
387 S2. The GHG mitigation potentials for bedding and separation systems are always lower than
388 24%, while for the two liquid systems (deep-pit and pull-plug), some combinations of effective

389 mitigation options can have significant GHG mitigation potentials of 47-51% (Figure 5).
390 However, the baseline GHG emissions from the separation system without any mitigation
391 measures, are still lowest when compared with GHG emissions using the mitigation scenarios for
392 the other three MMSs. The largest NH₃ reduction potential for the four MMSs could be 65-94%.
393 The major reductions in NH₃ stem from use of plastic storage covers and changing manure
394 application from surface broadcast to injection or rapid incorporation (Figure 5).

395 **3.4.1 Emission mitigation in the deep-pit system.** Of all the mitigation strategies, the most
396 effective GHG mitigation design for the deep-pit system is the combination of LCP diet,
397 biofilters, and slurry acidification (LCP+BF+S_AC; 1877 kg ±54.2 CO₂-eq AU⁻¹ yr⁻¹, a 47%
398 reduction from the baseline, Figure 5; Scenario DPS-S18 in DeepPitSystem tab in Dataset S1,
399 Figure S2A). The largest mitigation potential comes from CH₄ emissions during the outdoor
400 (manure storage and treatment) phase. As a final step in the manure management chain, the NH₃
401 mitigation potential from the land application process was critical for NH₃ control, thus adding
402 slurry injection (S_INJ) could increase the NH₃ mitigation potential from 38% to 82% compared
403 with the LCP+BF+S_AC scenario (Figure 5). The most effective NH₃ mitigation system design
404 is the combination of LCP diet, biofilters, plastic cover on slurry storage, and injection of slurry
405 (LCP+BF+S_PC+S_INJ; 2.9 ±0.1 kg NH₃ AU⁻¹ yr⁻¹, a 94% reduction, Figure 5; Scenario DPS-
406 S21 in DeepPitSystem tab in Dataset S1, Figure S2A). The combined design of LCP diet,
407 biofilters, slurry acidification and slurry injection (LCP+BF+S_AC+S_INJ, Scenario DPS-S19 in
408 DeepPitSystem tab in Dataset S1) would achieve both low GHG (2057 ±55 kg CO₂-eq AU⁻¹ yr⁻¹)
409 and NH₃ (9.4 ±0.5 kg NH₃ AU⁻¹ yr⁻¹) emissions (Figure 5).

410



411
 412 **Figure 5.** GHG and NH₃ emissions of baseline scenarios and recommended mitigation scenarios
 413 for deep-pit, pull-plug, bedding and separation systems, with baseline scenarios defined in Figure
 414 1; the numbers in parentheses indicate the mitigation efficiency (see DeepPitSystem tab,
 415 PullPlugSystem tab, BeddingSystem tab and SeparationSystem tab in Dataset S1 for numeric
 416 data). N₂O_d=direct N₂O emission; N₂O_ind=indirect N₂O emission; in=in-house; out=outdoor;
 417 land=land application; LCP=low crude protein; BF=biofilter; S_AC=slurry acidification;
 418 S_PC=slurry plastic cover; S_INJ=slurry injection; C_AD=compost additive; C_INC=compost
 419 incorporation; AU=animal unit (1AU= 500kg).

420
 421 **3.4.2 Emission mitigation in the pull-plug system.** The recommended integrated mitigation
 422 options under the pull-plug system are the same as those under the deep-pit system (Figure 5).
 423 The lowest GHG emission and NH₃ emission achieved by the mitigation combinations would be
 424 1404 ±63 kg CO₂-eq AU⁻¹ yr⁻¹ and 3.6 ±0.2 kg NH₃ AU⁻¹ yr⁻¹, respectively (Figure S2B).

425 **3.4.3 Emission mitigation in the bedding system.** The system-level GHG mitigation
 426 efficiencies of all mitigation scenarios are less than 11% from the bedding system, resulting from
 427 the high baseline N₂O emissions and a low corresponding in-house N₂O mitigation potential (see

428 Figure 5 and Figure S2C). Meanwhile, the uncertainty of the GHG emission value from the
429 designed mitigation system with LCP was greater compared with the baseline (Figure 5), due to
430 the high uncertainty of mitigation efficiency of LCP (8% \pm 42%, median \pm 95%CI, K31 in
431 MitigationEffect tab in Dataset S1). The combination of LCP and biofilters, compost additives
432 and incorporation of manure in land application (LCP+BF+C_AD+C_INC) resulted in the
433 lowest system NH₃ emission of 15.3 \pm 0.3 kg AU⁻¹ yr⁻¹, a 65% reduction (Figure 5; Scenario
434 BDS-S15 in BeddingSystem tab in Dataset S1).

435 **3.4.4 Emission mitigation in the separation system.** The separation system has the lowest
436 baseline GHG emissions, and the GHG mitigation potentials for all the mitigation scenarios are
437 less than 24% (Figure 5, Figure S2D). This phenomenon is caused by the major fraction of VS in
438 raw manure being separated into the solid fraction (usually higher than 90%) with low CH₄
439 emissions. However, the mitigation potential for NH₃ could reach 78% leading to a final
440 emission of 11.5 \pm 0.2 kg NH₃ AU⁻¹ yr⁻¹ through use of LCP, biofilters, compost additives and
441 incorporation of the separated solid fraction, plastic cover and injection for the separated liquid
442 fraction [LCP+BF+C_AD(S_PC)+C_INC(S_INJ), Figure 5; scenario SGS-S26 in
443 SeparationSystem tab in Dataset S1], since both the liquid and solid manure could achieve high
444 NH₃ mitigation potential.

445
446 **3.5 Mitigation of gaseous emissions by changing the swine manure management system.**
447 Liquid MMSs are widely used in large-scale confined swine operations because of simplicity in
448 the building structure, reduced labor requirements and advanced mechanization, e.g. for pumping
449 the slurry between different manure management phases. Based on our meta-analysis, changing
450 MMS may be advantageous for some countries, e.g., with a high proportion of liquid systems,

451 such as in The Netherland with 100% liquid production systems. In the case of the Netherlands,
452 the national GHG emissions could be reduced by 1.3%-1.8% on 1990 levels if conventional
453 liquid pig manure systems were transferred to separation systems. This emission reduction would
454 be significant considering the reduction for the Netherlands, as a member of EU which submitted
455 a pledge to reduce its GHG emissions by 2020 by 20 % compared to 1990 levels.⁶⁰ Furthermore,
456 with 50% of global pork production, it is estimated that GHG emissions from China's swine
457 industry would be 213 Tg and 85 Tg CO₂-eq in 2014 using the assumptions of all deep-pit
458 systems and separation systems, respectively. Substituting the deep-pit system with a separation
459 system would lead to a GHG emission reduction of 128 Tg, representing a 15.6% reduction in
460 China's total agricultural GHG emissions, or a 1.8% reduction in China's total GHG emissions
461 from all sources (2005 value).²³ Putting this into perspective, such GHG emission reductions in
462 China's pig production sector, would be greater than GHG emissions for the entire agricultural
463 sector of France, Australia, or Germany, or the total national GHG emissions of New Zealand.

464 With reference to NH₃ mitigation, the effect of a simple change from a deep pit system to a
465 separation system would not be so substantial (only 1.0 kg NH₃ AU⁻¹ year⁻¹), but changing
466 manure application from a surface broadcasting practice to injection or incorporation is
467 recommended. The NH₃ emissions from China's swine industry would be 3.24 Tg and 1.82 Tg
468 NH₃ in 2014 using the assumptions of all deep-pit systems and separation systems plus
469 injection/incorporation method, respectively. Substituting the deep-pit system with a separation
470 system plus injection/incorporation method would lead to a NH₃ emission reduction of 1.42 Tg,
471 representing a 14.0% reduction in China's total national NH₃ emissions (2005-2008 value).²⁴
472 Putting this into perspective, such NH₃ emission reduction in China's pig production sector
473 would be equivalent to 40% of total NH₃ emissions from the European Union.²⁴

474 Although this study is based on a large number of reported observations, they may or may not
475 represent emission factors for the whole world as well as some individual countries, because of
476 the large variety of influence factors, including climate, weather, availability of oxygen, the
477 chemical composition of the manure (e.g., Carbon/Nitrogen-ratio), and soil properties in
478 different locations. The application of EFs or recommended mitigation strategies should take into
479 account these local circumstances.

480 In addition, economic viability will largely determine the selection and implementation of a
481 mitigation system or measure. However, such an economic analysis is beyond the scope of this
482 study. In addition, data are currently lacking about the economic effectiveness of various systems
483 and mitigation measures. Future work should focus on collection of these data which will allow
484 such economic viability analysis to occur.

485 ASSOCIATED CONTENT

486 **Supporting Information**

487 The Supporting Information is available free of charge on the ACS Publications website at [http://](http://pubs.acs.org)
488 pubs.acs.org.

489 The SI includes brief description of some manure management terms, also the detailed
490 methods, equations and assumptions for calculating the emissions for baseline and mitigation
491 scenarios of each phase and whole systems. They are unit conversion method (Table S1);
492 detailed set of the baseline scenario and the mitigation scenarios for each MMS (Table S2),
493 calculated gas emission factors for pig manure management in three stages (Tables S3-5), gas
494 mitigation efficiency of each mitigation option (Tables S6-8), and other parameters used in gas
495 emission calculation (Tables S9-12). In addition, Figure S1 shows the location and distribution

496 of the data used in this study, and Figure S2 shows the GHG and NH₃ emissions in baseline and
497 mitigation scenarios for each MMS. (PDF)

498 Dataset 1 includes the gas emissions calculation process, the parameters used for calculation,
499 as well as raw data from literature. (XLSX)

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503 **Author Contributions**

504 The manuscript was written through contributions of all authors. All authors have given approval
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