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Research Paper

Effects of housing system, floor type and temperature on ammonia and methane emissions from dairy farming: A meta-analysis

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This study provides an overview of ammonia (NH_3) and methane (CH_4) emissions from measurements conducted on a practical scale in different dairy housing systems. In addition, the influence of housing system, floor type and air temperature on NH_3 and CH_4 emissions is statistically analysed using the wide range of data provided by various studies. A number of overviews of NH_3 and CH_4 emission data differentiated according to dairy housing system and season exhibit wide ranges of emission data both between and within individual studies. Although differences in both farm conditions (e.g. herd size, breed, animal productivity, area ratios, ventilation, feeding strategy, management) and measurement concept (e.g. analytics, methods, measurement duration, single farm vs. several farms) make data comparison difficult, clear effects on NH_3 and CH_4 emissions can be demonstrated. The NH_3 emissions of tied housing are lower than those of loose housing systems with cubicles ($p = 0.001$). Furthermore, within the 'loose housing system with cubicles' category, air temperature influences both NH_3 ($p < 0.001$) and CH_4 ($p < 0.001$) emissions. As the air temperature rises, so do the emissions. This also leads to a close positive correlation between NH_3 and CH_4 emissions ($r = 0.80$). There are no differences for either NH_3 or CH_4 emissions ($p = 0.76$ and $p = 0.49$, respectively) between the 'perforated' and 'solid' floor types in loose housing systems with cubicles.

1. Introduction

Studies from the literature on ammonia (NH_3) and methane (CH_4) emissions from dairy housing vary in terms of housing system, floor type, feeding strategy, survey concept, measurement method, etc. (see Appendix A). As a result, the range of emission values both within and between the studies is very wide, in some cases. In order to determine the best mitigation approaches, a knowledge of relevant factors influencing NH_3 and CH_4 emissions is indispensable.

Studies with measurements conducted at different temperatures show that when the temperature rises, so do NH_3 emissions (e.g. Rong, Liu, Pedersen, & Zhang, 2014; Saha et al., 2014; Schiefler, 2013; Schrade et al., 2012; Zhang et al., 2005). In

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studies conducted on several farms within a fairly wide temperature range in each farm, there is an obvious temperature effect both between and within the farms (e.g. Schrade et al., 2012; Zhang et al., 2005). In a statistical analysis of data from the literature encompassing both dairy housing with perforated or solid floor as well as housing systems with open lots, Bougouin, Leytem, Dijkstra, Dungan, and Kebreab (2016) demonstrated a correlation between outside temperature and NH_3 emissions, as well as a significant effect of season on the NH_3 emissions.

The NH_3 emission factors listed in the German emissions inventory for loose housing systems with cubicles as well as for deep-litter and bedded, sloped-floor housing are around three time higher than the emission factor for tied housing (Döhler et al., 2002, p. 192). In case of dairy husbandry, emission data are mainly available for loose housing systems with cubicles followed by tied housings (see Fig. 1), which reflects the relevance of these housing systems. To date, there have been no comparative emission measurements for loose and tied housing. A statistical analysis of data from the literature comparing ‘open lot’ vs. ‘naturally ventilated housing’ vs. ‘mechanically ventilated housing’ systems revealed no significant effect on NH_3 emissions (Bougouin et al., 2016). The reason given for this was that the effect of housing system was masked by other effects (e.g. floor type, dung removal system).

Comparative studies on the influence of floor type on NH_3 emissions in dairy loose housing are very few in number: Braam, Ketelaars, and Smits (1997) compared NH_3 emissions of both perforated and solid floor with and without a transverse slope (3%) in an experimental loose housing system with mechanical ventilation. Whilst there were scarcely any differences in NH_3 emissions between perforated and solid floors without slope (12 dung removal events per day), NH_3 emissions for solid floors with slope were a good 20% lower (Braam et al., 1997). With measurements taken in a naturally ventilated dairy loose housing system with cubicles, slurry homogenisation in the channels beneath the slats dominated the effect on the NH_3 emissions in the case of the perforated floors (Schiefler, 2013), which decreases the informative value of the comparison of perforated and solid floors. In a meta-analysis carried out by Bougouin et al. (2016), the comparison of NH_3 emissions from open lots (open floors comprised of soil) loose housing with perforated floors and loose housing with solid floors difference between perforated and solid floor was relativised by evidently high NH_3 emission values originating from open lots.

Existing reviews on CH_4 emissions from dairy farming primarily address the effects of feeding strategy, ruminal fermentation or animal productivity on enteric CH_4 emissions, and ways to reduce the latter (e.g. Beauchemin, Kreuzer, O'Mara, & McAllister, 2008; Boadi, Benchaar, Chiquette, & Massé, 2004; Knapp, Laur, Vadas, Weiss, & Tricarico, 2014). According to international conventional values for western European dairy farming conditions, the ‘manure management’ percentage, to which emissions from housing as well as from storage and spreading are to be attributed, accounts for around 15–44% of total CH_4 emissions from dairy farming (IPCC, 2006). This range reflects the temperature dependence of the values calculated for the ‘manure management’ category (IPCC, 2006). According to updated calculations taking account of changes in animal husbandry (e.g. live weight, feeding strategy, milk yield, housing and manure management), the CH_4 emissions from dairy farming in subsequent years continued to rise vis-à-vis the IPCC values (IPCC, 2006), with the increase in manure management being greater than that of enteric fermentation (Wolf, Asrar, & West, 2017).

CH_4 emissions were measured on a practical scale in individual studies (e.g. Rong, Liu, Pedersen, et al., 2014; Saha et al., 2014; Samer, Ammon, et al., 2012; Schiefler, 2013). Whereas Samer, Ammon, et al. (2012) and Schiefler (2013) demonstrated a temperature effect on CH_4 emissions, Rong, Liu, Pedersen, et al. (2014) showed an effect of wind speed on CH_4 emissions. Saha et al. (2014) cited animal activity and feed as reasons for the differences in CH_4 emissions. In studies on a pilot-plant scale conducted by Pereira et al. (2011) with both perforated and solid floors, an increase in temperature was accompanied by increased CH_4 emissions. To date, there have been no reviews or meta-analyses on the influence of housing system and floor type on CH_4 emissions across several farms and studies.

Our study aims to provide a meta-analysis of previously published practical-scale studies of NH_3 and CH_4 emissions from dairy housing in terms of the influence of housing system, floor type and air temperature. Among other things, this could allow the derivation of mitigation approaches or the validation of emission values and the quantification of the effects of housing system, floor type and air temperature with comparative studies in the experimental dairy housing for emission measurements (Schrade et al., 2015).

In this context, the following hypotheses are tested:

- NH_3 emissions from loose housing systems with cubicles are higher than those from tied housings.
- There are no significant differences between these two housing systems in terms of CH_4 emissions.
- Both NH_3 and CH_4 emissions are higher for dairy loose housing systems with cubicles and perforated floor than for dairy loose housing systems with cubicles and solid floors.
- NH_3 and CH_4 emissions from dairy loose housing systems with cubicles increase along with an increase in air temperature.
- There is a strong correlation between the NH_3 and CH_4 emissions.

2. Materials and methods

2.1. Data sources

This analysis of the literature encompasses data on NH_3 and/or CH_4 emissions from dairy housing from 44 publications published between 1990 and 2015 (see Appendix A). These consisted of 25 peer-reviewed papers, ten conference publications, five different other reports and four dissertations. The studies come from different countries: the Netherlands (n = 11 studies), Germany (n = 9), the USA (n = 4), Denmark (n = 4), the United Kingdom (n = 6), Sweden (n = 3), Austria (n = 3), China (n = 1), Belgium (n = 1), France (n = 1) and Switzerland (n = 1).

In some cases, there are major differences between the publications both in terms of study design (e.g. measurement method, measurement approach, number of farms, number of surveys per farm, measurement duration, survey of accompanying parameters, etc.) and farm conditions (e.g. herd size, feeding approach, breeds, animal productivity, management, etc.).

The following criteria were established for the selection of the publications: (i) Measurement on a practical scale at the 'housing system' level; (ii) Practical conditions of dairy housing; (iii) Measurement concept and method are comprehensible, established, and geared to the measurement situation; (iv) Emission data given in, or convertible to, g LU^{-1} d^{-1} (g per livestock unit per day); (v) Complete description of the housing system.

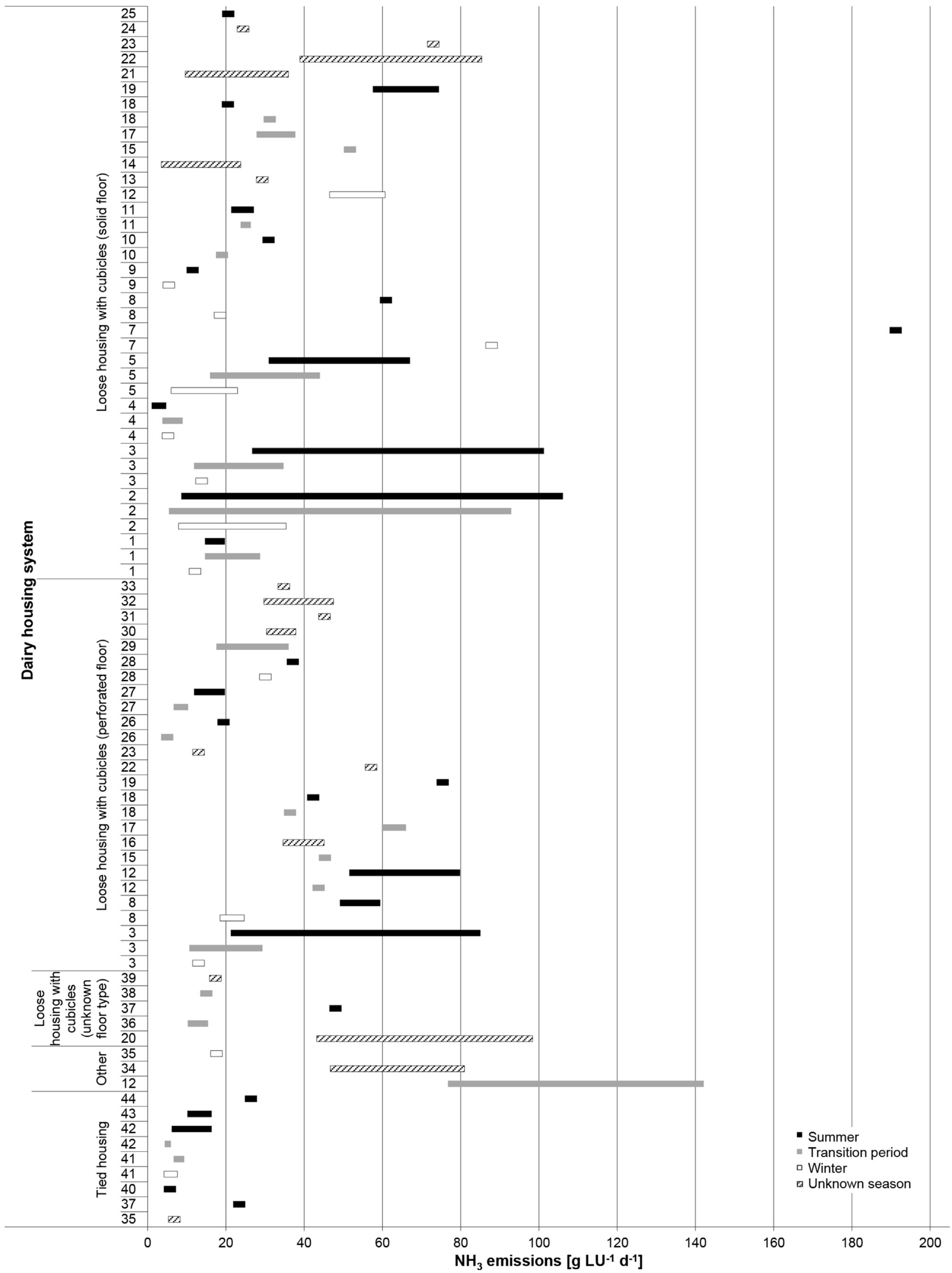
Duplicates were excluded from the overview and the meta-analysis, e.g. the values of the reliable tracer-gas technique (Samer, Ammon, et al., 2012) being used for simultaneous measurements as part of a comparison of measurement methods. Since the focus is on housing systems that are common in central Europe, data from e.g. open lots are not included in the statistical analyses. Nor are measurement data on grazing, or on a combination of indoor and pasture rearing, taken into consideration. First of all, and as an overview, the NH_3 and CH_4 emission data were each presented in a graphically differentiated fashion according to housing system and season.

For the statistical analysis of NH_3 or CH_4 emissions according to housing system, floor type and air temperature, separate subsets were formed as follows:

- The data source for comparison of the NH_3 emissions according to housing system is the **Subset housing system NH_3** (studies in Appendix A: 1, 2, 3, 5, 7, 8, 9, 11, 12, 13, 15, 16, 17, 19, 20, 21, 22, 23, 25, 26, 27, 28, 29, 30, 32, 33, 35, 36, 37, 38, 40, 41, 42, 43, 44) comprising seven studies with measurements in tied housing and 29 studies with measurements in loose housing with cubicles. One of these studies includes data from both loose housing with cubicles (with an unknown variant of floor type) and from tied housing. In the 'loose housing with cubicles' category, 11 studies investigated solid floors, seven studies perforated floors and eight studies both variants of floor type. There were no details on floor-type variant for three studies conducted in loose housing with cubicles.
- **Subset housing system CH_4** (studies in Appendix A: 1, 2, 3, 6, 7, 8, 11, 12, 15, 20, 21, 22, 26, 27, 36, 37, 40) consists of two studies with measurements in tied housing and 16 studies with measurements in loose housing systems with cubicles. One of these studies includes data from both a cubicle loose housing system (with an unknown variant of floor type) and from tied housing. From the 'loose housing with cubicles' category, seven studies had solid floors and two studies perforated floors. A further five studies looked at both floor-type variants. In two studies of loose housing with cubicles, the floor type was unknown.
- **Subset floor type NH_3** (studies in Appendix A: 1, 2, 3, 5, 7, 8, 9, 11, 12, 13, 15, 16, 17, 19, 20, 21, 22, 23, 25, 26, 27, 28, 29, 30, 32, 33) consists solely of studies in loose housing with cubicles, in which floor type is differentiated according to whether it is solid (19 studies) or perforated (15 studies). Dung was removed from the solid floors – some of which had a transverse slope – at different intervals. The perforated floor consisted of both housing with a slurry storage beneath the slats (seven studies) and housing systems with slurry channels combined with a slurry storage outside of the housing (three studies). In five studies, no information was provided on slurry storage. In five studies dung was removed from the perforated floor, whilst no additional dung removal took place in a further eight studies. In two studies, there was no information available concerning dung removal from perforated floor. In four studies, dung was removed from the channels beneath the slats with scrapers; in three of these studies, this occurred in addition to dung removal from the perforated floors; in one study, there was no information on dung removal from the floors.
- **Subset floor type CH_4** (studies in Appendix A: 1, 2, 3, 6, 7, 8, 11, 12, 15, 20, 21, 22, 26, 27) is based on studies in loose housing with cubicles in which floor type is differentiated according to whether it is solid or perforated. The solid floors – some of which had a transverse slope – was cleaned of dung at different frequencies. The perforated floors were a feature of housing with slurry storage beneath the slats (three studies) as well as housing systems with slurry channels combined with a slurry storage outside of the housing (two studies). In two studies, no details were given on slurry storage. In one study, dung was removed from the perforated floors; in a further four studies, no dung removal took place.

In one study, both the perforated floors and the channels under beneath the slats were cleaned of dung with scrapers. In one other study, there was no information on dung removal from the perforated floors, but the channels beneath the slats were cleaned of dung with scrapers.

- To analyse the effect of air temperature on NH_3 or CH_4 emissions from loose housing systems with cubicles, **Subset air temperature NH_3** and **Subset air temperature CH_4** were created from studies with cubicle loose housing with known air temperatures during the emission measurements. Only studies with emission and air temperature data from at least two seasons were used (studies in Appendix A for Subset air temperature NH_3: 1, 2, 3, 5, 7, 8, 11, 12, 26, 27; studies in Appendix A for Subset air temperature CH_4: 1, 2, 3, 6, 7, 8, 11, 12, 26, 27). The temperature values used related to the air temperature in the housing. Only in the case of one naturally ventilated cubicle housing (Fiedler & Müller, 2010) was the outside temperature adopted, due to the fact that the inside temperature was missing from the data. No distinction was made according to perforated or solid floors.
- **Subset correlation NH_3 and CH_4** studies made use of cubicle loose housing systems in which NH_3 and CH_4 emissions were measured simultaneously (studies in Appendix A: 1, 2, 3, 7, 8, 11, 12, 26, 27), with no distinction made according to floor type.


Dairy housing system
Loose housing with cubicles (solid floor)
Loose housing with cubicles (perforated floor)
Loose housing with cubicles (unknown floor type)
Other
Tied housing
25 24 23 22 21 19 18 18 17 15 14 13 12 11 11 10 10 9 9 8 8 7 7 5 5 5 4 4 4 3 3 3 2 2 2 1 1 1
33 32 31 30 29 28 28 27 27 26 26 23 22 19 18 18 17 16 15 12 12 8 8 3 3 3
39 38 37 36 20
35 34 12
44 43 42 42 41 41 40 37 35
0 20 40 60 80 100 120 140 160 180 200
NH_3 emissions [g LU^{-1} d^{-1}]
Summer
Transition period
Winter
Unknown season

The emission data from the studies were mainly available as daily averages with the unit g LU^{-1} d^{-1}, and were incorporated as such in the statistical analyses. In cases where the emission data were given as mean values per minute, hour or year, they were converted into the required unit g LU^{-1} d^{-1}. The conversion factor defined by the Association for Technology and Structures in Agriculture (KTBL, 2014) was used to convert into livestock units (1 LU = 500 kg live weight).

2.2. Statistical analysis

The overview graphs in Figs. 1 and 5 were designed with Microsoft® Excel® 2016. The statistical analysis and the visualisation of further graphs (Figs. 2–4 and 6–9) of NH_3 and CH_4 emissions were performed using TIBCO Spotfire S+® 8.2 for Windows. For the box plots, the box represents the range between the 25% and 75% quartiles and the horizontal line mark the median value. The whiskers extend to the most extreme data points up to 1.5 times the inter-quartile range. Individual outliers beyond the whiskers are shown as dots. Linear mixed-effect models were used to evaluate the fixed effects: type of housing, floor type and air temperature. Depending on the subset (see 2.1), each model consisted of NH_3 or CH_4 emissions as the response variable and of one of the fixed effects listed in the sentence before. Additionally, all models take account for the hierarchical data structure of farm and study in the form of nested random effects. A normal quartile - quartile plot of residuals was used to visually check the distribution properties of response variables. The NH_3 und CH_4 emissions were subjected to a natural logarithmic transformation to satisfy assumptions of normal distribution. The significance threshold was set at 0.05. The confidence interval was 95%. The coefficient of correlation (r) was calculated for NH_3 and CH_4 emissions.

3. Results and discussion

3.1. NH_3 emissions

3.1.1. Overview of data from the literature on NH_3 emissions from dairy housing

Figure 1 gives an overview of NH_3 emissions from the literature. Data are grouped according to the following housing system categories: loose housing with cubicles (solid floor); loose housing with cubicles (perforated floor); loose housing with cubicles (unknown floor type); other loose housing systems; tied housing. Insofar as possible, the range of NH_3 emissions of the individual studies is shown differentiated according to season. For this, the definition of the seasons according to daily mean temperature (Schrade, 2009) was adopted: winter < 5 °C; transition period 5–13 °C; summer > 13 °C.

The 'loose housing with cubicles' system is the one with the most studies available. Of these, 18 fall into the 'loose housing with cubicles (perforated floor)' and 22 into the 'loose housing with cubicles (solid floor)' category. A further five studies give NH_3 emissions from loose housing with cubicles with no indication of floor type. Three studies were carried out in the loose housing systems with unstructured lying areas (e.g. deep-litter housing). Seven studies investigated the NH_3 emissions of tie-stall housing systems. Comparison of the data from the different studies is made difficult by differences in both basic conditions (e.g. area ratios, feeding strategy, management) and measurement approaches (e.g. analytics, methods, measurement duration, single farm vs. several farms).

Five publications (Mosquera et al., 2010, p. 28; Phillips, Bishop, Price, & You, 1998; Saha et al., 2014; Schrade et al., 2012; Zhang et al., 2005) contain measurements taken in all three seasons. With 27 studies, the dataset for the summer is the largest, followed by the transition-period dataset with 23 studies. There are 14 studies available for the winter. In a further 17 studies no data is available on air temperature, so no allocation to a season is possible. A large spread in NH_3 emissions can be observed in some cases both between the studies and within individual studies. Emission data for the solid-floor variant of the loose housing with cubicles vary especially strongly, ranging from 1.1 g LU^{-1} d^{-1} to 191.2 g LU^{-1} d^{-1} across all seasons. Ranging from 4 g LU^{-1} d^{-1} to 85 g LU^{-1} d^{-1}, the spread for loose housing with perforated floors is somewhat smaller. At 4.2 g LU^{-1} d^{-1} to 25.4 g LU^{-1} d^{-1} d, the range of NH_3 emissions from the tied housing is considerably smaller. This could be explained by either a smaller dataset or a narrower temperature range. The tied-housing emission levels are clearly lower than the NH_3 levels of the majority of the loose housing systems. Most studies with measurements taken in several seasons exhibit a significant seasonal effect, with higher NH_3 emissions in the warmer seasons (Kroodsma, Huis in 't Veld, & Scholtens, 1993; Mosquera, Hol, & Huis in 't

Fig. 1 – Overview of NH_3 emissions [g LU^{-1} d^{-1}] from dairy housing shown according to housing system and differentiated according to season (1: Mosquera et al. (2010, p. 28); 2: Saha et al. (2014); 3: Zhang et al. (2005); 4: Phillips et al. (1998); 5: Schrade et al. (2012); 7: Samer, Ammon, et al. (2012); 8: Schiefler (2013); 9: Schmidt et al. (2002); 10: Adviento-Borbe et al. (2010); 11: Ngwabie, Jeppsson, Nimmermark, Swensson, and Gustafsson (2009); 12: Seipelt (1999); 13: Demmers, Burgess, et al. (1997) and Demmers, Phillips, et al. (1997); 14: Misselbrook, Webb, Chadwick, Ellis, and Pain (2001); 15: Schneider, Eichelser, and Neser (2006); 16: Schiefler and Büscher (2012); 17: Swierstra, Braam, and Smits (2001); 18: Huis in 't Veld, Smits, and Monteny (2003); 19: Braam et al. (1997); 20: Fiedler and Müller (2010); 21: Ngwabie, Jeppsson, Gustafsson, and Nimmermark (2011); 22: Snell, Seipelt, and Van den Weghe (2003); 23: Brehme (2000); 24: Demmers, Burgess, et al. (1997) and Demmers, Phillips, et al. (1997); 25: Smits, Valk, Elzing, and Keen (1995); 26: Rong, Liu, Zong, Zhang, and Pedersen (2014); 27: Brose (2000); 28: Kroodsma et al. (1993); 29: Kroodsma and Ogink (1997); 30: Hansen, Kai, and Zhang (2012); 31: Oosthoek, Kroodsma, and Hoeksma (1990); 32: Pollet et al. (1998); 33: van't Ooster, Scholtens, and van der Heiden-de Vos (1994); 34: Charpiot et al. (2012); 35: Amon, Amon, and Boxberger (1998); 36: Ngwabie, VanderZaag, Jayasundara, and Wagner-Riddle (2014); 37: Groot Koerkamp and Uenk (1997); 38: Zhu, Jacobson, Schmidt, and Nicolai (2000); 39: Dore et al. (2004); 40: Amon et al. (2001); 41: Amon et al. (1997); 42: Powell, Broderick, and Misselbrook (2008); 43: Groenestein (1993); 44: Gustafsson, Hultgren, and Jeppsson (2001)).

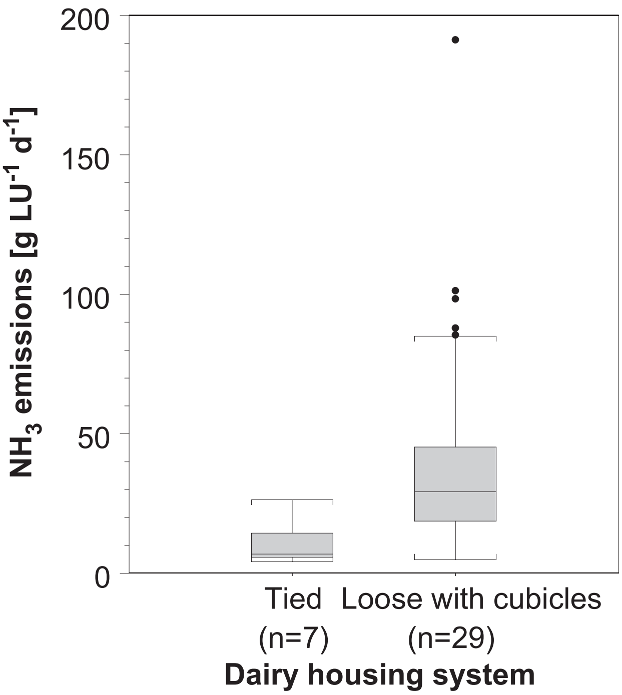


Fig. 2 – Comparison of the NH_3 emissions [g LU^{-1} d^{-1}] of tied housing systems and loose housing systems with cubicles (n = number of studies).

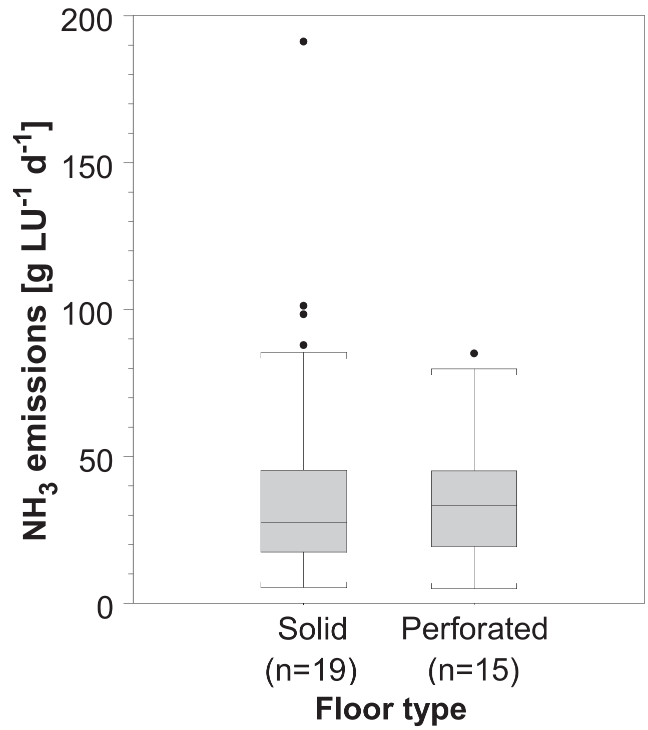


Fig. 3 – Comparison of the NH_3 emissions [g LU^{-1} d^{-1}] of solid and perforated floors in dairy loose housing systems with cubicles (n = number of studies).

Veld, 2005; Saha et al., 2014; Schiefler, 2013; Schmidt, Jacobson, & Janni, 2002; Schrade et al., 2012; Zhang et al., 2005).

3.1.2. *Effect of type of housing system on NH_3 emissions*

The statistical analysis shows lower NH_3 emissions (p = 0.001) from the tied housing (median: 6.9 g LU^{-1} d^{-1}) than from the loose housing with cubicles (median: 29.3 g LU^{-1} d^{-1}), thereby supporting our hypothesis on the effect of type of housing system (Fig. 2). The higher NH_3 emission potential of the loose housing with cubicles can be attributed to the larger soiled surface area (Keck, 1997; Monteny & Erisman, 1998). For example, the floor considered to be soiled surface area fell within the range of 2.4 m^2 per LU (Seipelt, 1999) and 6.4 m^2 per LU (Pollet, Christiaens, & Van Langenhove, 1998) in cubicle loose housing without an outdoor exercise area, and within the range of 4.3–7.7 m^2 per LU (Schrade et al., 2012) in cubicle loose housing with an outdoor exercise area. By contrast, at 1.9 m^2 per LU (Groenestein, 1993), the soiled surface area in tied housing was substantially smaller. Although the minimum values of the observed NH_3 emissions for tied and cubicle loose housing systems lie within a similar range (4.2 g LU^{-1} d^{-1} and 5.0 g LU^{-1} d^{-1}, respectively), the range for cubicle loose housing systems (up to 191.2 g LU^{-1} d^{-1}) is considerably greater than for tied housing systems (up to 26.4 g LU^{-1} d^{-1}). It is possible that factors such as air temperature (Groot Koerkamp & Uenk, 1997), floor type (Braam et al., 1997), and manure management (e.g. slurry or straw based system) (Amon et al., 1997, 2001) lead to a wider spread for the loose housing systems.

In a meta-analysis of data from the literature, Bougouin et al. (2016) noted no significant effect of housing system differentiated according to tied housing, loose housing with cubicles, loose housing without cubicles, and open lots on the NH_3 emissions. Despite this, they attributed lower NH_3 emissions to the tied housing than to the other housing systems mentioned in the comparison.

3.1.3. *Effect of floor type on NH_3 emissions*

Although at 33.3 g LU^{-1} d^{-1} the median of the NH_3 emissions from cubicle loose housing with perforated floors was somewhat higher than the median for cubicle loose housing with solid floors (27.6 g LU^{-1} d^{-1}) (Fig. 3), the statistical analysis revealed no difference (p = 0.76) and hence disproves our hypothesis.

Simultaneous measurements conducted by Schiefler (2013) in cubicle loose housing with separate experimental compartments with different floor types also failed to reveal any significant differences between the annual averages of the NH_3 emissions for solid floors (34.9 g LU^{-1} d^{-1}) and for perforated floors with two different intensity levels of slurry homogenisation beneath the slats. Only the more intensive slurry homogenisation resulted in substantially higher NH_3 emissions than for the less-intensive homogenisation (38.4 g LU^{-1} d^{-1} and 29.8 g LU^{-1} d^{-1}, respectively) (Schiefler, 2013). Furthermore, the effect of season was more important than the effect of floor type in these simultaneous measurements (Schiefler, 2013).

In the meta-study conducted by Bougouin et al. (2016), loose housing systems with solid floors exhibited higher NH_3 emissions (47.7 g LU^{-1} d^{-1}) than loose housing systems with

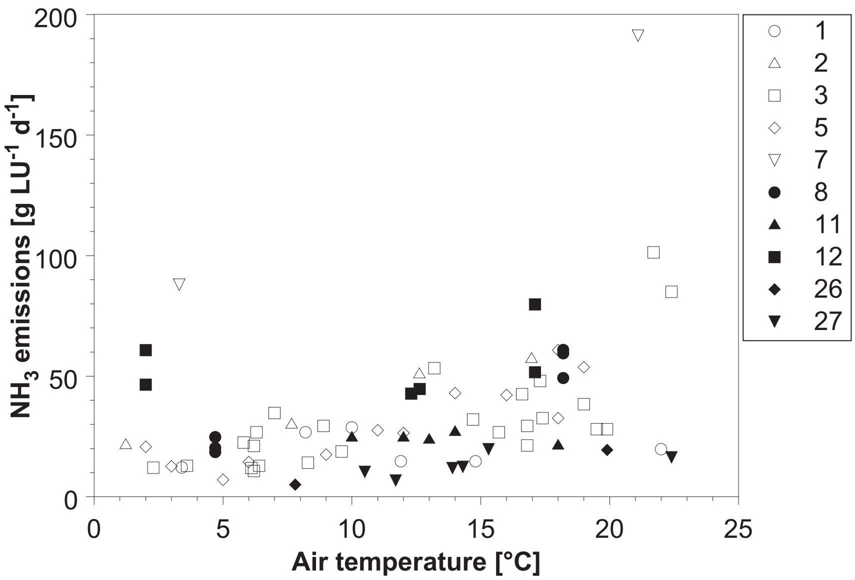


Fig. 4 – NH_3 emissions [g LU^{-1} d^{-1}] of dairy loose housing with cubicles as a function of air temperature, differentiated according to study (1: Mosquera et al. (2010, p. 28); 2: Saha et al. (2014); 3: Zhang et al. (2005); 5: Schrade et al. (2012); 7: Samer, Ammon, et al. (2012); 8: Schiefler (2013); 11: Ngwabie et al. (2009); 12: Seipelt (1999); 26: Rong, Liu, Zong, et al. (2014); 27: Brose (2000)).

perforated floors (40.4 g LU^{-1} d^{-1}). In contrast with the present study, in the category of loose housing with solid floors loose housings without cubicles (e.g. deep-litter housing) were included in this meta-study along with loose housing with cubicles (Bougouin et al., 2016).

Pereira et al. (2011) compared a solid floor element to a perforated floor element with a channel beneath on a pilot-plant scale at different temperature levels. The mixture of dairy-cow urine and faeces was spread evenly onto the floor elements. Whilst the NH_3 emissions for the solid floor element were significantly higher than for the perforated floor element at high temperatures (15 °C and 25 °C), there were no differences between perforated and solid floor elements at 5 °C (Pereira et al., 2011).

The maximum emission values for solid floors and for perforated floors were 191.2 g LU^{-1} d^{-1} and 85 g LU^{-1} d^{-1} respectively, which points to the variability between studies within the same floor type. The range of NH_3 emissions for the two floor types may be attributable *inter alia* to major differences in dung removal management, area ratios and climatic conditions in this sample. Samer, Ammon, et al. (2012) ascribed the very high value for the solid floor to climatic conditions during the measurements.

3.1.4. *Effect of air temperature on NH_3 emissions*

The statistical analysis revealed an influence of air temperature on the NH_3 emissions ($p < 0.001$). Figure 4 shows that NH_3 emissions in the cubicle loose housing systems increase with rising air temperature, which confirms our hypothesis. This is particularly evident when we consider the data from studies with different temperature ranges (Samer, Ammon, et al., 2012; Schiefler, 2013; Schrade et al., 2012). The present analysed dataset from the literature thus already confirms the influence of temperature on the formation and release of NH_3 described by Monteny and Erisman (1998) and Samer (2016). In their meta-analysis of emission data from dairy housing, Bougouin et al. (2016) also noted a significant influence of air temperature on the NH_3 emissions.

Here, both the range and absolute level of NH_3 emissions vary significantly. Whilst the NH_3 emissions from the data of Mosquera et al. (2010, p. 28) were comparatively low and a rise in temperature led to only a slight increase in NH_3, in the study of Samer, Ammon, et al. (2012) and Samer, Berg, et al. (2012) the level of NH_3 was higher and the increase in NH_3 emissions greater in a comparable temperature range. Furthermore, there are differences within individual studies. For simultaneous measurements in a cubicle loose housing system carried out by Schiefler (2013), for example, differences in NH_3 emissions at the same temperature are explained by the different manure management (perforated floors with intensive or non-intensive homogenisation of the slurry beneath the slats and for the solid floors): 4.7 °C (24.7 g LU^{-1} d^{-1}, 20.2 g LU^{-1} d^{-1} and 18.5 g LU^{-1} d^{-1} or for the temperature, 18.2 °C (59.4 g LU^{-1} d^{-1}, 49.2 g LU^{-1} d^{-1} and 60.9 g LU^{-1} d^{-1}, respectively). In Seipelt's study (1999), the differences in emissions can be attributed to the repeated measurements in the same cubicle loose housing system in different years (Fig. 4). In studies encompassing several farms, the farm effect may also have an influence on the absolute emission levels in each case, and hence on the spread of the NH_3 emissions within a temperature range (e.g. Schrade et al., 2012; Zhang et al., 2005).

For future emission measurements, studies should be conducted in several seasons, in order both to describe the temperature effect and to cover climatic conditions over the year (Kroodsma & Ogink, 1997; Schrade, 2009; VERA Test

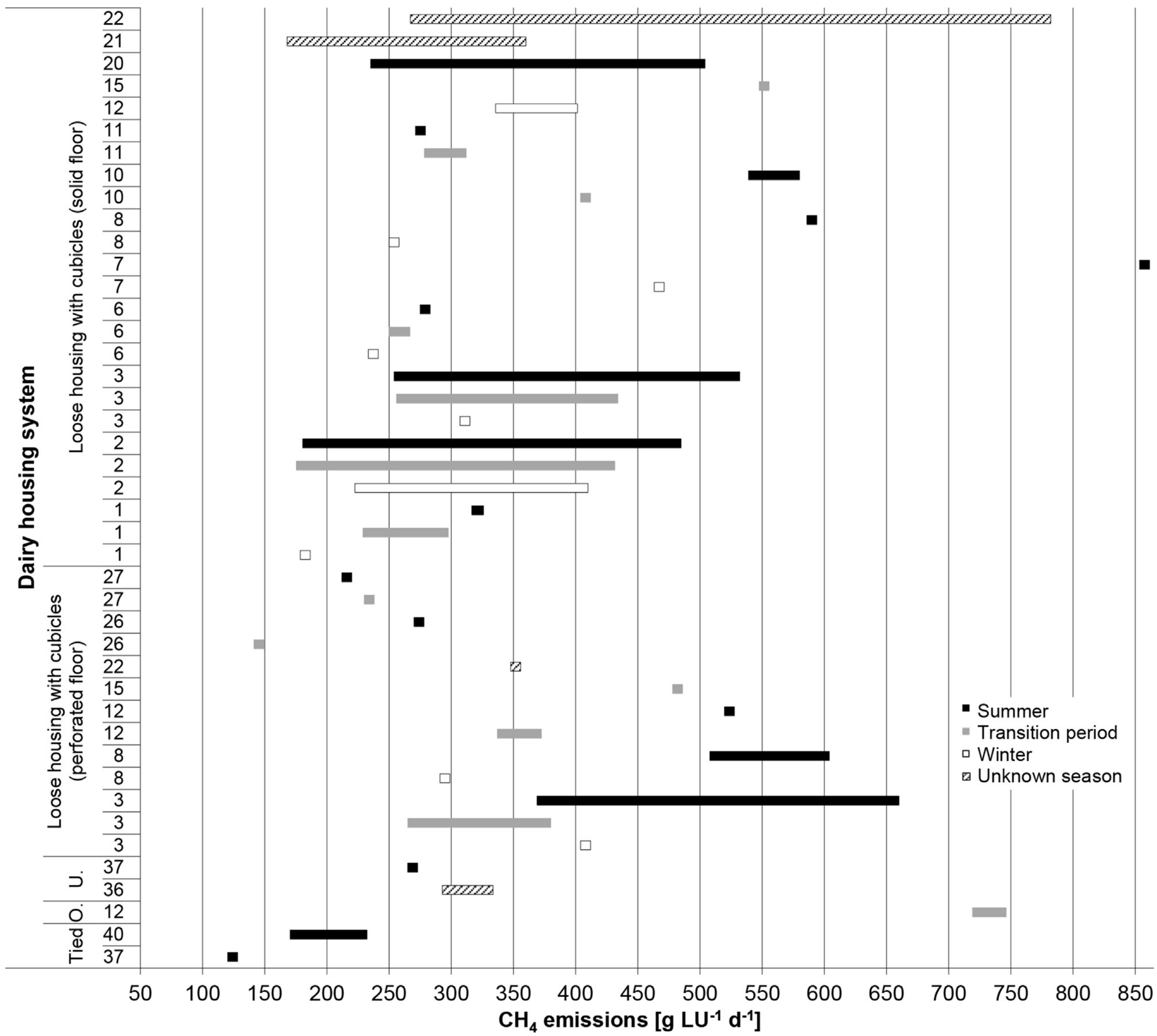


Fig. 5 – Overview of CH_4 emissions [g LU^{-1} d^{-1}] from dairy housing shown according to housing system and differentiated according to season (U. = loose housing with cubicles (unknown floor type); O. = other loose housing systems; Tied = tied housing) (1: Mosquera et al. (2010, p. 28); 2: Saha et al. (2014); 3: Zhang et al. (2005); 6: Gao et al. (2011, p. 7); 7: Samer, Ammon, et al. (2012); 8: Schiefler (2013); 10: Adviento-Borbe et al. (2010); 11: Ngwabie et al. (2009); 12: Seipelt (1999); 15: Schneider, Eichseler, and Neser (2006); 20: Fiedler and Müller (2010); 21: Ngwabie et al. (2011); 22: Snell et al. (2003); 26: Rong, Liu, Zong, et al. (2014); 27: Brose (2000); 36: Ngwabie et al. (2014); 37: Groot Koerkamp and Uenk (1997); 40: Amon et al. (2001)).

Protocol, 2011). For system comparisons or for the evaluation of mitigation measures, simultaneous emission measurements under the same climatic conditions should be aimed for, as with Schiefler (2013).

3.2. CH_4 emissions

3.2.1. *Overview of data from the literature on CH_4 emissions from dairy housing*

Figure 5 shows an overview of CH_4 emissions from dairy housing from studies from the literature, grouped according to housing system category: loose housing with cubicles (solid floor); loose housing with cubicles (perforated floor); loose housing with cubicles (unknown floor type); other loose housing systems; tied housing. In addition, the ranges of the CH_4 emissions of the individual studies are given differentiated according to season. The seasons are defined as described above (see chapter 3.1.1).

Thirteen of the studies were carried out in cubicle loose housings with solid floors, and seven in cubicle loose housings with perforated floors. For two studies, no details are available on the floor type. In addition, there was one loose housing system with an unstructured lying area, as well as two tied housing systems.

Four of the studies presented show CH_4 emissions from all three seasons (Gao, Yuan, Li, Liu, & Desjardins, 2011, p. 7;

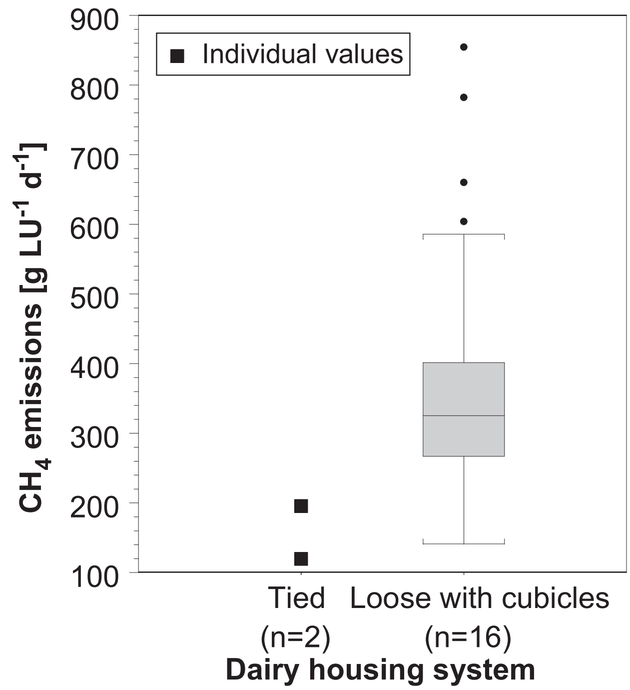


Fig. 6 – Comparison of CH_4 emissions [g LU^{-1} d^{-1}] of tied housing systems and loose housing systems with cubicles (n = number of studies).

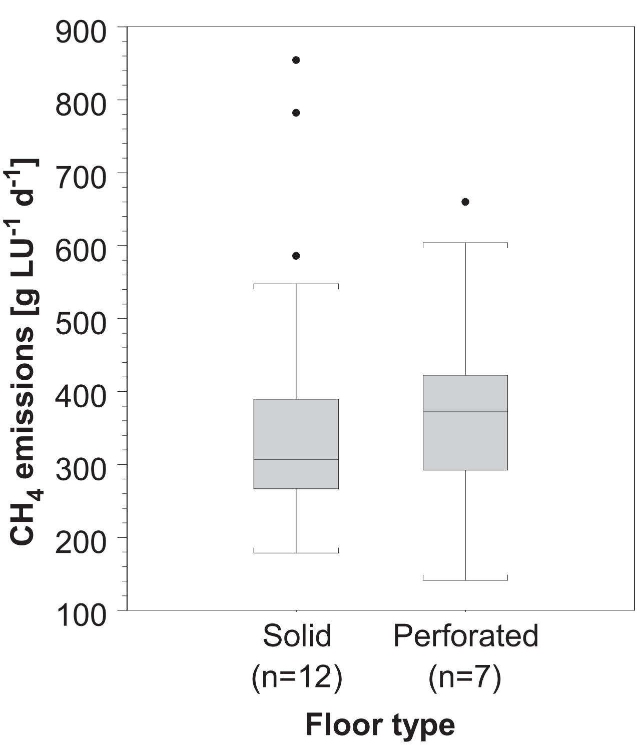


Fig. 7 – Comparison of CH_4 emissions [g LU^{-1} d^{-1}] of solid and perforated floors in dairy loose housing systems with cubicles (n = number of studies).

Mosquera et al., 2010, p. 28; Saha et al., 2014; Zhang et al., 2005). With 17 studies with measurements taken in the summer and 13 studies with measurements taken in the transition period, the warmer seasons predominate. There are winter measurements for nine studies. Four of the studies cannot be allocated to any season.

The CH_4 emission data for the cubicle loose housing systems across all floor types and seasons range between 141.3 g LU^{-1} d^{-1} and 854.5 g LU^{-1} d^{-1}. The CH_4 emissions for the two tied housing studies are comparatively lower, ranging between 120.2 g LU^{-1} d^{-1} and 194.4 g LU^{-1} d^{-1}. Visually, there are no obvious effects of either season or floor type on CH_4 emissions in the loose housing with cubicles. The spread of the given CH_4 emissions varies from study to study. Differences in terms of farm conditions (e.g. feeding strategy, management, area ratios) and measurement approaches (analytics, methods, measurement duration, single farm vs. several farms) make a comparison of the data difficult. In studies, using chamber methods sources such as CH_4 from ruminating (enteric CH_4) may not be included.

3.2.2. *Effect of type of housing system on CH_4 emissions*

The statistical analysis of the CH_4 emissions reveals a difference between tied housing and loose housing with cubicles ($p = 0.007$). This is congruent with Groot Koerkamp and Uenk (1997) measurements for both housing systems, which also show significantly lower CH_4 emissions for the tied housing than for the cubicle loose housing (120.2 g LU^{-1} d^{-1} vs. 264.9 g LU^{-1} d^{-1}, respectively). However, the small range of the tied-housing sample, with just two studies, limits the informative value of the comparison of the two housing systems' CH_4 emissions (Fig. 6). According to estimates, the percentage of total CH_4 emissions of enteric origin in western-European-style dairy housing conditions ranges from around 56 to 85% (IPCC, 2006). The wide range of CH_4 emission data from studies with measurements taken in loose housing systems with cubicles thus demonstrates the wide variability within this housing category (Fig. 6).

3.2.3. *Effect of floor type on CH_4 emissions*

Below, the effect of floor type on CH_4 emissions within the category of loose housing systems with cubicles is analysed in greater detail. The statistical analysis reveals no difference in CH_4 emissions between cubicle loose housing systems with solid floors and those with perforated floors ($p = 0.49$).

The comparison of solid and perforated floors on a pilot-plant scale likewise revealed no significant effect of floor type on CH_4 emissions (Pereira et al., 2011). Simultaneous measurements in a cubicle loose housing system also failed to show any significant differences between solid and perforated floors (Schiefler, 2013). Moreover, as seen in the study of Schiefler (2013), the significant differences in annual average CH_4 emissions within the 'perforated floor' category between the variant with intensive slurry homogenisation (381.7 g LU^{-1} d^{-1}) and the variant with less-intensive homogenisation of the slurry (324.9 g LU^{-1} d^{-1}) point to the importance of slurry management.

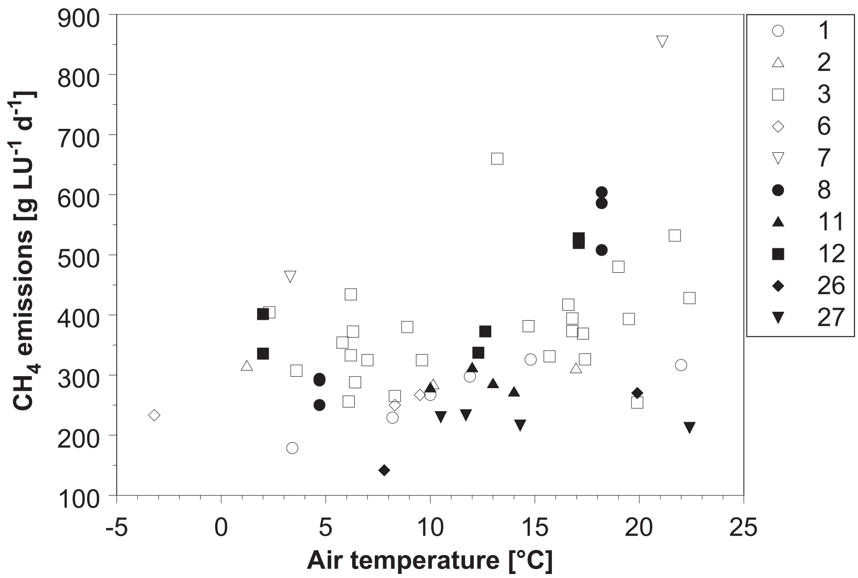


Fig. 8 – CH_4 emissions [g LU^{-1} d^{-1}] from dairy loose housing systems with cubicles as a function of air temperature, differentiated according to study (1: Mosquera et al. (2010, p. 28); 2: Saha et al. (2014); 3: Zhang et al. (2005); 6: Gao et al. (2011, p. 7); 7: Samer, Ammon, et al. (2012); 8: Schiefler (2013); 11: Ngwabie et al. (2009); 12: Seipelt (1999); 26: Rong, Liu, Zong, et al. (2014); 27: Brose (2000)).

3.2.4. *Effect of air temperature on CH_4 emissions*

In loose housing systems with cubicles, the air temperature in the housing has an effect ($p < 0.001$) on the CH_4 emissions. As assumed in the hypothesis, CH_4 emissions increase along with air temperature (Fig. 8), with the housing temperature in the analysed studies ranging from −3.2 °C to 27.3 °C.

The temperature effect within individual studies on a practical scale (Rong, Liu, Zong, et al., 2014; Samer, Ammon, et al., 2012; Schiefler, 2013) can also be identified in a graphic representation (Fig. 8). As with the NH_3 emissions (Fig. 4), the values from the study of Samer, Ammon, et al. (2012) are highest in the respective temperature range, and can be

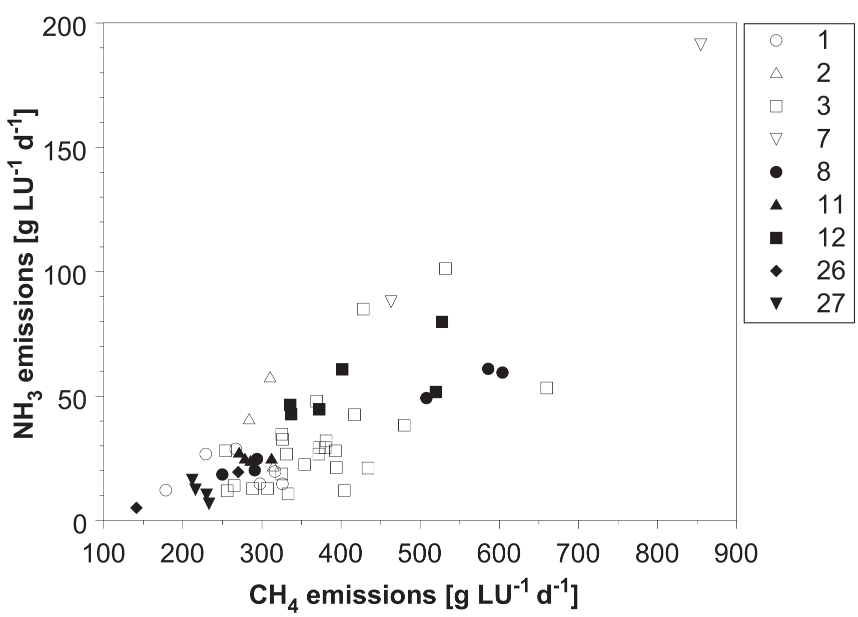


Fig. 9 – Correlation between NH_3 and CH_4 emissions [g LU^{-1} d^{-1}] in dairy loose housing systems with cubicles, differentiated according to study (1: Mosquera et al. (2010, p. 28); 2: Saha et al. (2014); 3: Zhang et al. (2005); 7: Samer, Ammon, et al. (2012); 8: Schiefler (2013); 11: Ngwabie et al. (2009); 12: Seipelt (1999); 26: Rong, Liu, Zong, et al. (2014); 27: Brose (2000)).

explained by the climatic conditions during the measurements. Pereira et al. (2011) also highlighted a temperature effect on CH_4 emissions in studies on a pilot-plant scale with two floor types and graduated air temperatures (5 °C, 15 °C and 25 °C).

3.2.5. Correlation between NH_3 and CH_4 emissions

Figure 9 shows a close positive correlation between NH_3 and CH_4 emissions. The correlation coefficient r equals 0.80. The emission data available here are for the air-temperature range of 1.2 °C–22.4 °C. The correlation between NH_3 and CH_4 emissions is particularly clear in the studies of Samer, Berg, et al. (2012) and Schiefler (2013), where an increase in temperature was shown to lead to a clear rise in the individual NH_3 (Fig. 4) and CH_4 (Fig. 8) emission parameters. The large spread in NH_3 and CH_4 emissions, in the study of Zhang et al. (2005), for example, can be explained by the emission measurements in several loose housing systems.

4. Conclusions

The present study provides a comprehensive overview of the literature on NH_3 and CH_4 emissions from measurements on a practical scale made in various dairy-cattle housing systems. Although differences between the studies in terms of basic conditions (e.g. herd size, animals, area ratios, ventilation, feeding strategy, management, etc.) and measurement concept (analytics, methods, measurement duration, single farm vs. several farms, etc.) reduce the comparability of the data, effects on NH_3 and CH_4 emissions in our meta-analysis can be shown to exist. The NH_3 emissions from tied housing systems are significantly lower than those from loose housing systems with cubicles, for example – and within the 'loose housing systems with cubicles' category, no significant differences can be detected between the 'perforated' and 'solid' floor types for either NH_3 or CH_4 emissions.

The wide-ranging dataset of practical measurements taken in loose housing systems with cubicles shows air temperature to be a significant influencing factor with regard to NH_3 and CH_4 emissions. As the air temperature in the housing increases, so do emissions of NH_3 and CH_4. This temperature effect is also a reason for the close correlation between NH_3 and CH_4 emissions from loose housing systems with cubicles. When seeking to mitigate NH_3 emissions, therefore, the soiled area and temperature in the housing system should be considered.

In order to improve the data basis for such meta-analyses in the future and to compare data from various studies, relevant influencing variables should be documented and a detailed description of the measurement situation should be provided.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biosystemseng.2019.03.012.

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