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# *Invited review:* Combined mitigation of methane and ammonia emissions from dairy barns through barn design, ventilation and air treatment systems

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## ABSTRACT

Removal of contaminants and gases from air in cattle housing systems makes a positive contribution to in-house air quality, thereby benefiting both animal and human welfare as well as reducing the environmental pressure from cattle. In this review, we aimed to combine knowledge of the capture of ammonia and methane from dairy cattle facilities by removing and oxidizing these gases from the ventilation air in one process. For cattle housing, several techniques are currently available and in various stages of development and application to capture ammonia from the air. A central component of these approaches is an air scrubber with acid to remove the ammonia from the ventilation air flow. In this review, we focused particularly on enteric methane from ruminants, because that represents the largest methane output on the dairy farm (~80%) and remains the biggest challenge. We sought suitable physicochemical and microbiological methods and applications that absorb or oxidize methane from the air. Our literature review showed that the concentration of methane in modern, naturally ventilated, open cattle barns is relatively low (averages of 5 to 100 ppm), and at present, no cost- and climate-effective technology is available that can capture and oxidize methane at this low concentration. It was apparent that most techniques may only be able to capture or convert methane at concentrations above 500 ppm (and preferably >2,000 ppm). The limiting factor is the diffusion speed of methane and the competition with other gases in case filtering or adsorption techniques are used. Therefore, we formulated the ventilation challenge, which refers to smart ventilation techniques that would allow capturing methane from the barn air at higher concentrations. In addition, technologies that have the capacity to capture ammonia and methane from the air are described separately and in combination. Then, inventive designs are presented to picture capturing of ammonia and methane in a one-process approach. Applying selected innovations, promising results are expected in lowering methane emissions from barns and storage areas (~one-fourth reduction at the farm level). The development of more efficient adsorbents and bio and soil filters to optimize the process of adsorption and oxidation at low concentrate levels would enhance this reduction.
**Key words:** methane, ammonia emission, air filtering, ventilation techniques, innovation

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## INTRODUCTION AND APPROACH

The successful development of agriculture by maximizing production at minimum costs and inputs has led to a situation where it is now responsible for a range of adverse environmental effects. Although the environmental load per unit of produce, e.g., per kg milk, is relatively low, the load per surface area is high. This is especially so in densely populated and agriculturally intensive areas such as Western Europe and similar regions around the world. The dairy sector, which includes grazing periods for cattle as in Western Europe and New Zealand and all year indoors as in the United States, using ruminating animals as means of production, contributes substantially to the overall environmental effects. Reductions in nutrient losses and emissions have been achieved to varying extents by single-issue approaches (supported and enforced by policies) and modifications to the biophysical production system. But further improvements to all environmental aspects are required, without undue trade-offs and negative side effects.

In this review, we focus on the gaseous emissions of ammonia ($NH_3$) as nitrogen gas and methane ($CH_4$) as a GHG. Mitigating these emissions is a challenge, notably for the dairy sector. Currently, several management practices are advocated or still in development to reduce ammonia emissions, for example, by more grazing (Voglmeier et al., 2018), cutting grass at a later stage

The list of standard abbreviations for JDS is available at adsa.org/jds-abbreviations-25. Nonstandard abbreviations are available in the Notes.

**Table 1.** Overview of enteric methane production rates by dairy cattle

| Methane production rate[1] | Reference |
|---|---|
| 100–450 g $CH_4$/d per cow | Grainger et al. (2007); dependent on animal weight and milk production |
| 264–768 g $CH_4$/d per 500 kg LW | Snell et al. (2003) |
| 200–400 g $CH_4$/d per HPU | Zhang et al. (2005) |
| 102–503 g $CH_4$/d per 500 kg LW | Qu et al. (2021) |
| 26 ± 8.5 g $CH_4$/h per LU | Vechi et al. (2022) |
| 11–54 g $CH_4$/h per LU | |
| 11.2–15.0 g $CH_4$/h per LU | Amon et al. (2001), Austria |
| 11–14 g $CH_4$/h per LU | Bühler et al. (2021), Switzerland |
| 28.7–50.5 g $CH_4$/h per LU | Hensen et al. (2006), Netherlands (all cited by Vechi et al., 2022) |

[1]HPU = heat producing unit (1 HPU = 1,000 W); LU = livestock unit (1 LU = 1 dairy cow); LW = live weight.

(Klootwijk, 2019), and lowering the protein content in the ration (Ferreira et al. 2023; Chowdhury et al., 2024). Beauchemin et al. (2022) reviewed the state of enteric methane mitigation options, especially modifications in ration composition and grazing practices, use of feed additives, and genetic selection of cows. All these practices to reduce ammonia and methane emissions are based on the adaptation of the animal and its diet.

Various other mitigation options for ammonia and methane, however, focus on adapting the living environment of the animals and hardly require any adaptation or change of the animal or its diet. This refers to techniques such as dilution of manure (van Dooren et al., 2022), separation of manure into thick (mostly feces) and thin (mostly urine) fractions (Aguirre-Villegas et al., 2024; Becciolini et al., 2024), acidification of the manure (Fuchs et al., 2021; Puente-Rodríguez et al., 2022), and fermenting manure to biogas (Shih et al., 2008). Until now, relatively little work has been done in the dairy sector on capturing gases from exhaust barn air. This contrasts with the pig sector (Melse and Hol, 2017; Pexas et al., 2020), where air filtering technologies are widely implemented (e.g., the Netherlands) and high reductions are achievable (e.g., >90% for $NH_3$; Melse and Ogink, 2005).

Therefore, the aim of this review is to describe the state of art of capturing, processing and reusing ammonia and methane gas from dairy barns, including manure storage areas, in a one-system approach. We focus on mitigation of enteric methane production from cows. This was chosen because most development is still needed in the mitigation of methane from barn air, and because the largest proportion of methane at the farm level comes from the cows.

We reviewed 2 topics related to mitigation of both gases from dairy barns: (1) ventilation and air circulation techniques aimed at capturing methane and ammonia gases, and (2) filtering techniques to convert methane and ammonia in an air flow by using physical, chemical, or biological processes and involved adsorbents or substances. Ideally, part of the captured products can be harvested and reused.

The following activities were undertaken, and the results were systematically registered and used for this review:

- A literature review was performed to produce an inventory of the state of the art of knowledge and technology relevant for the 2 review lines.
- External parties were mobilized to explain experimental and field applications of practices and techniques contributing to the capture of ammonia and methane from the air of housing facilities for cattle and discuss gaps in knowledge and the system approach.
- Fourteen farmers and companies with innovative ventilation and air treatment technologies were visited, and observations and discussions were reported.
- Study trips were made to Northern Germany, Denmark, and Belgium (Galama et al., 2023), and the latest developments in manure management were studied in 8 European countries in the framework of the EU Climate Care Cattle farming project.
- Five international expert webinars about the topic of this study were organized.
- Interim findings of mitigation of emissions theories and practices in the field were presented and discussed at congresses of the European Federation of Animal Science (EAAP) and American Dairy Science Association in 2022, 2023, and 2024.
- Concepts that combine mitigation of ammonia and methane gases by innovative ventilation techniques were designed and visualized.
- New ventilation systems with air filtering techniques were qualitatively evaluated and compared with commonly used mitigation practices based on the following criteria: societal and economic effects, environmental effects, and practical applicability.

In this review, we typically refer to farming systems with cubicle houses (freestalls) with manure storage under slatted floors or solid floors with additional outside manure storage and a barn ventilation flow of at least 500 $m^3$/h per animal. The sides of the barns are partly or almost completely open, and cows have optional access to grazing. The review first presents an overview of methane and ammonia emissions and concentrations and their sources in dairy barns followed by principles for how to reduce these emissions, the ventilation challenge, and methods to capture the gas flows. Next we present, successively, integrated and inventive designs, an evaluation and discussion, and the final conclusions.

**Table 2.** Methane concentrations in air of dairy cattle barns

| Barn and storage system | $CH_4$ concentration range (mean, ppm) | Reference |
|---|---|---|
| Dairy barn with manure pit; I = slatted floors, II = low $NH_3$ emission floor | I. 0–50 (14)[1] II. 10–180 (45)[1] | May–Sep.; van Well et al. (2021) |
| Air in cow barn | 47–94[1] | Snell et al. (2003) |
| Forty dairy barns: 5 tiestalls and 36 cubicle barns in 7 EU countries | 5–80 (25) | Average of farms per country and season; Kuipers et al. (2023) |
| Four dairy barns | 13–199 | Cold climate; Tabase et al. (2024) |
| Dairy barn | 35–74 | Mean monthly (Jan.–May) concentrations; Ngwabie et al. (2009) |
| Loose house with controlled natural ventilation | 5–74 (39.4) | Ngwabie et al. (2011) |
| Experimental dairy farm with cubicles | 10–50 | Daily mean of 8 sampling spots during 1 yr; Wu et al. (2016) |

[1]Converted from mg/$m^3$ to ppm, assuming 1 mol of methane equals 24.5 L.

## METHANE AND AMMONIA EMISSIONS AND THEIR CONCENTRATIONS IN DAIRY BARNS

### *Methane*

Methane in dairy barns originates from 2 sources. The major source is enteric methane from rumen fermentation. A dairy cow emits between 100 and 700 g methane day, as summarized from literature in Table 1 (equal to 150 to 1,050 L/d). The second source results from methane fermentation (i.e., anaerobic metabolization) of organic material during the storage of manure (including slurry). This emission from manure varies from 10% (Rojas-Downing et al., 2017; calculated on global scale) to 22% (Vellinga and Groenestein, 2023; calculated on dairy sector scale, i.e., the Netherlands) of the total methane emissions from the housing facilities. Methane development from manure at individual farms can vary widely dependent on temperature, season, grazing, and manure management system, possibly leading to higher relative contributions from the manure (e.g., Ward et al., 2024).

The production of carbon dioxide and enteric methane by cows is correlated. The $CH_4/CO_2$ ratio in the barn is usually 0.06 to 0.10 (Madsen et al., 2010). A (temporal) rise in this ratio indicates methane fermentation of the in-barn stored manure, and in this process, carbon dioxide can also be converted in methane by methanogens (Jiang et al., 2018).

The amount of enteric methane produced depends primarily on DMI and ration composition (Niu et al., 2018), and for manure emissions, temperature and season play a major role (Poteko et al., 2019).

Within the rumen, headspace gas consists of 68% to 78% carbon dioxide, 20% to 30% methane, and some nitrogen gas (Moate et al., 1997; van Lingen et al., 2017). Emissions show diurnal patterns in methane concentration, with typically higher peaks after feeding (Kinsman et al., 1995; Crompton et al., 2011). Methane is emitted by belching, which occurs roughly once per minute (Bell et al., 2014), leading to mixing of rumen methane with exhaled air from the lungs (Hardan et al., 2021). This results in eructation peaks and troughs in methane concentrations near the mouth and nostrils of the cow. The peak concentrations of methane vary over the day depending on the activity of the cow. The peak concentrations measured depend also on how close to the point of emittance a sensor can be placed and the reaction time of the sensor (Wu et al., 2018). Peak methane values of 2,500 to 3,000 ppm have been reported in exhaled air of dairy cows when measured near the mouth (Bell et al., 2014; Wu et al., 2015; Hardan et al., 2021). Throughout the article, ppm is given as volume/volume (1 ppm = 1 mL/$m^3$). Bell et al. (2014) found that measuring methane close to the mouth led to a 50% underestimation of the real daily emission by the cow, underlining that methane is rapidly diluted with exhaled and surrounding air. This finding of rapid dilution, mainly caused by natural or mechanical ventilation, is also supported by data from an experiment simulating patterns of methane emissions of dairy cows by Wu et al. (2018).

When manure is stored in the barn under slatted floors, then a variable amount of methane gas is produced. Depending on the production level, the ventilation regimen, and the amount of methane produced from the manure storage in the barn, methane concentrations measured in the barn are typically in the range of 5 to 100 ppm (see Table 2).

### Ammonia

Urea in urine is transformed to ammonia by the enzyme urease present in manure. Hristov et al. (2011) stated in a review that "The spatial variation of ammonia concentrations is still a major technical difficulty in accurate determination of ammonia losses from feedlots and dairies. These uncertainties are reflected in the wide range of ammonia emission data found in the literature." For 31 studies of dairy facilities, the average ammonia emissions were 59 g/d per cow with an SD of 65 and range of 0.82 to 250 g/d. A meta-analysis by Poteko et al. (2019) indicated that the ammonia emitted from manure ranges from 1.1 to 191.2 g/d per livestock unit (**LU**) for the solid floor, highly depending on season and temperature. The emission ranges are somewhat lower for cubicle housing with slatted floors and much less for tiestalls (4.2 to 25.4 g/d per LU). Similar results were reported by Çinar et al. (2023) and Vitaliano et al. (2024) in their reviews (range of 0.04 to 146.7 g/d per LU). The regulation in the Netherlands for cattle housing construction permits states 13 kg/yr (or 35.6 g/d) per cow place for standard cubicle housings with slatted floors (BAL, 2025). Ammonia has the characteristic that it becomes nonvolatile as ammonium under acidic conditions, which can be enhanced by adding chemicals such as sulfuric, nitric, or propionic acid:

$$NH_3 + H^+ \rightarrow NH_4^+ \text{ (acid dissociation constant p}K_a = 9).$$

## PRINCIPLES TO REDUCE METHANE AND AMMONIA EMISSIONS FROM DAIRY BARNS

### Methane

The methane from manure that is stored in a pit under the floor of the barn mixes with air in the barn. Methanogenesis (i.e., microbial production of methane) in manure is not a constant process and varies over time. It depends on many factors, including storage time, temperature, and manure composition. Methanogenesis in manure can be prevented by a combination of management measures, for example, thorough annual cleaning of the manure pit, addition of inhibitory concentrations of acetic acid or other acids, and maintaining a low temperature (Dalby et al., 2021). Further, methane emission to the environment can be curtailed by having a covered outside manure storage area (Melse and van der Werf, 2005) and processing of manure in a methane digestion unit (Browne et al., 2015).

When the methane production by cows and manure is taken for granted, the only strategy that remains is to capture and treat methane after emission by the animal and manure. The difficulties in capturing methane from the air in dairy barns are multifactorial. First, the methane molecule is relatively inert and does not easily react with other chemicals, including acids and bases. It dissolves poorly in hydrophilic as well as in hydrophobic liquids, and it has a relatively high combustion temperature. Its molecular size is similar to that of nitrogen gas ($N_2$) and carbon dioxide ($CO_2$) gases. Furthermore, to maintain a healthy climate in barns, adequate ventilation is needed, which leads to dilution of the methane. Possible methods to convert methane under varying concentrations are reviewed in the section "Physicochemical and Biological Methods to Convert Methane."

### Ammonia

Principles for reducing the formation of ammonia from urea or reducing evaporation of ammonia from the manure in dairy barns are as follows (van Dooren and Smits, 2007; Snoek et al., 2014; Aguirre-Villegas et al., 2024): minimization of the volume of urine puddles; application of urease inhibitors on the floor or in the manure; separation of urine and feces at the source; cooling of the manure; dilution of the manure with water; quick removal of the manure from the barn (to a controlled storage area); and addition of acid to manure or urine to lower the pH. Often, suitable combinations of these practices are applied. Depending on the housing facilities, these combinations can reduce ammonia emissions from barns by amounts ranging from 30% to 50% (Evers et al., 2019), when applied and maintained carefully. In addition, end-of-pipe air filtering technology using air scrubbers can remove ammonia from housing facilities utilizing different ventilation techniques, such as lowering the air flow and minimizing ventilation of the head space in the slurry pit.

Partial pit ventilation was also described for Danish growing-finishing pig houses by Zhang et al. (2014a), showing that with 10% to 20% of the total ventilation rate (spatial differentiation), 65% to 75% of the total ammonia emission could still be captured. Melse et al. (2006) showed that only 10% to 20% of the emission from poultry and pig houses would be untreated when reducing the size of the standard air scrubber by 50%.

## PHYSICOCHEMICAL AND BIOLOGICAL METHODS TO CONVERT METHANE

### Mitigation of Industrial Sources

Apart from dairy farms and manure storage areas, several other sources, including ventilation air from mines (Yang et al., 2022), sewer systems (Khabiri et al., 2022), and landfills (Mønster et al., 2019), emit methane at variable concentrations. In research projects aimed at capturing methane from such sources, 2 main strategies are followed. At higher concentrations (>10%), methane can be captured, concentrated, and purified from undesired gases such as nitrogen and carbon dioxide, so it can be used as an energy source (Biogas Danmark, 2023). At intermediate concentrations between 0.2% and 10% (2,000 ppm to 100,000 ppm), technologies aim to capture and oxidize methane to carbon dioxide (Maasdam et al., 2024). The level of 0.2% is still 20 to 400 times the concentrations found in the ventilation air of dairy barns. For oxidation of methane concentrations from 0.2% to 10%, 2 main methods exist: physicochemical and biological conversion. Research on oxidation of ventilation air from coal mines at these concentration levels is oriented on physicochemical oxidation by a combination of adsorbents and catalysts (Chen et al., 2016). For methane from landfills and manure storage areas, research focuses on microbiological oxidation (Majdinasab and Yuan, 2017). However, transfer of methane from the gaseous phase to the water film surrounding methane-oxidizing bacteria is an obstacle due to relative chemical inertness and low solubility of methane in water (~22 mg/L at 20°C).Thus, the methods can be distinguished according to their mode of action and the concentration of methane involved.

## Conversion Technologies

Jackson et al. (2020) and Ming et al. (2022) identified 6 major search directions. It should be kept in mind that these authors focus on technologies intended to have effects on a global scale and not on point or local diffuse sources of methane as on dairy farms. We will outline briefly the basics of the approaches identified, and, next, consider whether these approaches could possibly contribute to converting methane from dairy farms. The first 4 directions are based on physicochemical conversion, the last 2 on microbiological conversion.

***A. Photocatalysis.*** Combinations of light of specific wavelengths and a photocatalyst ($CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$) can oxidize methane. Examples of photocatalysts are $TiO_2$, $ZnO_2$, Ag-ZnO, and AgO. The photocatalysts should be applied in thin layers (e.g., coatings) to achieve the maximum reactive surface. Many photocatalysts are most effective in the UV part of the light spectrum (compare review paper by Li et al., 2022). For example, Chen et al. (2016) coated ZnO semiconductors with Ag and found 8% oxidation of methane at a wavelength below 400 nanometers (nm) and more than 0.1% at 470 nm at ambient temperatures. Laboratory results have been reported up to 100% oxidation of low concentrations of methane (10–300 ppm) at ambient temperature with different photocatalysts (Johannisson and Hiete, 2022). Reaction times varied from 0.5 to more than 3 h.

Laboratory experiments have been largely performed with a fixed volume of gas, for example, air spiked with methane that is subjected to the test conditions. This contrasts with a farm situation where a flow of ventilation air must be treated. To oxidize a significant amount of methane, large surfaces of layers are needed, and daylight is mostly absent. For these reasons, photo-oxidation of methane as a technique to remove methane from a dairy barn does not seem to be an option in the near future.

***B. Adsorbents and Catalysts (Without Light).*** Methane is oxidized without catalysts at temperatures of 1,500°C and higher. With catalysts, oxidation occurs at lower temperatures. A high-performance catalyst for methane should allow oxidation at a low temperature, have high selectivity for methane, and be resistant to poisoning or deactivation by other products, including water and sulfur dioxide (Chen et al., 2016). Metal oxides and noble metals, such as palladium and platinum, are effective catalysts (Gélin and Primet, 2002), and their effects can be enhanced by dispersing the metal on a porous supporting material. The enhancing effect is attributed to sorption of oxygen and methane in the pore structure of the supporting material. Supporting materials include metal oxides, zeolites, and metal organic frameworks (**MOF**). Zeolites and MOF can also be used as adsorbents, without catalytic activity, to capture and concentrate methane (Zhang et al., 2023). Concentration then requires cycles of capture and removal of the methane from the adsorbent and a subsequent oxidation step for oxidation (Lin et al., 2023). These techniques show some promise for application to air from dairy barns.

***C. Membranes.*** Instead of adsorbing methane, an enrichment of methane could also be obtained by gas selective membranes. Such membranes can be based on porous materials. Usually passage of the bulk gas (often $N_2$ or $CO_2$) is restricted and thus the membrane passing gas (in this case methane) is concentrated. He and Lei (2021) gave a review of membranes that combine low permeability for $N_2$ with high selective permeability for $CH_4$. They indicate that SAPO-34 could be a suitable membrane for enrichment of methane from gas with 0.5% to 1.5% methane and flows of 10,000 $m^3$/h. They indicate that enrichment up to 10% methane is possible.

***D. Imitating Natural Sink of Methane in the Troposphere.*** The main natural sinks of methane in the atmosphere are reactions with hydroxyl and chlorine radicals under the influence of UV radiation. Annually, ~500 Mt of methane is broken down in the troposphere and stratosphere (Searchinger et al., 2021). These are complex photochemical reactions catalyzed by UV light. Ultraviolet light leads to the conversion of ozone in oxygen and an oxygen radical, which gives hydroxyl radicals by reacting with water. These react with methane (Rohrer et al., 2014).

$$O_3 + \text{UV light} \rightarrow O_2 + O.$$

Then, the oxygen atom (O) reacts with water vapor to produce 2 OH radicals.

$$5\ O + H_2O \rightarrow 2\ OH, \text{ then } CH_4 + OH \rightarrow CH_3 + H_2O.$$

These reactions can be simulated using ozone and hydroxyl or chlorine radical generators (e.g., iron salts) and light-emitting diode-derived UV light. However, these technologies are in their infancy, and the reactants ozone, hydroxyl radicals, and UV light should not come into contact with human beings or animals because of the risk for health effects (Ming et al., 2022; Nisbet-Jones et al., 2022).

***E. Imitating Natural Sinks of Methane in the Soil.*** The basic idea is to direct ventilation air into the soil and let the natural population of methanotrophs oxidize the methane. Knief (2019) reviewed the microbial species and consortia involved in the production and degradation of methane in the soil.

In soils, both methanogenesis and methane oxidation occur, although spatially separated. Methanogenesis usually occurs in deeper layers where organic material is degraded. Depending on the type of the soil, methane can be oxidized anaerobically by consortia of methane-oxidizing bacteria with sulfate, iron, manganese, some organic compounds, nitrite, and nitrate as electron acceptors. When methane reaches the aerobic interface, it can be oxidized by methanotrophs to carbon dioxide and water. Zhao et al. (2021) estimated that on a global scale, 80% of the methane produced in soils and aquatic systems is anaerobically or aerobically degraded before it is emitted into the atmosphere. Wetlands, rice fields, and melting tundra are examples of soils that are net emitters of methane into the atmosphere. Other, drier soils ("upland soils") are net sinks for methane from the atmosphere. Soil covers are at present used as a mitigation practice for methane originating from manure storage areas (Oonk and Koopmans, 2012) and landfills (Sadasivam and Reddy, 2014). Improvement of methane uptake has been reported with soil amendments such as compost (biocover; van den Bergh et al., 2023) and by paying attention to land use practices such as soil compaction, fertilization, and crop growth, which tend to reduce methane uptake (Täumer et al., 2021).

Most of the experiments have been microcosmic experiments (sample in a closed vial and methane in the headspace), often with 1% concentrations of methane or higher. Thus, a potential rather than an actual methane uptake is measured. Consistent with the findings of Täumer et al. (2021), forests show higher potential methane uptake than grasslands and arable land, and fertilization, mowing, and tillage decreases methane uptake. Although, even in controlled conditions, the variability between soils is large. Therefore, the potential of soil filters in animal husbandry needs further investigation.

***F. Biofilters.*** Some authors have considered the possibility of using soil as a filter to remove methane from the ventilation air on dairy barns (Oonk and Koopmans, 2012). This idea is supported by the estimation that annually ~30 Mt atmospheric (ambient) methane is oxidized by methanotrophs in soils (Saunois et al., 2025). Methane-oxidizing bacteria (methanotrophs) oxidize methane as their main source of energy. Their capacity to oxidize methane has been applied and further investigated to remove methane from several sources, including ventilation air from animal confinement buildings. This approach is referred to as biofiltration. The structure of the reactor in which the biofiltration occurs varies with the source and concentration of methane. For landfills and manure storage areas, with methane concentrations on the order of 3% to 70%, soil covers and biocovers are applied (Melse and van der Werf, 2005; Sadasivam and Reddy, 2014). Here, the natural flow of methane-containing gas is led through a layer of soil (soil cover) or through a mixture of compost and porous packing material (biocover), which is inoculated with a source of methanotrophs. van den Bergh et al. (2023) found that certain types of methanotrophic bacteria were a main responsible factor for the methane uptake rates by compost, with green compost showing the highest potential uptake rate.

Biofilters for removing methane from sources with intermediate concentrations (<0.2%–10%), the design of such biofilters (Khabiri et al., 2022), the nature of packing materials (La et al., 2018), and physicochemical conditions have been investigated to maximize removal efficiency (Ahmadi et al., 2024). These filters do work in principle. However, the low methane concentrations (5–100 ppm) in cattle barns combined with the high flow rates of ventilation air (on the order of 500 $m^3$/h per cow) would demand (unrealistically) large biofilters (Melse and van der Werf, 2005; Girard et al., 2011; Veillette et al., 2012).

### *Conversion at Low Methane Concentrations (<0.2% or 2,000 ppm)*

Several authors have proposed research to capture and oxidize methane from the air surrounding us at the low level of 2 ppm (Yoon et al., 2009; Jackson et al., 2019, 2020; Ming et al., 2022; Nisbet-Jones et al., 2022). This concentration is at the low end of concentrations in cattle barns. He and Lidstrom (2024) reviewed current information regarding how methanotrophs grow on low methane concentrations in the context of developing treatment strategies that could be applied for both decreasing methane emissions and removing methane from

**Table 3.** Overview of experiments on removing methane at low concentrations

| Habitat | Methodology[1] | Methane removal | Reference |
|---|---|---|---|
| Noble-based catalysts | Review: Oxidation of methane at low temperatures | | Gélin and Primet (2002) |
| Soil: upland soils and forests; (meta)-analyses | Microcosmos experiments | 0–5 kg/yr per kg DM (0–13.7 g/d per kg) | Täumer et al. (2021) |
| Laboratory biofilters (11.2 L) with mycelium | EBRT: 25 s<br>Input: 90–120 ppm (58–78 mg/$m^3$)<br>$CH_4$ flow rate: 1.46 $m^3$/h | 0.5–1.5 g $CH_4/m^3$ per hour (5%–15% removed) | Oliver et al. (2016); Oliver and Schilling (2016) |
| Laboratory biofilters (11.2 L) with mycelium (A) or methanotrophic consortium (B) | Input: 20 to 100 ppm (13–65 mg/$m^3$)<br>$CH_4$ flow rate: 1.46 $m^3$/h<br>EBRT: 25 s | A. 0.0–0.5 g $CH_4/m^3$ per hour<br>B. 0.5–2.0 g $CH_4/m^3$ per hour (41% removed; largest adsorption at beginning experiment) | Oliver et al. (2016); Oliver and Schilling (2016) |
| Laboratory biofilters (11.8 L) filled with 7.6 L of compost plus straw (1:1 by volume) | Input: 300 ppm, 0.036 $m^3$/h<br>EBRT: 0.21 h<br>Max. ox. rate: 1.68 μg $CH_4$/gdw/h | Removal efficiency up to 100%; winter conditions gave variable efficiencies | Fedrizzi et al. (2018) |
| Methane-oxidizing bacteria immobilized on autoclaved aerated concrete | Cows in a respiration chamber.<br>Avg. methane concentration: 61.9 ppm.<br>Gas feed flow rate: 1.2 $m^3$/h | Avg. removal efficiency: 17.5% | Ganendra et al. (2015) |
| Farm scale wood chip biofilters (0.25 m deep) | A: surface 68 $m^3$, treating 75,000 $m^3$/h EBRT: 0.8 s. poultry manure dryer<br>B: surface 188 $m^2$, 100,000 $m^3$/h, 1.7 s ventilation air piggery<br>C: surface 440 $m^2$, 300,000 $m^3$/h, 1.4 s ventilation air piggery | A: conc. in 3.2 ppm, out 3.1 ppm<br>B: conc. in 31 ppm, out 38 ppm<br>C: conc. in 117 ppm, out 109 ppm<br>Increase in $N_2O$ | Melse and Hol (2017) |
| Culture collection | Methanotrophic strains | High methane oxidation at 100–500 ppm | He et al. (2023) |
| Methane eradication photochemical system; flow of 30 L/min; reactor volume of 90 L | UV power input: 368 nm at 110 W<br>Chlorine concentration: 99 ppm<br>Methane concentration: 55 ppm | 58% removal efficiency | Krogsbøll et al. (2024) |

[1]EBRT = empty bed reaction/residence time; gdw = gram dry weight.

air. However, they acknowledge that at present it is not feasible to remove methane concentrations as low as 2 ppm from the air in practice.

The limited number of published experiments with input concentrations of methane that are comparable to ventilation air on dairy farms are listed in Table 3. Such research is mostly restricted to laboratory experiments. In these experiments, the reduction of methane was rather low (5%–17.5%). Recently, Krogsbøll et al. (2024) presented the first results of a method based on using chlorine atoms in the gas phase. A laboratory prototype of "the methane eradication photochemical system technology" achieved 58% removal efficiency with a flow capacity of 30 L/min, a reactor volume of 90 L, UV power input at 368 nm of 110 W, chlorine concentration of 99 ppm, and methane concentration of 55 ppm. They wrote (p. 5) that "subsequent to the lab scale prototype tests, a larger field prototype will be tested in these environments (pig and cow barns) before the design is scaled up." Furthermore, Brenneis et al. (2021) reported experiments in which methane was adsorbed using a biomimetic self-assembled device of copper and zeolite. Methane concentrations at dairy farm levels were used (range: 2–20,000 ppm). The step to practice is being investigated.

Melse and Hol (2017) reported on the use of biofilters with wood chips on farms. These filters were primarily meant for odor control, and no methane reduction was obtained. Moreover, in 2 of the filters, the emission of nitrous oxide ($N_2O$) was doubled. However, more positive results have also been reported. Fedrizzi et al. (2018), simulating Canadian winter conditions in a laboratory experiment with a ventilation flow rate of 43 $m^3$/h per cow and a methane concentration of 300 ppm, showed up to 100% methane removal. With a relatively long residence time (0.21 h), a filter for ~10 $m^3$ per cow is needed. Lidstrom (2023, p. 5) stated about low levels of methane (100–500 ppm) that "commercial biofilter-based methane removal technology provides an existing platform of success on which to build enhanced systems, perhaps with a modified bioreactor configuration." Lidstrom added (personal communication) that recently up to 90% removal rates were achieved at 500 ppm levels in bioreactor experiments by use of special methanotroph bacteria strains. However, dealing with high airflow rates as in open barns remains a big challenge.

## THE VENTILATION CHALLENGE

In the former chapter, it was argued that microbiological as well as physicochemical methods are available for capturing and oxidizing methane at concentrations of 0.2% to 10%. The very low concentrations of methane

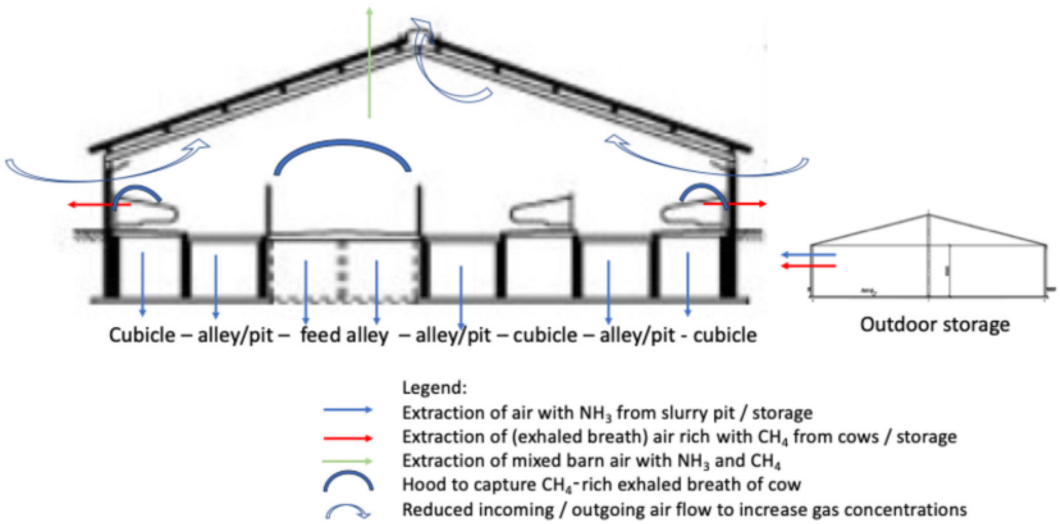


**Figure 1.** Cross-section of a typical cubicle barn with slurry pits. Arrows indicate extraction points of air to be transported to a treatment unit for ammonia and methane removal (Source: authors).

found in dairy barns (0.0005%–0.01%; 5–100 ppm) are the main obstacle to applying these methods effectively. Thus, an important question is whether it could be possible to concentrate the methane and capture it at a higher concentration. So, one approach could be capturing the air flows with higher methane concentration levels near the sources, being the animal and the manure. Another option could be the development of ventilation systems that result in less dilution of methane in the current, rather open cattle barns or redesign the cattle housing facility to obtain a stream of air with levels of methane that would allow capture and treatment.

We considered 3 possibilities (and combinations) for capturing methane in housing facilities, as depicted in Figure 1: (1) capturing the air flow close to the animal with elevated levels of methane (and treat it afterward); (2) capturing the air flow from the manure pit in the barn or from an external closed manure storage area to which fresh manure is ideally transported daily; (3) reducing the net ventilation rate by recirculating ventilation air in the barn and thus creating an airflow with higher concentrations of both methane and ammonia for further treatment; and (4) combining the separate air flows of (1) to (3) smartly to achieve a sufficiently high methane concentration for treatment.

## CAPTURING AND CONCENTRATING TECHNIQUES FOR METHANE IN DAIRY BARNS

We looked at methane capturing techniques that are being adapted to the common cow cubicle house (freestall) with slatted or solid floors. The gas capture takes place near the source, for example, for the cow, it is near the mouth continuously or at peak times (after feeding), and for the manure, it is on the floor of the barn and in the storage pit.

### Cannulas and Wearables

To avoid the dilution of methane by air, attempts have been reported to capture methane by inserting a cannula into the rumen for collection into a bag attached to the back of the animal. Up to 300 L of methane per day per animal can be collected in this way. Seemingly, the goal of doing so was primarily to collect methane for fuel in remote areas and not abatement of GHG emissions (INTA 2013, cited by Rivero and Daim, 2017).

Another recent approach is mounting a mask on the snout of the cow with methane sensors near the nostrils and capturing methane by adsorbents followed by combustion (Norris and Norris, 2018). Apart from technical challenges, both approaches could be at odds with animal welfare and practicality. The Zelp mask has recently been tested as a less costly alternative for measuring gases of cows compared with respiration chambers (Coetzee and Bica, 2025).

### Hoods Above the Laying and Feeding Area

Several authors have reported on ventilation hoods or head boxes fitted more or less closely around the head of the cow to monitor gas emissions. These systems have primarily been developed for research purposes to assess methane production by individual animals (Johnson and Johnson, 1995). Place et al. (2011) measured methane levels of up to 1,200 ppm in a head box. A

**Figure 2.** Cows in box with hood for capturing methane (experimental setups). Left and center: Levrault (2024); right: M. Myllerup (SEGES, Aarhus, Denmark, personal communication).

closely fitting hood or box may be acceptable for research purposes, but for methane removal on a commercial farm, animal movement should not be hindered. Thus, a hood-like system would be probably best placed above the lying bed where the cow resides during rumination or above the feeding alley.

M. Myllerup and A. J. Freudendal (SEGES, Aarhus, Denmark, personal communication), as well as Galama et al. (2023), Wu et al. (2018), and Levrault (2024), have reported placing a hood above the head end of the lying boxes (Figure 2) and assessing the methane concentrations of the breath samples captured from the air from the hood. Results to date (Levrault, 2024) show mean methane concentrations of 125 ppm with an SD of 56 ppm. Concentrations measured at the background points (on the cubicle construction outside the hood) were 35.3 ppm with an SD of 26.9. Thus, the concentration measured from air in the hood was on average 3.5 times as high as in the barn. This concentration could likely be increased to above 200 ppm when the exhaust ventilation rate of the hood is lowered (C. Levrault, Agricultural Biosystems Engineering, Wageningen University, Wageningen, the Netherlands, personal communication). During the experiments, no negative effects on cow behavior were observed. Cow welfare remains an important consideration in the further development of such a system. Tabase et al. (2024) reported that when hoods were placed over the cubicles in 2 barns, the hourly methane concentrations increased by 14% to 25% (to 14–225 ppm in a naturally ventilated barn and 31–322 in a mechanically ventilated barn) compared with the control situations and depending on the height of the cubicle hood from the floor. They reported "higher concentrations were measured closer to the animals, although these concentrations were more variable than farther away." This was supported by measuring methane concentrations each 30 min in a mechanically ventilated barn at the feeding alley, at the lying boxes, and in the concentrate feeder, resulting in 46 to 282 ppm, 53 to 731 ppm, and 49 to 3,303 ppm, respectively ("peaks and dips coincided with animal presence").

Another approach is to focus the suction of air to those periods when methane production is highest, thus, just after the feeding times. A rapid rise toward a methane production peak is reached at 30 to 140 min after feeding, followed by a slow decrease back to normal levels (Crompton et al., 2011; van Lingen et al., 2017). Instantaneous methane concentrations in exhaled breath during eructation can be above 1,000 ppm but are difficult to measure due to slow sensor response and air dilution. Therefore, Wu et al. (2015) carried out a simulation study and found peak concentrations up to 3,000 ppm. However, sensor development receives much attention, and we expect more precise measurements to be possible soon.

### *Concentration by Recirculation*

N. Edouard and P. Robin (INRAE, Rennes, France, unpublished data), as part of the EU Climate Care Cattle farming project, housed cows in a research facility that could be closed and measured accumulation of gases. The facility has different ventilation systems, one of which is for air conditioning with a recycling option (size barn unit 833 $m^2$; airflow 300 $m^3$/h). In the trials, 3 cows inside this barn unit were fed maize silage and a soybean supplement. With air conditioning and the 100%

recycling option turned on, the concentration of gases initially increased with time. However, after some hours, the rate of increase slowed, likely due to some leakage ventilation (Table 4). The concentrations that were achieved during a 10-h period with 3 cows were ~4,900 ppm $CO_2$ and 210 ppm $CH_4$, on average.

By recirculating and concentrating methane in a barn, the levels of other gases such as ammonia and hydrogen sulfide ($H_2S$), as well as moisture, heat, and particles, rise simultaneously. Depending on their concentrations, these substances represent a danger to animal and human health (Cao et al., 2023). The challenge in designing alternative ventilation systems is to obtain airstreams that allow removal of ammonia and methane without compromising animal or farm worker health.

**Table 4.** Carbon dioxide and methane concentrations during 2 trials with reduced ventilation rates in an experimental unit with 3 cows (N. Eduard and P. Robin, INRAE, Rennes, France, personal communication)

| | Trial 1 | | Trial 2 | |
|---|---|---|---|---|
| Time (h) | $CO_2$ (ppm) | $CH_4$ (ppm) | $CO_2$ (ppm) | $CH_4$ (ppm) |
| 0 | 800 | 30 | 1,100 | 55 |
| 3 | 3,029 | 136 | 3,146 | 158 |
| 6 | 4,105 | 187 | 4,133 | 207 |
| 10 | 5,358 | 199 | 4,365 | 219 |

### Combine Flows with High and Low Concentrations

This approach is to combine the targeted ventilation air of a hood system around the lying or feeding area with air from closed manure storage areas, either with or without activated anaerobic fermentation. This combination would facilitate oxidation of part of the enteric methane captured in the barn along with methane captured from the manure storage area. Specifics of how much ventilation air of the barn can be combined with the more concentrated air from the closed manure storage areas would depend on the weather conditions (higher temperature results in more methane production in the manure storage area). Combining air flows facilitates the possibility of obtaining sufficiently high concentration of methane, enabling to oxidize it into carbon dioxide. A combination of ventilators, methane gas sensors, and a control unit can regulate a more or less stable inflow of methane to the filtering or oxidation bed or reactor. A somewhat similar approach was described for ventilation air with methane from mines; this gas flow (methane concentrations vary from 0.1% to 1.0%) is used in a combustion engine together with a fossil fuel (Zhang et al., 2014b).

### Biogas Plants

Aside from capturing methane from the air flow, other on-farm techniques are better known for producing a useful rest product from carbon in manure and forages. Biogas plants are increasingly becoming an integral part of dairy farming (Biogas Danmark, 2023; El Mashad et al., 2023). The anaerobic bacterial process in the biogas plant results in the production of a mix of methane and carbon dioxide (~60% $CH_4$, 35% $CO_2$, and 5% other), which is used as renewable energy for on- and off-farm purposes. The biogas can be upgraded to "green gas" (at least 80% $CH_4$ and 20% or less $CO_2$) by removing the other gases ($H_2S$ and $H_2O$) from the mix. Green gas (also called a "renewable natural gas;" Grubert, 2020) can be added to the fossil natural gas grid (Green Gas Certification Scheme, 2025).

The drawback of the current biogas installations for production of biogas from animal manure is the need for larger scale to keep the plant economically viable. On a smaller scale, it is also possible to design closed manure storage areas on the farm without any energy from the grid for heating of the manure. Maasdam et al. (2024) showed that during the warmer months, closed manure storage areas can produce methane streams with 60% to 80% methane that can be used on a small-scale flare to oxidize methane into carbon dioxide. Farmer P. van Roessel (Haarsteeg, the Netherlands, personal communication) manages filling small gas cylinders with methane from the closed manure storage area by compressing and cleaning the collected biogas into green gas for sales purposes. The methane production in the manure storage area follows a passive process that does not require energy from the grid. The collection of methane is by a mobile system in cooperation with an energy supply company and does not require direct access to the gas grid, which is an advantage in present times of overload on the grid systems. Ward et al. (2024) refer to a similar setup in southern England, in which the cleaned and compressed methane gas from manure is used for vehicles.

## CAPTURING TECHNIQUES FOR AMMONIA IN DAIRY BARNS

Several principles of dealing with ammonia are listed in the "Principles to Remove Ammonia From Dairy Barns" section. We restrict ourselves to describing those technologies that can be considered end-of-pipe solutions dealing with ammonia emissions, as fitting to the aim of this review.

### Air Scrubber Technology

Air scrubbing systems can be categorized in 3 classes: (1) systems with low water pH, generally controlled by an acid supply; (2) so-called biotrickling systems with nitrification and possibly denitrification; and (3) biobeds with natural contact material. Mostly acid scrubber systems are applied in Western Europe and, for instance, introduced in China to take dust and ammonia from the mechanically ventilated air from pig and poultry barns (Cao et al., 2023). An acid air scrubber is a monolith with a large contact surface between the passing air flow and the recirculating water with a low pH value (range: 1.0–5.5). The ammonia is bound as ammonium in the liquid phase. The ammonium containing excess water can be used as fertilizer. The ammonia reduction of acid scrubbers in pig and poultry housings is generally above 90% (Melse and Ogink, 2005; BAL, 2025).

### *Air Scrubber for Air Flows from the Whole Dairy Barn*

The application of air scrubbers in dairy barns is very limited because of the openness and size of these barns and the very high ventilation rates. In the Netherlands, ~30 of those air scrubber systems are in use on dairy farms. The ventilation through the side walls is restricted by wind break mess or traditional solid walls to create sufficient under pressure limiting outflows of barn air not being treated. The additional energy needed for recirculating water and the mechanical ventilators is seen as a costly component of this system. Air scrubbers for dairy barns have to be large, when dimensioned correctly, due to the high ventilation rates per cow and in total, making them relatively expensive.

When the air scrubber is well positioned and the barn well adapted to this system, it should be possible to reach ammonia reduction levels that are close to applying this equipment in pig and poultry housings.

### *Regular Removal of Manure from the House to a Closed Storage or for Direct Treatment*

To prevent uncontrolled emissions of ammonia (and other gases) from manure in the barn, the most efficient approach is to regularly (e.g., daily) remove the slurry from the pit to a closed storage system. A low and controlled ventilation rate in the headspace of such storage areas allows concentrating released ammonia and methane from the manure and applying subsequent air treatment. Regular removal of manure is often combined with manure treatments such as solid (~38% DM) and liquid (1%–2% DM) separation to allow cheaper off-farm transport of surplus nutrients. Advanced treatment systems for manure have been described by Gollenbeek et al. (2022), including the latest developments, such as $N_2$ Applied Plasma Technology (Ingels, 2022) and the N-Cracker (Elling, 2022), a nitrogen stripper and scrubber technology that is already applied on farms.

## INTEGRATED SOLUTIONS AND DESIGNS

### *Integrated Solutions*

Although this study concentrates on the reduction of methane emissions from cows and manure, in several regions of the world, there is emphasis on reducing nitrate leaching and ammonia emissions (Pexas et al., 2020; Kuipers and Galama, 2023). Technologies and practices to curtail ammonia emissions are either under consideration or have already been applied, as listed in the section "Principles to Remove Methane and Ammonia Emissions from Dairy Barns." However, a major concern with such technologies is the danger of a possible future lock-in when reducing methane emissions from livestock units becomes obligatory. Accordingly, we surveyed the possibilities of ammonia abating technologies that have the potential to simultaneously reduce both ammonia and methane emissions.

Whole-farm approach. Several nitrogen mitigation practices also affect GHG emissions to a modest degree. The AgreCalc carbon footprint tool from SRUC, Scotland, and the nutrient management ANCA tool from the Netherlands show such effects on farm-level calculations (McNicol et al., 2024). When nitrogen or concentrate inputs on farms are reduced, less energy is needed to manufacture those products, thus lowering production of GHG gases (mainly $CO_2$) somewhat. When recycling nitrogen on the farm by filtrating ammonia from the air and reusing it as fertilizer, the requirement for fertilizer nitrogen is reduced, thus lowering the carbon footprint. These combined effects of nitrogen or ammonia and carbon or methane reductions are particularly relevant in realizing integrated environmental solutions.

Regular removal of manure from the barn and (central) digestion. This system is, for instance, applied in Denmark, where manure from farmers is collected and centrally digested in regional plants. Already 30% of the Danish gas used comes from cooperative and private biogas plants with manure as the main component, and the goal is to increase this to almost 100% by 2030 (Biogas Danmark, 2023; Galama et al., 2023). In California, a network for manure and gas transport has been implemented to support biogas production and distribution (El Mashad et al., 2023), as well as in India (Sawale and Kulkarni, 2022). Verdoes et al. (2023) conducted a study with 26 dairy farmers on the prospects of rapidly removing manure from the barn and centrally digesting and stripping it. The reduction of ammonia throughout the manure processing chain amounted to 46%, and methane emissions from manure were reduced by ~78%.

Acidification of manure. Manure acidification lowers pH to 5.5 to shift the chemical equilibrium from $NH_3$ to $NH_4^+$, resulting in a reduction in N loss of 40% in the

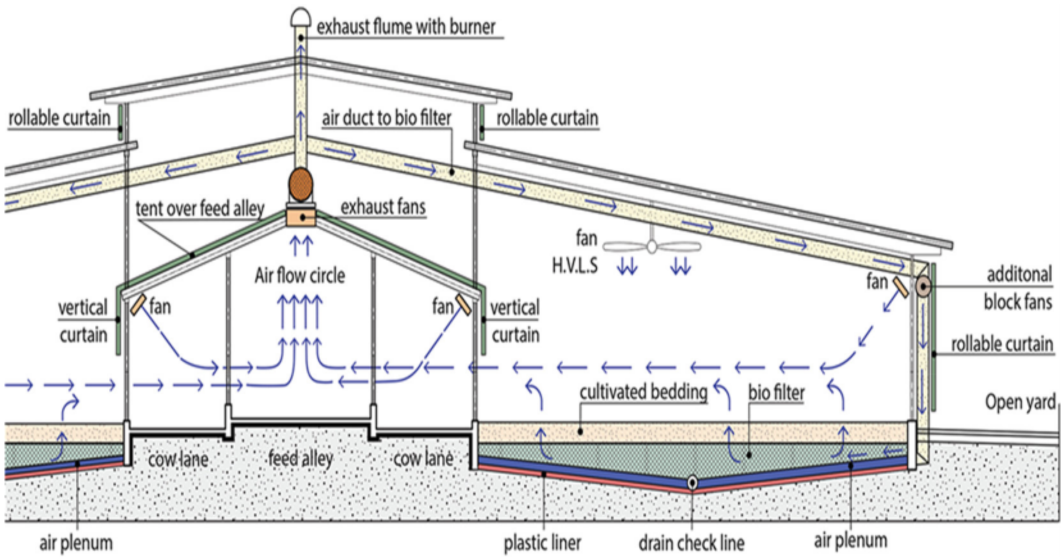


**Figure 3.** Multiclimate and low gas and odor emission animal housing (source: Sprecher Architects, Israel, personal communication; Galama et al., 2019). Fan H.V.L.S. = high-volume, low-speed fan; arrows indicate direction of air flows.

barn and 49% during the application in the field (Puente-Rodríguez et al., 2022). Fuchs et al. (2021) reported greater reductions in ammonia emissions of 56% to 85% by acidification of manure in the barn. The variation in results arises from the fact that both laboratory and in-field experiments are performed under varying circumstances. Most research and experiences with acidification come from Denmark, where a limited number of dairy farms (less than 100) operate such a system. Recently, an extension expert from Denmark mentioned lower reduction percentages of 30% to 35% in barns (A. J. Freudendal, SEGES, Aarhus, Denmark, personal communication).

The effect of acidification is (partly) retained when applying the manure to the fields. Pedersen and Nyord (2023) described experiments in which acidifying the digested cattle manure equal to the crop sulfur requirement (low-dose acidification) reduced $NH_3$ emission by 13% compared with nonacidified trailing shoe application. As part of the Baltic slurry acidification project, manure was treated just before application to the fields. The effects on ammonia and methane and crop yield were measured (Juškienė et al., 2022). They concluded that "mild acidification of cattle manure at application time can be a successful solution to help farmers reduce $NH_3$ and $CH_4$ emissions and at the same time improve the fertilization value."

Acidification is also a promising method for reducing methane emissions from manure. At a lower pH, the activity of methanotrophic bacteria is restricted or blocked. At pH 5.5 or lower, reductions in methane emissions of 65% to 90% (Puente-Rodríguez et al., 2022) and 63% to 99% (Fuchs et al., 2021) have been reported. Lemes et al. (2022, p. 1) reported reduction percentages from both cattle and pig manure in concrete manure storage tanks at pH 5 of 95%, on average, and concluded it "to be a promising technology for mitigation of methane from manure storage," whereas Ma et al. (2022, p. 1) reported on basis of economic calculations "low-dose acidification to be a viable strategy for GHG mitigation." Furthermore, it appears that the positive effects on methane emission are retained during the application of the manure to the fields.

However, the additional input of acid components to the farm system and the corrosion and other effects acid can have on barn and manure handling facilities cause serious hesitations for applying acidification techniques.

Feces-urine segregation and pit ventilation with air scrubber. This system combines various principles and techniques presented before and has been developed and brought to practice as the Sphere system (van den Berg et al., 2017; Gollenbeek et al., 2022). The openings in the traditional slatted floor are covered by strips with small holes that enable quick drainage of urine to the pit underneath, with the feces staying on top. Feces are regularly removed with an autonomous collector robot, preventing mixing with urine, and stored separately. Partial pit ventilation with sufficient under pressure is applied, and this air flow goes through an acid scrubber. Overall, an ammonia reduction of 75% can be achieved (BAL, 2025). Moreover, this Sphere system with source segregation of feces and urine offers opportunities to reduce nitrogen and methane losses by additional treat-

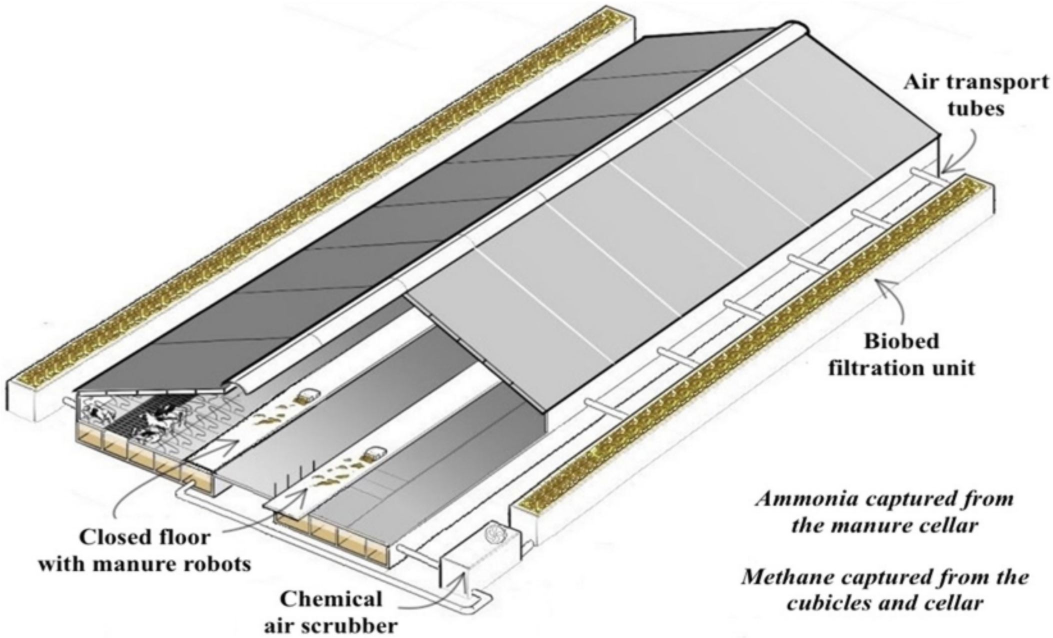


**Figure 4.** Design concept 1. The generic solution illustrates a selective airflow in the barn for capture of methane and an acid scrubber for capturing ammonia from the manure pit and floor surface.

ments in the whole manure chain up to field application, as shown by Mahdi et al. (2024).

### Integrated Designs

Under the assumption that in addition to ammonia methane can also be adsorbed, converted to gases with lower global warming potential, or both, several designs were made and are presented hereafter. The designs combine potentially promising emission reducing practices and techniques (already in practice or still in pilot stage) as described and discussed in this review.

***Design: Multiclimate Shed.*** The multiclimate shed of Sprecher, Israel, has been described by Galama et al. (2020). The multiclimate aspect is achieved with a "tent" type additional roofing above the feeding area (see Figure 3 for cross-section of building). This tent creates a microclimate within the entire building with respect to temperature, humidity, and fresh air, and it provides the possibility of removing gases (ammonia and methane) and odors. The reversed V shape of the tent structure enables the collection of air in the top of the building and conducts it through pipes toward the floor beneath the bedding and into the bedding material. The hypothesis is that the "in-house biofilter" (bedding with wood chips) can remove the ammonia and odor. Part of the air leaves the building at the top, and the methane is oxidized with a burner, whereas the other part of the air is recycled in the barn. The multiclimate shed as a whole system has not been built yet, but elements of it have already been incorporated into existing innovative building designs.

***Designs: Generic, Organic, and Recirculation.*** Based on intermediate information gathered in this review, Wiering and Groot Koerkamp (2022) sought to design a dairy barn to mitigate ammonia as well as methane emissions. This resulted in 3 theoretical designs.

Design 1: The generic solution emphasizes a configuration that ensures minimal airflow within the barn to elevate the methane concentration for efficient capture with maintenance of a healthy climate (see Figure 4). Emissions are contained close to their source; semi-closed slatted floors allow urine to drain into a sealed pit, and a robot cleans and deposits feces into a separate pit to inhibit ammonia formation. Under-pressure ventilators extract air from these pits, directing it through an acid air scrubber to capture ammonia before releasing it to a biobed for further treatment. Methane exhaled by cows is captured using hoods installed above cubicles, preventing to some degree dilution with barn air. This air is channeled to a biobed treatment unit where methanotrophic microorganisms are present to oxidize the methane, ensuring effective mitigation.

Design 2: The organic solution adapts emission reduction strategies to meet the requirements of organic farming, where on-farm recycling of byproducts is essential. The design builds upon the generic solution by including

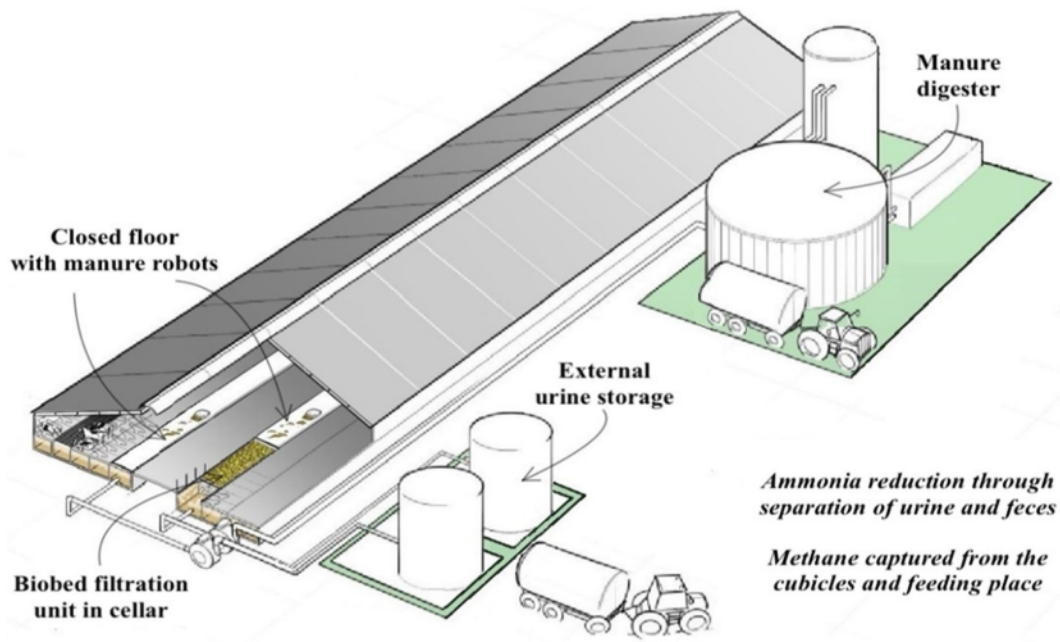


**Figure 5.** Design concept 2. The organic solution uses a manure digester and a biobed filtration unit.

solid floors and manure-collecting robots (see Figure 5). Feces are directed to an external biodigester to contain methane, whereas urine is stored separately to contain ammonia. Feed alleys are replaced with conveyor belts equipped with methane-capturing hoods. Additionally, the design integrates combined feeding and lying areas, with hoods placed strategically to capture methane-rich air from cows facing one another. The manure cellar space is repurposed for a biobed, where methane captured within the barn is oxidized, ensuring compliance with organic standards and achieving emission reductions.

Design 3: The recirculation solution adopts a centralized approach to emission management within a standard cubicle barn with slatted floors, where manure is stored in a pit beneath the floor. Barn air gases are extracted from within the barn and channeled to an extended compartment of the barn, where treatment takes place with advanced air scrubbing systems (see Figure 6). The treatment involves 3 stages: an acid water scrubber removes ammonia and particulate matter, an alkaline scrubber captures carbon dioxide and odors, and a biofilter oxidizes methane and remaining particulates. Treated air is recirculated into the barn to maintain a stable oxygen concentration, supplemented with fresh air if necessary.

### Inventions in the Field

We would report on ideas and practices of farmers that we came across during our inventory. However, most of these inventions are under development and have to be examined for their working principle and effectiveness. As an example of innovativeness, farmer L. Ten Have (Lettelle, the Netherlands, personal communication) built a dairy barn that enables lower ventilation rates as incoming air is cooled in ducts in the ground(water) and air from the pit head space is planned to be extracted to a biobed for air treatment. Farmer Dick (2023) in British Columbia, Canada, has developed a whole-farm system in which the barn and manure storage include a combination of techniques described elsewhere herein with the intention of resulting in a climate-neutral barn. A farmer in Denmark installed a large duct with holes above the cubicles to collect methane from the barn air and subsequently treat it outside (Galama et al., 2023). Farmer S. Bosman (De Krim, the Netherlands, personal communication) uses the water drains in his grass fields to push and distribute barn air into the soil where the ammonia and methane is expected to degrade, enriching the soil.

## EVALUATION AND DISCUSSION

Ammonia and methane production on a dairy farm differ in source and place. Methane is predominantly produced in the rumen of the cow and exhaled. In addition, methane is released from the manure stored in pits under slatted floors or in storage facilities outside. Ammonia is primarily and rapidly formed upon hydrolysis of urea in urine and more slowly from protein degradation during

**Table 5.** Indications of methane concentration and treatment from cow to manure storage derived from this study's literature review

| Place of air | Concentration (ppm) | Treatment |
|---|---|---|
| In closed manure storage | 600,000–800,000 | Capture as green gas |
| In rumen | 200,000–300,000 | |
| Near mouth or breath and in concentrate feeder (peaks) | 2,000–3,000 | Oxidize |
| In head hood | 400–1,400 | Oxidation in development |
| In hood duct | 150–300 | |
| In barn | 5–100 | Oxidation not possible |
| In ambient air | 2 | |

storage of manure. Thus, solid floors and manure storage in and outside barns are the sources of ammonia emissions from the housing and storage facilities.

This difference in main source (animal vs. excreta) and main location within the barn (animal height vs. floor and manure pit) of emissions of methane and ammonia offer an opportunity to reduce both. Separate ventilation of the manure pit including the floor top with rapid cleaning of the floor and then scrubbing ammonia from the air can reduce ammonia emissions from the barn by up to 75%. Recently, equipment has been developed and installed on farms based on this approach.

Another approach is quick and frequent removal of all excreta from the barn. Provided ammonia emissions during storage and land spreading are prevented or greatly reduced, almost similar reductions in ammonia can possibly be obtained as with the air washer system. In some regions, such as California and Denmark, increasingly the mixed excreta (preferably fresh manure) are transported to on-farm digesters and central biogas plants.

Extensive research is ongoing to reduce animal methane emissions by genetic selection and use of feed additives that influence rumen fermentation. Because methane—as the major electron acceptor in the rumen—is driving the fermentation process that provides nutrients from the feed to the animal, it is considered unlikely that methane production can be largely prevented by only animal-based measures. Furthermore, a series of manure management techniques has received ample attention, such as floors and handling of manure in barn and storage. Each of these practices is helpful in reducing ammonia and methane emissions in a modest way. However, their implementation in practice is hampered by the complexity of applying those practices in existing barns. Moreover, the aggregation of practices elaborates farm management. This contributes to the observation that theoretical or experimentally obtained reduction percentages are difficult to achieve in practice and not add up (Bremmer et al., 2022; van Wagenberg and Groot Koerkamp, 2024). This also affects negatively certification procedures of such practices or techniques and may initiate and support juridical complaints.

Capturing and oxidizing methane from the ventilation air could be an alternative to reducing methane emissions in a substantial way by adapting the environment to the animal and farm families. The methane concentrations observed in this review with possible treatments are summarized in Table 5. As can be seen, capturing and oxidizing methane from the air is hampered by the low concentrations (5–100 ppm) of methane in the barn, which cannot be effectively dealt with by existing technologies. Capturing airflows that have an elevated concentration of methane (less diluted) could be the basis of a solution.

Recirculation of air inside the barn to increase methane concentration demands that side walls are closed or permanently covered with wind break mesh (netting) or combinations of those. This requires additional technologies, such as filters, to remove undesirable and health-impairing gases in the recirculation process.

Capturing methane close to the mouth of a cow by a hood system is a promising option. Experiments are in progress with hoods above the laying bed or feed alley to capture methane in higher concentrations. At present, concentrations of ~150 to 250 ppm are measured by suction of air from the hoods and 1,200 ppm when measured in the hood. Ways to further increase the concentration of methane from the hood without impairing air quality are, for instance, lowering air flows by creating separate ventilation systems for both the manure pit and the barn or by combining head space gas from the manure storage with air extracted from under the hoods in the barn.

Applying the innovations presented in this review study raise an additional challenge. The introduction of cubicle houses dates from the 1960s and was then embraced as saving labor and giving the animals freedom of movement. However, it is now necessary to search for new ways to mitigate emissions from barns. Adaptations of present dairy barns to achieve this are likely to be more complicated and more expensive than redesigning building facilities including the new emission reduction techniques. On the basis of the information gathered in this review, one existing inventive housing design is presented (Sprecher Architecs, Israel, personal communication), and, additionally, 3 theoretical housing designs were developed integrating emission reduction technology (Wiering and Groot Koerkamp, 2022).

Following a successful application of alternative and innovative ventilation and air filtering techniques, authors tentatively calculated a potential reduction in methane emissions on the farm level of almost one-fourth, assuming that 65% of captured methane is oxidized (Table 6). When assuming 75% of the methane in the combined air flow oxidized and the herd confined throughout the

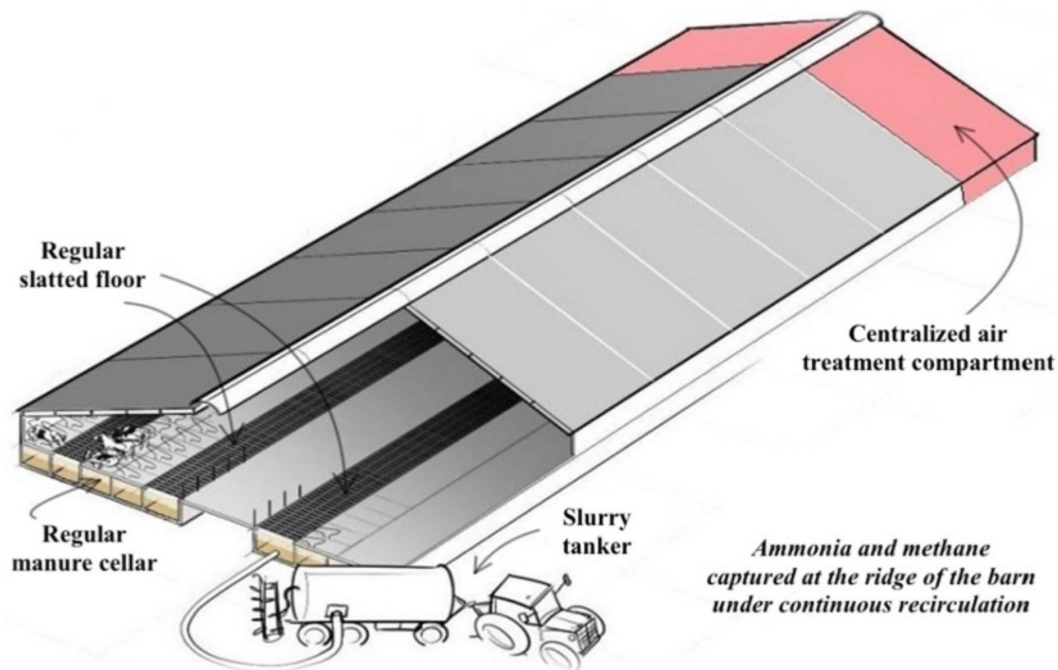


**Figure 6.** Design concept 3. The recirculation solution illustrates barn gases channeled to an extended compartment for treatment, and then the treated air is recirculated to the barn.

year, the reduction could be up to almost one-third of the methane present. With colder air and lower airflows, resulting in somewhat higher gas concentrations (Fedrizzi et al., 2018; Tabase et al., 2024; farmer L. Ten Have, Lettelle, the Netherlands, personal communication), the size of a biofilter needed per cow is expected to be less, that is, from ~30 $m^3$/cow with 100 ppm to 10 $m^3$/cow with 300 ppm (see also IGEM, 2021).

Additionally, an expert analysis approach was conducted by the authors and colleagues to qualify the air filtering system on basis of the knowledge and experiences presented in this review. The evaluation criteria as listed in the "Introduction and Approach" section of this paper were used, including socioeconomic insights. The outcomes of the discussions are described in Table 7. Indeed, air capturing technology does show promise. The certification of these types of equipment, installed for the long term, may be easier to accomplish than with day-to-day animal and management related mitigation practices. Another advantage of capturing techniques is that other gases such as hydrogen sulfide as well as dust particles can potentially be filtered from the air in a stepwise process. This results in a more pleasant environment for both humans and animals (Zhao et al., 2007; Jouneau et al., 2022). In the same context, the removal of gases from the manure storage pits will result in minimizing the danger of explosions from mixture of gases or poisoning by those gases. However, air filtering systems including the ventilation techniques require considerable investment and energy costs because of the large volumes of air to be treated (Lackner 2020; Nisbet-Jones et al., 2022). Gollenbeek et al. (2022) estimated costs and returns for manure handling techniques, such as those listed in this review. The techniques require investments at varying scales. Larger farms can better cope with the higher investments. As an alternative, cooperation as with biogas plants may be an option for smaller farms. However, prices, costs, and management conditions differ in regions around the world, necessitating economic evaluations adapted to specific regions.

On the debit side, filtration techniques for catching or stripping ammonia from the manure produce a concentrate of nitrogen. Such mineral concentrates are in the process of being accepted by the European Union for use as a fertilizer, called "Renure" (REcovered Nitrogen from manURE), provided they fulfill requirements in terms of production process and composition (Huygens et al., 2020; European Commission, 2024). Rather than buying artificial fertilizer nitrogen from off the farm, the nitrogen from the manure produced on the farm can be used instead. The creation of specific manure products offers excellent opportunities for precision application of nitrogen to plants with fewer losses to the environment (Schils et al., 2020). This is an example of the circular economy in operation at the farm level. The same applies for collecting methane gas from manure

**Table 6.** Calculation of potential reduction in methane emissions when capturing and converting methane from the less diluted barn air (Case 1[1]), and when capturing methane from a mix of less diluted barn air and highly concentrated air from the manure storage (Case 2[2])

| Item | $CH_4$ production (kg) | Units $CO_2$ (kg) | Conversion $CO_{2\text{-eq}}$ | Total $CO_{2\text{-eq}}$ |
|---|---|---|---|---|
| Original situation | 100 | | 28 | 2,800.0 |
| Case 1[1] | | | | |
| During grazing (20%)[3] | 20 | | 28 | 560.0 |
| In barn (enteric + manure) | 80 | | | |
| 50% emitted (not captured) | 40 | | 28 | 1,120.0 |
| 50% captured in barn | 40 | | | |
| $CH_4$ not degraded: 35%[4] | 14 | | 28 | 392.0 |
| $CH_4$ oxidized to $CO_2$: 65%[4] | 26 | 71.5[5] | 1 | 71.5 |
| Total of new situation | | | | 2,143.5 |
| Reduction to original situation (%) | | | | 23.5 |
| Case 2[2] | | | | |
| During grazing (20%)[3] | 20 | | 28 | 560.0 |
| In barn and storage (enteric + manure) | 80 | | | |
| In barn (25% of enteric captured)[2] | 15 | | | |
| In barn (75% of enteric not captured)[2] | 45 | | 28 | 1,260.0 |
| Closed manure storage (100% captured) | 20 | | | |
| $CH_4$ not degraded: 35%[4] | 12.25 | | 28 | 343.0 |
| $CH_4$ oxidized to $CO_2$: 65%[4] | 22.75 | 62.6[5] | 1 | 62.6 |
| Total of new situation | | | | 2,225.6 |
| Reduction to original situation (%) | | | | 20.5 |

[1]Case 1: 50% of barn methane captured.

[2]Case 2: 25% of enteric methane captured in the barn and 100% methane captured outside covered manure storage.

[3]Based on 180 d grazing per year during 10 h per day, ~20% of the time.

[4]Conversion efficiency of 65% of methane into $CO_2$ and 35% not.

[5]Conversion of 1 kg of $CH_4$ gives 2.75 kg of $CO_2$.

storage areas and biogas plants for green gas purposes. In this context, the economic calculations of Gollenbeek et al. (2022) indicated that digestion of manure may be a relatively positive option compared with other manure management and filtering techniques. Ward et al. (2024) also emphasized the potential value of biogas as a valuable new income stream for farm businesses. The marketing of other manure products has been discussed by Dahlina et al. (2015), Dadrasnia et al. (2021), and Kuipers et al. (2022).

## CONCLUSIONS

Both air filtration of ammonia in the manure pit and close to the floors, and in the case of more closed buildings in the whole barn, have been accomplished by using acid scrubbers. Ammonia reduction percentages of 75% to 90% may be expected by applying smart ventilation techniques, as discussed in this review. This study indicates that combined airflows for ammonia and methane to deal with both gases are difficult to realize because of the different characteristics and sources of the gases. Furthermore, methane concentrations in present-day open cattle housings are too low to be captured or oxidized effectively by presently known techniques. Therefore, several smart ventilation techniques were found and described to increase concentrations to processable levels: (1) timed suction systems instead of continuous suction. For instance, only collecting the air during and after cattle feeding (usually twice daily) when methane concentrations are highest; (2) combining air flows with high and low concentrations (from manure storage and cow); (3) well-placed ventilation systems that only ventilate barn sections where relatively high methane concentrations are present. For instance, using hood (cap) constructions above or around the heads of cows and over the feed alley; (4) Recycling the air within a barn to increase methane concentration. When recycling air, the concentrations of other gases are also concentrated to a similar degree. Thus, additional technical measures are needed to deal with the possible increased concentrations of other gases and dust. Technologies to do so are available; (5) Use of wind break mess as side walls or, most helpful, more closed buildings; and (6) Combinations of 1, 2, 3, 4, and 5. Employing such innovations, we expect that approximately one-fourth methane reductions at the farm level may be achievable. However, present-day dairy farms have largely been developed in an era when ammonia and GHG emissions were of lesser concern. A complete redesign of new (and existing) cattle housing would be the best route to realizing maximum reductions in gas emissions in line with present and future increas-

**Table 7.** Qualitative evaluation of new ventilation systems with air filtering to capture or convert ammonia and methane in air flows from cubicle houses for dairy cows (for criteria see "Introduction and Approach" section)

| Criterion | Score[1] | Explanation |
|---|---|---|
| Reduction potential emissions | | |
| Ammonia | CPE | With air scrubbers that capture all barn air or with air from manure pit and part of the barn, an ammonia reduction of 75% to 90% is possible. |
| Methane | PE | Approximately 80% is enteric methane, the rest comes from manure. Thus, focus on barn air has great potential, but it is technically a challenge to realize. |
| | ID | Options are increasing the concentration of $CH_4$ in-barn air by extracting it locally and at peak times or by recirculating the air. |
| | ID | The potential also depends on the effectiveness of the filtration technology. |
| Applicability | | |
| Innovation status (TRL) | PE | Air scrubbers to reduce ammonia emissions are well known and widely applied in practice (TRL9). |
| | NE | Ventilation techniques to increase methane concentration in air flows from dairy barns requires further development; an international approach is desired. |
| | NE | Filtration and oxidation techniques for $CH_4$ require further development; indication biobed of ~100 $m^3$/cow needed; effect of chemical techniques uncertain. |
| Securing ammonia | PE | Securing ammonia via existing air scrubber technology seems feasible. |
| Securing methane | ID | Securing methane filtration by chemical filtration techniques or oxidation requires further development. |
| Economic aspects | | |
| Investments | CNE | Adapting or applying new ventilation systems and investing in filtering techniques require additional costs and increase energy use. |
| Economics | PE | Economy can become favorable if captured ammonia and methane can be upgraded into green fertilizer and energy, respectively. |
| | PE | Economics may become more favorable if the manure products from the system qualify as Renure (N concentrate) and methane reductions are valued with payments (carbon-credits). |
| Societal aspects | | |
| Animal welfare and health | ID | Uncertainty as to what extent new ventilation techniques to increase $CH_4$ concentrations affect barn climate and gas concentrations ($CO_2$ and $O_2$). |
| Animal habitat | PE | Unlike feeding and breeding strategies, the intention is not to affect the animal, but rather to improve the cow habitat; requires good ventilation design. |
| | NE | If only exhaust air is filtered, the $CO_2$, $NH_3$, and $CH_4$ concentrations in the barn air can still be high. |
| Landscape and openness? | NE | A more closed barn reduces visibility of animals depending on design. Degree of openness, climate, and visual perception are aspects of further research. |
| Risks for humans | PE | Closed nonventilated manure storage areas can create high concentrations of noxious gases in the head space and barn; active pit ventilation can prevent this. |

[1]CNE = clear negative effect; CPE = clear positive effect; ID = in development; NE = negative effect; PE = positive effect; TRL = technology readiness level.

ing environmental demands toward climate-neutral dairy production. Moreover, more efficient adsorbents and bio and soil filers should be further developed to optimize the process of adsorption and oxidation at low concentrate levels for both ammonia and methane. Finally, the economic valorization of the filtered and stripped nitrogen and carbon products and credits are essential for the success of the manure management and air treatment systems described in this review.

## NOTES

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**Nonstandard abbreviations used:** CNE = clear negative effect; CPE = clear positive effect; EBRT = empty bed reaction/residence time; HPU = heat producing unit; gdw = gram dry weight; ID = in development; LU = livestock unit; LW = live weight; MOF = metal organic framework; NE = negative effect; PE = positive effect; TRL = technology readiness level.

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