Chapter IV: Housed livestock, manure storage and manure processing

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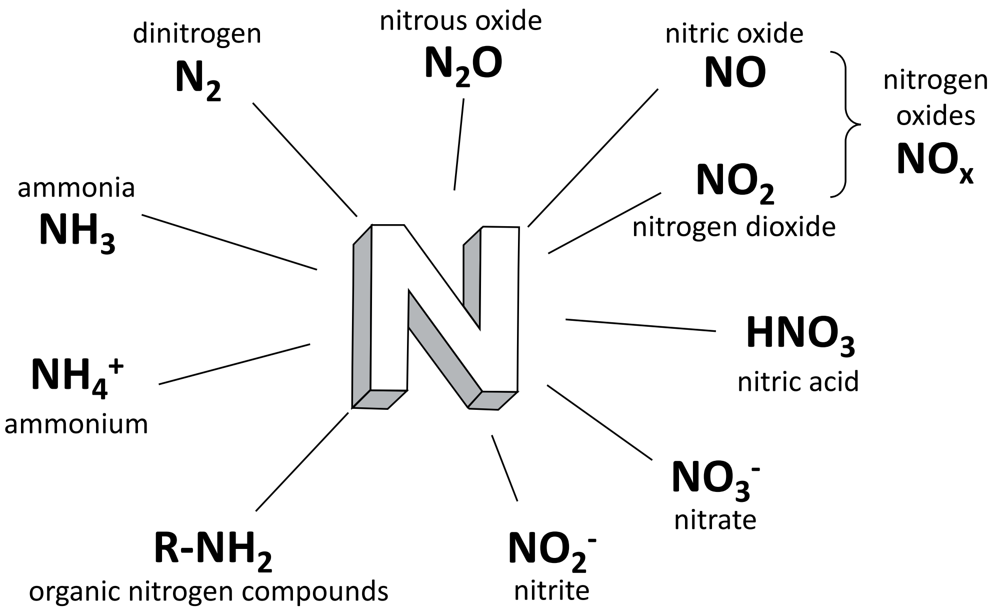
A. Introduction and background

145. Nitrogen (N) can take various forms (see figure IV.1), including atmospheric dinitrogen (N_2) and a wide range of reactive nitrogen (N_r) compounds, including all forms of nitrogen that are biologically, photochemically and radiatively active. Compounds of nitrogen that are reactive include ammonia (NH_3) and ammonium (NH_4^+), nitrous oxide (N_2O), nitrogen oxides (NO_x)[14], nitrite (NO_2^-), nitrate (NO_3), nitric acid (HNO_3) and a wide range of organic nitrogen compounds (R-NH_2). Reactive forms of nitrogen are capable of cascading through the environment and causing an impact through smog, acid rain, biodiversity loss, etc.,[15] as well as affecting climate (Butterbach-Bahl and others, 2011b). The design of abatement/mitigation measures requires a sound knowledge of the processes that influence formation and emission of all N_r compounds and N_2 into the environment, where nitrogen is lost to a wide range of atmospheric and aquatic pathways.

Ammonia

146. The principles of ammonia formation and the influencing factors are well known. Degradation of N containing organic substance results in ammonium formation. There is an equilibrium between ammonium and ammonia. The degree to which ammonia forms the ammonium ion depends on the pH of the solution. If the pH is low, the equilibrium shifts to the right: more ammonia molecules are converted into ammonium ions. If the pH is high, the equilibrium shifts to the left: the hydroxide ion

Figure IV.1: Major forms of nitrogen occurring in the environment



Source: The figure was created for the present document.

Note: The sum of all forms except N_2 is often termed fixed or reactive nitrogen (N_r).

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[14] See footnote 2.

[15] See www.n-print.org/node/5.

abstracts a proton from the ammonium ion, generating ammonia. See the following equation:

$H_2O + NH_3 \rightleftharpoons OH^- + NH_4^+$

147. Ammonia emissions are governed by the difference between solution and atmosphere NH_3 partial pressure. High NH_3 concentrations in the solution and low NH_3 concentrations in the surrounding atmosphere increase NH_3 emissions. According to Henry's Law, ammonia emissions are also temperature dependent, with rising temperatures increasing emissions (see figure IV). Denmead and others (1982) give the following equation:

$NH_{3(solution)}$ = $(NH_{3(solution)} + NH_4^+{}_{(solution)})/(1 + 10^{0.09018+(2729.92/T)-pH})$

where

$NH_{3(solution)}$ = NH_3 concentration in the solution

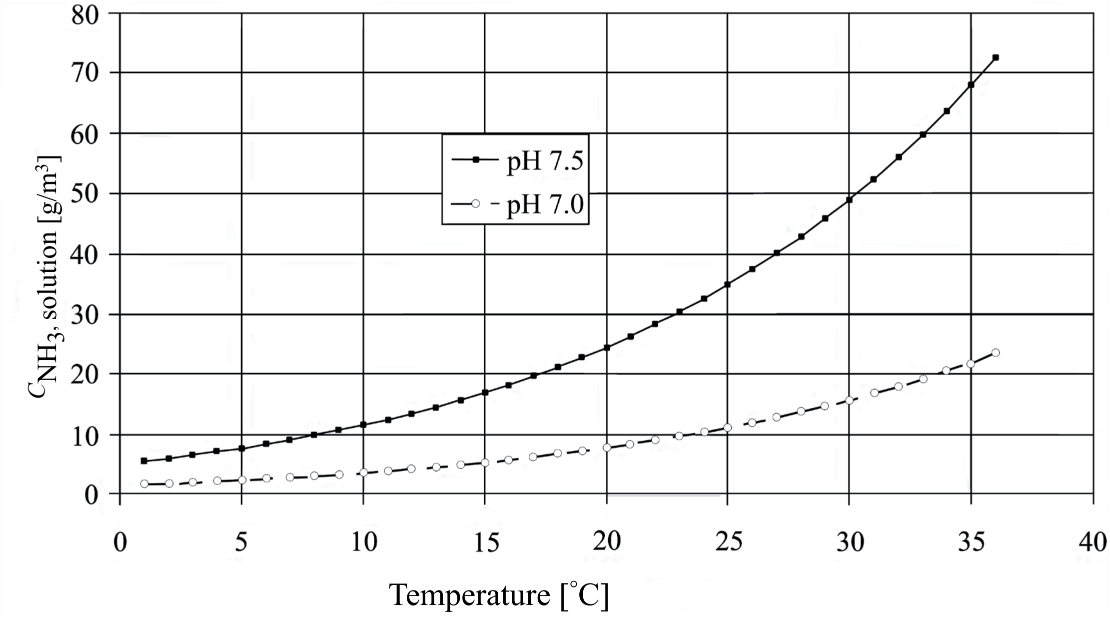
$NH_{3(solution)} + NH_4^+{}_{(solution)}$ = The sum NH_3 and NH_4^+ in the solution

T = Temperature in the solution [K]

pH = pH value in the solution

148. Ammonia emissions associated with animal housing, manure storage and processing result from the degradation of urea by the ubiquitous enzyme urease, which results in NH_4^+ formation. Urea is mainly excreted in the urine and, once it is hydrolysed, it is much more prone to ammonia losses than organic nitrogen excreted in faeces. In the case of poultry, nitrogen is excreted largely in the form of uric acid, which hydrolyses like urea to produce ammonia. Where it is possible to dry excreta (for example, in poultry litter), strategies may focus on reducing the hydrolysis rate of uric acid and urea. Once ammoniacal nitrogen (the sum of NH_3 + NH_4^+) is formed, strategies in animal housing and manure management focus on avoiding its volatilization to the atmosphere; for example, by reducing access to air, by reducing pH, or by keeping the manure surface cool (cf. figure IV.2).

Figure IV.2: NH_3 concentration in the solution as a function of temperature for pH 7.0 and pH 7.5 given a constant value of NH_4^+ in solution



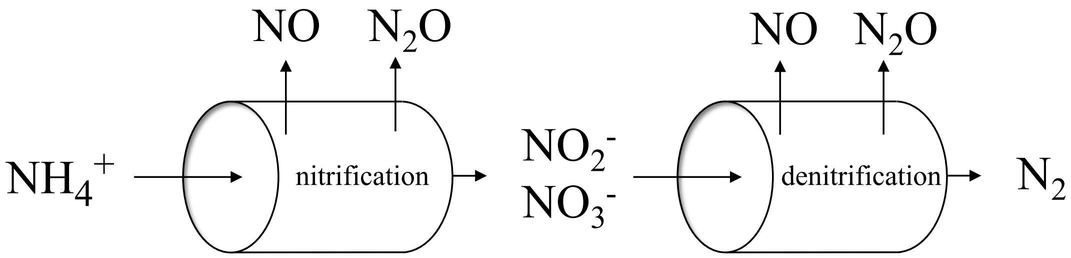
Source: After Denmead and others (1982).

Nitrous oxide and dinitrogen

149. The gases N_2O, NO_x and N_2 are formed during both the nitrification and the denitrification processes in the environment. The "leakage" model developed by Firestone and Davidson (1989) shows N_2O, and NO_x losses as leakage flows during nitrification and denitrification (figure IV.3).

150. Nitrification oxidizes ammonium via nitrite to nitrate. This process is strictly aerobic. Autotrophic nitrifying bacteria belong to the widespread group of Nitrosomonas, Nitrospira and Nitrobacter, which are capable of growing on carbon dioxide (CO_2), oxygen (O_2) and NH_4^+. Availability of NH_4^+ is mostly the limiting factor, as CO_2 and O_2 are available in abundance. Low pH, lack of phosphorus (P) and temperatures

Figure IV.3: Leaky Pipe model for N_2O and NO_x losses during nitrification and denitrification



Source: After Firestone and Davidson (1989).

below 5°C or above 40°C lead to a reduction in nitrification activities. A water content of around 60 per cent of the soil's water holding capacity is optimal for the nitrification process.

151. At low pH values, nitrification is carried out by bacteria and fungi. In contrast to the autotrophic nitrifiers, they need carbon sources for their growth. Their turnover rate is much lower compared to the autotrophic nitrifiers, but a substantial total turnover can still be achieved as a wider range of species have the ability for heterotrophic nitrification. N_2O production during nitrification is around 1 per cent, NO_x production ranges between 1 and 4 per cent of N inputs (Butterbach-Bahl and others, 2011a).

152. Denitrification reduces nitrate (NO_3^- to nitrite (NO_2), NO_x, N_2O or N_2 when oxygen availability is low. NO_3^-, NO_x and N_2O all serve as alternative electron acceptors when O_2 is lacking, and hence denitrification occurs only under strictly anaerobic conditions. Molecular N_2 is the ultimate product of the denitrification reaction chain and is the only biological process that can turn reactive nitrogen into non-reactive molecular N_2. Denitrifying bacteria are heterotrophic and facultative anaerobic. This means that they use O_2 as an electron acceptor and switch to alternative electron acceptors (NO_3^-, NO_x and N_2O) when oxygen availability is low. Denitrifying bacteria are widespread and show a high biodiversity.

153. Controlling factors for denitrification have been extensively investigated, mainly under laboratory conditions. Complex interactions exist between the various influencing factors, which make an actual prediction of N_2O emissions in time and space difficult under practical conditions.

154. Denitrification is mainly governed by oxygen availability. Denitrification starts when the O_2 concentration decreases to below 5 per cent (for example, Hutchinson and Davidson, 1993). This may be the case in poorly aerated soils (for example, high water content, in excess of 80 per cent water-filled pore space), but also in soils where a high biological turnover consumes the oxygen faster than the supply. Easily degradable carbon (C) sources and high nitrate concentrations also enhance the denitrification rate, while low temperature and low pH limit denitrification activity.

155. The relationship between N_2 and N_2O formation is mainly governed by the relationship between electron acceptor and reducing agent, and by the O_2 concentration in the substrate. N_2 is only formed under strictly anaerobic conditions and a wide C:NO_3^- ratio. High nitrate concentrations increase the rate of N_2O production. These differences have effects in practice concerning N losses from housed livestock and manure storage, according to the extent of oxygen and carbon availability in different systems.

Nitrate and other nitrogen leaching and run-off

156. Diffuse pollution of groundwater and surface waters with N (and phosphorus) is a problem in many regions of the world, especially in areas with high livestock production. Animal manures contain substantial quantities of organic matter, N and P that, if managed inappropriately, may be lost from animal housing, manure storage or after field application.

157. Nitrogen and organic matter losses to aquatic systems mainly occur by leaching through the soil profile and through surface run-off when the infiltration capacity of the soil is exceeded. Point-source emissions can also be acutely damaging to local environments, for example, in the case of slurry store leakages. In surface waters, the losses cause problems with eutrophication and algal bloom, and in areas that rely on the use of groundwater, high nitrate concentrations can be a problem for the potable water quality. For drinking water, the European Union limit has been set at a nitrate (NO_3^-) concentration of 50 mg l^{-1} (see European Union Drinking Water Directive)[16]. Once leached to surface waters, this N may also become a source of emissions of nitrous oxide, which is a potent greenhouse gas. In addition, significant loss of N resources is also an economic cost for the farmer, and N fertilizer production uses substantial amounts of fossil energy, causing global warming and other environmental emissions. Appropriate management and use of manures is therefore essential for minimizing nutrient

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[16] Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption, *Official Journal of the European Communities*, L 330 (1998), pp. 32–58.

leaching and the environmental impact of agriculture.

Consideration of nitrogen flows

158. Measures to reduce nitrogen losses from livestock feeding, housing and manure processing need to be seen in relation to other measures described in this guidance document. "Manure management is a continuum from generation by livestock to storage and treatment and finally to land spreading" (Chadwick and others, 2011). This means that there is the potential for nitrogen, carbon and phosphorus losses at each stage of this continuum. A "mass flow" approach has been used by Webb and Misselbrook (2004) to estimate NH_3 emissions from the manure management continuum. This approach allows effects of measures to reduce emissions and conserve manure N at one state to be considered as the manure passes to the next stage in the continuum. Similarly, other gaseous N losses, including N_2O, NO_x and N_2, may be assessed using a mass flow approach in a manner similar to that of Dämmgen and Hutchings (2008). The importance of such a whole system approach is that effects of abatement methods at one stage are considered in downstream stages (Sommer and others, 2009; 2013), including losses of nitrogen to water through leaching and run-off.

B. Approach used to describe abatement measures

159. The following sections present the main management practices and abatement/mitigation measures that will influence N utilization and losses from housed livestock, manure storage, manure treatment and manure processing. Some measures will mitigate all forms of N loss, whereas others may mitigate a specific N loss pathway with either little impact or a negative impact on other N loss pathways. Enhanced abatement may be possible through the combined implementation of certain packages of measures.

160. Following the description of each measure, a table (see tables IV.1–IV.23 and IV.25–IV.40) summarizes for each form of N loss the UNECE category for effectiveness/practicality of implementation (using the approach of ECE/EB.AIR/120; Bittman and others, 2014)[17], and the magnitude of effect of each measure. Expert judgements are provided for NH_3 volatilization, losses as N_2O, NO_x and N_2, run-off and leaching losses as NO_3^-, as well as overall total N losses.

161. Where a measure is considered to result in an increase in losses of a specific nitrogen form, it is, by definition, also assigned to category 3 for that nitrogen form. The magnitude of effect can be considered as an indication of "effectiveness" of the measure, as distinct from the extent to which the measure is "applicable" in different contexts. Where clarification is necessary, magnitude of effect of a measure is described in comparison to a specified reference system. For example, in the case of livestock housing, this includes *ad libitum* feeding, as well as storage of slurry without cover and without an impermeable base. In some parts of the UNECE region, use of certain reference systems may be prohibited, for example, because of the associated pollution levels.

C Livestock feeding

162. The crude protein content and composition of the animal diet is the main driver of urine excretion. Excess crude protein (CP) that is not needed by the animal is excreted and can easily be lost in the manure management chain. Adaptation of crude protein in the diet to the needs of the animal is therefore the first and most efficient measure to mitigate nitrogen emissions. This measure reduces the loss of all N forms (see figure IV.1) because it reduces the amount of excreted nitrogen. As there is much natural variation in nitrogen use efficiency (NUE) between individual animals, targeted breeding for better NUE can also be an option.

163. Reduction of CP in animal feed is one of the most cost-effective ways of reducing N emissions throughout the entire manure management chain. For each per cent (absolute value) decrease in protein content of animal feed, NH_3 emissions from animal housing, manure storage and the application of animal manure to land are decreased by 5–15 per cent, depending also on the pH of the urine and dung. Low-protein animal feeding also decreases N_2O emissions and increases the efficiency of N use in animal production. Potential trade-offs with CH_4 emissions from enteric fermentation are not yet fully researched and need to be assessed. However, efficient N use is crucial for environmentally friendly milk production. Moreover, there are no animal health or animal welfare implications as long as the requirements for all amino acids are met.

164. Low-protein animal feeding is most applicable to housed animals. It is less applicable for grassland-based systems with grazing animals because grass is eaten by the animals at an early physiological growth stage and thus is typically high in degradable protein. It should be noted that grassland with leguminous species (for example, clover, lucerne) also has a relatively high protein content, and so may be associated with excess dietary N for livestock. Strategies to lower the protein content in herbage include: balanced N fertilization; grazing/harvesting the grassland at a later physiological growth stage, etc.; and alteration of the ration of grassland-based systems, such as use of supplementary feeding with low-protein feeds.

1. Dairy and beef cattle

Dietary Measure 1: Adapt protein intake in diet (dairy and beef cattle)

165. Lowering crude protein (CP) of ruminant diets is an effective strategy for decreasing NH_3 and overall N loss. The following guidelines hold:

(a) The average CP content of diets for dairy cattle should not exceed 15–16 per cent in the dry matter (DM)

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[17] See chapter I, paras. 16–20, of the present document for a description of the UNECE categories and system for representing the magnitude of effect.

(Broderick, 2003; Swensson, 2003). For beef cattle older than six months this could be further reduced to 12 per cent;

(b) Phase feeding can be applied in such a way that the CP content of dairy diets is gradually decreased from 16 per cent of DM just before parturition and in early lactation to below 14 per cent in late lactation and the main part of the dry period;

(c) Phase feeding can also be applied in beef cattle in such a way that the CP content of the diets is gradually decreased from 16 to 12 per cent over time. More information and associated costs can be found in the TFRN costs assessment (Chapter 3.4 "Low nitrogen feeding strategies in dairy cattle" in Reis and others, 2015).

166. In general, increasing the energy/protein ratio in the diet by using "older" grass (higher sward surface height) or swathed forage cereal and/or supplementing grass by high energy feeds (for example, maize silage) is a well-proven strategy for reducing levels of crude protein. However, for grassland-based ruminant production systems, the feasibility of these strategies may be limited, as older grass may reduce feeding quality, especially when conditions for growing high-energy feeds are poor (for example, warm climates), and therefore such feeds have to be purchased. Hence, full use of the grass production would no longer be guaranteed. In the absence of other measures, such a strategy may also risk increasing methane emissions.

167. In many parts of the world, cattle production is grassland-based or partly grassland-based. In such systems, protein-rich grass and grass products form a significant proportion of the diet, and the target values for CP may be difficult to achieve, given the high CP content of grass from managed grasslands. The CP content of fresh grass in the grazing stage (2,000–2,500 kg DM/ha) is often in the range of 18–20 per cent (or even higher, especially when legumes are present), whereas the CP content of grass silage is often between 16 and 18 per cent and the CP content of hay is between 12 and 15 per cent (for example, Whitehead, 2000). In contrast, the CP content of maize silage is only in the range of 7–8 per cent. Hence, grass-based diets often contain a surplus of protein and the magnitude of the resulting high N excretion strongly depends on the proportions of grass, grass silage and hay in the ration and the protein content of these feeds. The protein surplus and the resulting N excretion and N losses will be highest for grass-only summer rations (or grass-legume rations) with grazing of young, intensively fertilized grass or grass-legume mixtures.

168. Urine excreted by grazing animals typically infiltrates into the soil. This means that NH_3 emissions per animal are reduced by extending the periods during which animal graze compared with the time spent with animals housed, where the excreta is collected, stored and applied to land. It should be noted that grazing of animals may increase other forms of N emissions (for example, nitrate-N leaching and N_2O emissions). However, given the clear and well-quantified effect on NH_3 emissions, increasing the period that animals are grazing all day can be considered as a strategy to reduce emissions (see chapter V, Field Measure 18).

Table IV.1: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Dietary Measure 1

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	1	1	3[a]	1	2	1-2
Magnitude of Effect	↓↓	~↓↓	?[a]	↓↓	↓↓	↓↓[b]

[a] The measure would be expected to reduce NO_x emissions, though experimental data to demonstrate this are needed.

[b] As this measure reduces total N inputs, it can help to increase system efficiency and circularity, reducing wider N_r and N_2 losses.

Dietary Measure 2: Increase productivity (dairy and beef cattle)

169. Overall, increasing the productivity of dairy cattle in terms of milk or meat can decrease emissions per unit of animal production. Optimized productivity will also result in a reduction of enteric methane emissions. However, optimum productivity levels vary according to breed and region and must also take into consideration the fact that ruminants can only cope with a certain amount of concentrates and require sufficient roughage in their diet to stay healthy.

Table IV.2: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Dietary Measure 2

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	2	2	3[a]	2	2	2
Magnitude of Effect	↓	~-↓	?[a]	-	↓	↓[b]

[a] The measure would be expected to reduce NO_x emissions, though experimental data to demonstrate this are needed.

[b] As this measure reduces total N inputs, it can help to increase system efficiency and circularity, reducing wider N_r and N_2 losses.

Dietary Measure 3: Increase longevity (dairy cattle)

170. Productivity can be increased though increasing milk production per year and through increasing the amount of milk production cycles per animal. Optimized diet and housing conditions enable a higher longevity of dairy cattle. Improving the longevity of dairy cattle also decreases the number of young cattle necessary for replacement. Reducing endemic disease and genetic gain through targeted breeding can also offer value.

Table IV.3: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Dietary Measure 3

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	2	2	3[a]	2	2	2
Magnitude of Effect	↓	~-↓	?[a]	-	↓	↓[b]

[a] The measure would be expected to reduce NO_x emissions, though experimental data to demonstrate this are needed.

[b] As this measure reduces total N inputs, it can help to increase system efficiency and circularity, reducing wider N_r and N_2 losses.

2. Pigs

Dietary Measure 4: Adapt protein intake in diet (pigs)

171. Feeding measures in pig production include: phase feeding; formulating diets based on digestible/available nutrients; and using low-protein amino acid-supplemented diets and feed additives/supplements. Further techniques are currently being investigated (for example, different feeds for males (boars and castrated males) and females) and might also be available in the future.

172. The crude protein (CP) content of pig ration can be reduced if the amino acid supply is optimized through the addition of synthetic amino acids (for example, lysine, methionine, threonine, tryptophan, typically limiting amino acids, which are too low in normal grain rations) or special feed components, using the best available information on "ideal protein" combined with dietary supplementation. Lassaletta and others (2019) performed a global analysis for pig systems that included the simulation of changes in CP. More information and associated costs can be found in the TFRN Costs Assessment (chapter 3.2 "Low nitrogen feeding strategies in pigs", in Reis and others, 2015).

173. A CP reduction of 2–3 per cent in the feed can be achieved, depending on the pig production category and the current starting point (Canh and others, 1998). It has been shown that a decrease of 1 per cent CP in the diet of finishing pigs results in a 10 per cent lower total ammoniacal nitrogen (TAN) content of the pig slurry and 10 per cent lower NH_3 emissions (Canh and others, 1998). The inclusion of processed household and industry residues or wastes in the feed rations with a controlled energy/protein ratio is a complementary measure that reduces dependence on imported feedstuff. This measure also represents a reduction of upstream N_r emissions associated with feed production and downstream emissions associated with waste management (Lassaletta and others, 2019; zu Ermgassen and others, 2016).

Table IV.4: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Dietary Measure 4

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	1	1	3[a]	1	2	1
Magnitude of Effect	↓↓	↓↓	?[a]	↓↓	↓↓	↓↓[b]

[a] The measure would be expected to reduce NO_x emissions, though experimental data to demonstrate this are needed.

[b] As this measure reduces total N inputs, it can help to increase system efficiency and circularity, reducing wider N_r and N_2 losses.

3. Poultry

Dietary Measure 5: Adapt protein intake in diet (poultry)

174. For poultry, the potential for reducing N excretion through feeding measures is more limited than for pigs because the conversion efficiency currently achieved on average is already high and the variability within a flock of birds is greater. A CP reduction of 1–2 per cent may be achieved depending on the species and the current starting point but is already a well-proven measure for growers and finishers. Further applied nutrition research is currently being carried out in European Union member States and North America and this may support further possible reductions in the future.

Table IV.5: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Dietary Measure 5

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	1	1	3[a]	1	2	1
Magnitude of Effect	↓↓	↓↓	?[a]	↓↓	↓↓	↓↓[b]

[a] The measure would be expected to reduce NO_x emissions, though experimental data to demonstrate this are needed.

[b] As this measure reduces total N inputs, it can help to increase system efficiency and circularity, reducing wider N_r and N_2 losses.

D. Livestock housing

1. Cattle housing

175. When using measures to abate emissions from livestock houses of all types of animals, it is important to minimize loss of the conserved N during downstream handling of the manure, in storage and in spreading to maximize the benefit from the cost of abatement.

176. Housing systems for cattle vary across the UNECE region. While loose housing is most common, dairy cattle are still bred in tied stalls in some countries. In loose housing systems, all or part of the excreta is collected in the form of slurry. In systems where solid manure is produced (such as straw-based systems), it may be removed from the house daily or it may remain there for up to the whole season, such as in deep litter stables. The most commonly researched system is the "cubicle house" for dairy cows, where substantial NH_3 emissions arise from fouled slatted and/or solid floors and from manure in pits and channels beneath the slats/floor. There has been much less research to measure NO_x, N_2O and N_2 emissions from cattle housing, so recommendations in some cases have to be based on general principles and are therefore subject to larger uncertainty than for NH_3 emissions from such systems.

177. Housed cattle systems are generally set on stone or concrete bases, so direct nitrate leaching is not expected, unless there are cracked bases associated with poor maintenance. Run-off of N_r compounds from cattle housing systems may occur if ponded excreta is not correctly drained into storage tanks (for example, associated with flooding events).

178. While "hard standings" (typically concrete areas adjacent to dairies) provide a significant source of ammonia emissions outside of animal houses, in some parts of the UNECE region, cattle are kept in confined areas outside (for example, feed lots), where N_r leaching, run-off and gaseous N losses may be substantial.

179. Animal welfare considerations tend to lead to an increase of soiled walking area per animal, increased ventilation and an overall increase in emissions. Changes in building design to comply with new animal welfare regulations in some countries (for example, changing from tied stall to cubicle housing) will therefore increase NH_3 emissions unless abatement measures are introduced at the same time to combat this increase.

180. Solid versus slurry manure systems: straw-based systems producing solid manure for cattle are unlikely to emit less NH_3 in the animal houses than slurry-based systems. Furthermore, N_2O, NO_x and N_2 losses due to (de)nitrification tend to be larger in litter-based systems than slurry-based systems.

181. While straw-based solid manure can emit less NH_3 than slurry after surface spreading on fields (see, for example, Powell and others, 2008), slurry provides a greater opportunity for reduced emissions application methods.

182. Abatement options for cattle housing can be grouped into the following types:

(a) Floor-based systems and related management techniques (including scrapers and cleaning robots);
(b) Litter-based systems (use of alternative organic material);
(c) Slurry management techniques at pit level;
(d) Indoor climate control techniques;
(e) End-of-pipe techniques (hybrid ventilation + air cleaning techniques) and GHGs abatement/mitigation techniques.

183. Several pathways can be identified to further optimize existing and develop new abatement techniques. In this respect, emission reduction techniques at animal housing level should aim to affect one or more of the following important key factors and/or driving forces of the nitrogen emission process:

(a) Draining capacity of the floor for direct transportation of urine to the manure storage;
(b) Residence time of open urine/manure sources;
(c) Emitting surface area of open urine/manure sources;
(d) Urease activity in urine puddles;
(e) Temperature and urine/manure pH (see Housing Measures 6 and 8, respectively);
(f) Indoor air temperature;
(g) Air velocities at emitting surfaces (urine puddles and manure surface in the pit);
(h) Air exchange between pit headspace and indoor air;
(i) Exhaust of indoor air.

Housing Measure 1: Immediate segregation of urine and faeces (cattle)

184. A physical segregation (for example, keeping separately) of faeces, which contain urease, and urine in the housing system reduces hydrolysis of urea, resulting in reduced emissions from both housing and manure spreading (Burton, 2007; Fangueiro and others, 2008a, 2008b; Møller and others, 2007). Both acidification and alkalization of the in-house segregated urine reliably inhibits urea hydrolysis. The duration of the inactivation period can be adjusted by the dosage of acid or alkali addition (VDLUFA 2019).

185. Verification of any NH_3 emission reductions from using solid-manure versus slurry-based systems and from solid-liquid separation should consider all the stages of emission (housing, storage and land application). Additional advantages of solid-liquid separation can also be expected during land-application, where urine (containing most of the available ammoniacal N) infiltrates more easily due to its lower dry-matter content than slurry, reducing NH_3 emissions. Although solid manure does not infiltrate, it mainly consists of organic N forms, which are much less liable to NH_3 emissions. Less is known about the consequences of solid-liquid separation on the emissions of N_2O, NO_x, N_2 and nitrate leaching, although substantial adverse effects are not expected.

Table IV.6: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 1

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	1[a]	3	3	3	3	2
Magnitude of Effect	↓↓	?	?	?	?	↓

[a] Immediate segregation of urine and faeces will reduce NH_3 emissions substantially, in the same way as increased grazing period (category 1). However, subsequent separation of previously mixed slurry is considered less effective (category 2) (cf. Bittman and others, 2014, para. 159).

Housing Measure 2: Regular cleaning of floors in cattle houses by toothed scrapers (cattle)

186. The “grooved floor” system for dairy and beef cattle housing, employing “toothed” scrapers running over a grooved floor, is a reliable technique to abate NH_3 emissions. Grooves should be equipped with perforations to allow drainage of urine. This results in a cleaner, low-emission floor surface with good traction for cattle to prevent slipping. Ammonia emission reduction ranges from 25 to 46 per cent relative to the reference system (Smits, 1998; Swierstra and others, 2001). In the absence of measurement data, it is expected that use of the grooved floor system would have little impact on other N_r and N_2 losses since it is mainly directed to reducing immediate exposure to air of ammonium rich excreta.

Table IV.7: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 2

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	1	3[a]	3[a]	3[a]	3[a]	1
Magnitude of Effect	↓↓	-[a]	-[a]	-[a]	-[a]	↓

[a] Although this measure does not directly reduce other N_r and N_2 losses, where the NH_3^- saving contributes to replace inorganic fertilizer inputs from newly fixed N, it can help to increase system efficiency and circularity, reducing wider N_r and N_2 losses.

Housing Measure 3: Regular cleaning of floors in cattle houses

187. Thorough cleaning of walking areas in dairy cattle houses by mechanical scrapers or robots has the potential to substantially reduce NH_3 emissions. The automatic cleaning should be performed at regular intervals (for example, on an hourly basis) to achieve the full benefits of the measure.

Table IV.8: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 3

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE Category	1	3	3	3	3	1
Magnitude of Effect	↓	-	-	-	-	↓

Housing Measure 4: Frequent slurry removal (cattle)

188. Regular removal of liquid manure from under the slats in the house to an outside store can substantially reduce NH_3 emissions by reducing the emitting surface and the slurry storage temperature. A reduced storage temperature will also result in a reduction of methane emissions.

Table IV.9: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 4

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE Category	1-2	3	3	3	3	1-2
Magnitude of Effect	↓	-	-	-	-	↓

Housing Measure 5: Increase bedding material (cattle with solid manure)

189. Bedding material in animal housing can affect NH_3, N_2O, NO_x and N_2 emissions. The physical characteristics (urine absorbance capacity, bulk density) of bedding materials are of more importance than their chemical characteristics (pH, cation exchange capacity, carbon to nitrogen ratio) in determining NH_3 emissions from dairy barn floors (Misselbrook and Powell, 2005; Powell and others, 2008; Gilhespy and others, 2009). However, further assessment is needed on the effect of bedding on emissions for specific systems while taking into account the whole manure management path. The approach can have a positive interaction with animal welfare measures.

Table IV.10: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 5

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE Category	1	2	3	3	3	1
Magnitude of Effect	~/↓	~/↓	?	?	?	~/↓

Housing Measure 6: Barn climatization to reduce indoor temperature and air flow (cattle)

190. In houses with traditional slats (either non-sloping, 1 per cent sloping, or grooved), optimal barn climatization with roof insulation and/or automatically controlled natural ventilation can achieve a moderate emission reduction (20 per cent) of NH_3 due to the decreased temperature (especially in summer) and reduced air velocities (Bram and

Image 6: Regular scaping of animal house floors reduces ammonia emissions (photograph: © Agriculture and Horticulture Development Board (AHDB)).

others, 1997a, 1997b; Smits, 1998; Monteny, 2000). To the extent that such systems cool stored manure, emissions of methane will also be reduced.

Table IV.11: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 6

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category [a]	1	2-3	2-3	2-3	2-3	1
Magnitude of Effect	↓↓	~ -	-	-	-	↓

[a] Where two numbers are shown in this table separated by a hyphen, the first number is for the effect of reducing indoor temperature and the second number is for the effect of reducing airflow over manure-covered surfaces

Housing Measure 7: Use of acid air-scrubbers (cattle)

191. Chemical or acid air-scrubbers are effective in decreasing NH_3 emissions from force-ventilated pig housing. However, they cannot yet be generally implemented in cattle housing because these are mostly naturally ventilated across the ECE region. Also, there are few data on scrubbers for cattle (Ellen and others, 2008). In any situations where cattle are housed with forced ventilation, this measure can be considered as category 1. Recent developments consider combining targeted ventilation of naturally ventilated barns with air-scrubbers. More research and development are needed here.

Image 7: In animal housing with solid manure, adding sufficient bedding (**A**) can help absorb urine and decrease nitrogen emissions (Housing Measure 5), while benefiting animal welfare. Bedding left too long becomes wet (**B**) and is also associated with higher emissions (photographs: © Barbara Amon).

Table IV.12: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 7

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	1-2	3[a]	3[a]	3[a]	3[a]	1-2
Magnitude of Effect	↓↓	?[a]	?[a]	?[a]	?[a]	↓[a]

[a] Although this measure does not directly reduce other N_r and N_2 losses, where recovered N_r contributes to replace inorganic fertilizer inputs from newly fixed N, it can contribute to increased system efficiency and circularity, reducing wider N_r and N_2 losses.

192. Different improved floor types based on slats or solid, profiled concrete elements have been tested. These designs combine emission reduction from the floor (increased run-off of urine) and from the pit (reduction of air exchange by rubber flaps in the floor slots). The emission-abatement efficiency depends on the specific technical characteristics of the system.

193. Decreasing the amount of animal excrement in animal housing systems through increased grazing is an effective measure to decrease NH_3 emissions, as discussed further in chapter VI. Total annual emissions (including housing, storage and spreading) from dairy systems may decrease by up to 50 per cent with nearly all-day grazing, as compared with animals that are fully confined. While increased grazing is a reliable NH_3 emission reduction measure for dairy cows, the amount of emission reduction depends on the daily grazing time and the cleanliness of the house and holding area. In some cases, grazing may also contribute to increased run-off and leaching of NO_3^- and other N_r compounds, as well as N_2O and NO_x emissions. Grazing can also be associated with increased pathogen mobilization.

2. Pig housing

194. Designs to reduce NH_3 emissions from pig housing systems have been described in detail in the IPPC document on Best Available Techniques (BATs) (Santonja and others 2017). These apply the following main elements:

(a) Reducing manure surfaces such as soiled floors using channels for slurry holding surfaces and sloped walls. Partly slatted floors (~50 per cent area) generally emit less NH_3, particularly if the slats are metal- or plastic-coated rather than concrete, allowing the manure to fall rapidly and completely into the pit below. Emissions from the non-slatted areas are reduced by inclined, smooth surfaces, by locating the feeding and watering facilities to minimize fouling of these areas, and by good climate control in the building;

(b) Removing the slurry from the pit frequently to an external slurry store with vacuum or gravity removal systems or by flushing systems at least twice a week;

(c) Additional treatment, such as liquid/solid separation; provided that the storage of the separated fractions maintains low emissions;

(d) Circulating groundwater or other cooling agents in floating heat exchangers or walls of slurry pits to cool the surface of the manure in the underfloor pit to at least below12°C. Constraints include costs and need to locate a source of groundwater away from the source of drinking water;

(e) Changing the chemical/physical properties of the manure, such as decreasing pH;

(f) Using surfaces that are smooth and easy to clean (see above);

(g) Treatment of exhaust air by acid scrubbers or biotrickling filters;

(h) Lowering the indoor temperature and ventilation rate, taking into account animal welfare and production considerations;

(i) Reducing airflow over the manure surface.

195. For a given floor slat width, manure drains from concrete slats less efficiently than from steel- and plastic-covered slats and this is associated with greater emissions of NH_3. Note that steel slats are not allowed in some countries for animal welfare reasons. Cross-media effects have been taken into account in defining BATs for the various housing designs. For example, frequent flushing of slurry (normally once in the morning and once in the evening) causes nuisance odour events. Flushing slurry also consumes energy unless manually operated passive systems are used.

196. Use of straw litter in pig housing is expected to increase due to concern for the welfare of the pigs. In conjunction with (automatically controlled) naturally ventilated housing systems, straw allows the animals to self-regulate their temperature with less ventilation and heating, reducing energy consumption. In systems with litter, the pen is sometimes divided into solid areas with litter and slatted dunging areas. However, pigs do not always use these areas in the desired way, using the littered area to dung and the slatted area to cool off in warm weather. Generally, pens should be designed to accommodate desired excreting behaviour of pigs to minimize fouling of solid floors. However, this is more difficult in regions with a warm climate. Note that integrated evaluation of straw use should consider:

(a) The added cost of the straw and mucking out the pens;

(b) The possible increased emissions from storage and application of manure with straw; and

(c) The benefit of adding organic matter from straw to the soil.

197. The reference system, used commonly in Europe, is a fully slatted floor with a deep manure pit underneath and mechanical ventilation; emission ranges from 2.4 to 3.2 kg NH_3 per finisher pig place per year. Since growers/finishers are always housed in a group, most systems used for group housing of sows are applicable to growers. Emissions from different abatement/mitigation approaches are compared with this reference system in terms of the emission reduction amount (Bittman and others, 2014). Most data available are on NH_3, with little data concerning effects on N_2O, NO_x, N_2 and nitrate leaching. The underlying principles for these losses are largely similar to those for cattle housing systems, recognizing the different housing needs of pigs and the particular characteristics of pig excreta.

Housing Measure 8: Slurry acidification (pig and cattle housing)

198. Reductions in NH_3 emissions can be achieved by acidifying slurry to shift the chemical balance from molecular NH_3 to ionic NH_4^+. The manure (especially the liquid fraction) is collected into a tank with acidified liquid (usually using sulphuric acid, but organic acids can be used as well, though at higher cost) maintaining a pH of less than 6 (Bittman and others, 2014; Fangueiro and others, 2015). In pig housing systems, emission reductions of 60 per cent or more have been observed (Kai and others, 2008). The measure is not anticipated to affect other N_r or N_2 losses. Acidification of slurry is anticipated to be effective for both cattle and pig slurry, though measurements have so far concentrated on investigating pig slurry. One study (Petersen and others, 2012) showed that acidification of cattle slurry to pH 5.5 reduced the NH_3 emissions by more than 90 per cent and at the same time reduced emissions of the greenhouse gas (GHG) CH_4 by 67 to 87 per cent. As nitrification and denitrification are reduced, the method can also be expected to reduce emissions of NO_x, N_2O and N_2. Attention should be given to monitoring soil pH and metal content if acidified slurry is to be used in agriculture. In-house acidification will reduce NH_3 emissions throughout the manure management chain. Furthermore, slurry acidified with sulphuric acid is not suitable as the sole feedstock for biogas production (but can be used as a smaller proportion).

Table IV.13: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 8

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	1	2	2	3[a]	2	1[a]
Magnitude of Effect	↓↓	↓	~/↓?	~[a]	↓	↓↓[a]

[a] Although this measure is not known to reduce NO_3^- directly, where NH_3-saving contributes to replace inorganic fertilizer inputs from newly fixed N (for example, when fertilizer regulations require the improved fertilizer value to be taken into account), it can contribute to increased system efficiency and circularity, reducing wider N_r and N_2 losses.

Housing Measure 9: Reduce emitting surface (pigs)

199. Ammonia emissions can be reduced by 25 per cent by decreasing the surface area of the emitting floor through

frequent and complete vacuum-assisted drainage of slurry from the floor of the pit. Where this is possible, this technique has no cost. Partly slatted floors covering 50 per cent of floor area generally emit 15–20 per cent less NH_3, particularly if the slats are metal or plastic-coated which is less sticky for manure than concrete. Decreasing the risk of emissions from the solid part of the floor can be achieved by:

(a) Using an inclined (or convex), smoothly finished surface;

(b) Appropriate siting of the feeding and watering facilities to minimize fouling of the solid areas; and

(c) Good climate control (Aarnink and others, 1996; Guigand and Courboulay, 2007; Ye and others, 2008a, 2008b).

200. Further reduction of the emitting area can be achieved by making both the partly slatted area and the pit underneath smaller. With the smaller slatted area, the risk of greater fouling of the solid area can be mitigated by installing a small second slatted area with a water canal underneath at the other side of the pen where the pigs tend to eat and drink. The canal is filled with about 2 cm of water to dilute any manure that might eventually drop into it. This slatted area will have low emissions because any manure dropped here will be diluted. This combined manure-canal and water-canal system can reduce NH_3 emissions by 40–50 per cent, depending on the size of the water canal. This approach is not expected to have a significant effect on emissions of N_2 or other N_r compounds.

201. Reducing the emitting surface area by having one or two slanted pit walls, in combination with partly slatted floors and frequent manure removal, can reduce emissions by up to 65 per cent. Reducing the emitting surface area with shallow V-shaped gutters (maximum 60 cm wide, 20 cm deep) can reduce emission in pig houses by 40 to 65 per cent, depending on the pig category and the presence of partly slatted floors. The gutters should be flushed twice a day with the liquid (thin) fraction of the slurry rather than water; flushing with water dilutes the manure and increases the cost of transporting and applying it in the field.

Table IV.14: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 9

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE Category	1	3^a	3^a	3^a	3^a	1^a
Magnitude of Effect	↓↓	$-^a$	$?^a$	$?^a$	$?^a$	$↓↓^a$

[a] Although this measure does not directly reduce other N_r and N_2 losses, where the NH_3-saving contributes to replace inorganic fertilizer inputs from newly fixed N, it can help to increase system efficiency and circularity, reducing wider N_r and N_2 losses.

Housing Measure 10: Regular cleaning of floors (pigs)

202. Cleaning of floors in pig houses by mechanical scrapers or robots has the potential to substantially reduce NH_3 emissions. The automatic cleaning should be performed at regular intervals to achieve the full benefits of the measure (Amon and others, 2007). It is worth mentioning that, in warm countries (for example, Mediterranean region), for sanitary reasons, floor cleaning is done more frequently with consequences for the slurry composition, which may reach up to 98 per cent water.

Table IV.15: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 10

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE Category	1	3	3	3	3	1
Magnitude of Effect	↓	-	-	-	-	↓

Housing Measure 11: Frequent slurry removal (pigs)

203. Regular removal of slurry from under the slats in the house to an outside store can substantially reduce NH_3 emissions by reducing the emitting surface and the slurry storage temperature. A reduced storage temperature will also result in a reduction of methane (Amon and others, 2007).

Table IV.16: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 11

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE Category	1	3	3	3	3	1-2
Magnitude of Effect	↓	-	-	-	-	↓

Housing Measure 12: Increase bedding material (pigs with solid manure)

204. Bedding material in animal housing can affect NH_3, N_2O, NO_x and N_2 emissions. The physical characteristics (urine absorbance capacity, bulk density) of bedding materials are of more importance than their chemical characteristics (pH, cation exchange capacity, carbon to nitrogen ratio) in determining NH_3 emissions from dairy barn floors (Misselbrook and Powell, 2005; Powell and others, 2008; Gilhespy and others, 2009). However, further assessment is needed on the effect of bedding on emissions for specific systems while taking into account the whole manure management path. The approach can have a positive interaction with animal welfare measures. However, approaches benefiting animal welfare can also be operated as slurry-based systems, with only little straw supply.

Table IV.17: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 12

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE Category	1	2	3	3	3	1
Magnitude of Effect	~/↓	~/↓	-	-	-	~/↓

Housing Measure 13: Barn climatization to reduce indoor temperature and air flow (pigs)

205. Surface cooling of manure with fans using a closed heat exchange system is a technique with a reduction efficiency of 45–75 per cent depending on animal category and surface of cooling fins. This technique is most economical if the collected heat can be exchanged to warm other facilities such as weaner houses (Huynh and others, 2004). In slurry systems this technique can often be retrofitted into existing buildings. However, this system is not applicable when straw bedding is used or when the feed contains a lot of roughage. This is because a layer of floating residue may develop on top of the slurry.

Table IV.18: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 13

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category [a]	1	2-3	2-3	2-3	2-3	1
Magnitude of Effect	↓	-	-	-	-	↓

[a] Where two numbers are shown in this table separated by a hyphen, the first number is for the effect of reducing indoor temperature and the second number is for the effect of reducing air flow over manure-covered surfaces.

Housing Measure 14: Use of acid air-scrubbers (pigs)

206. Treatment of exhaust air by acid scrubbers (mainly using sulphuric acid) or biotrickling filters has proven to be practical and effective for large-scale operations in Denmark, France, Germany and the Netherlands (for example, see Melse and Ogink, 2005; Guingand, 2009). This is most economical when installed in new houses, because retrofitting in existing housing requires costly modification of ventilation systems.

Image 8: Fattening pigs on a low-emission straw system with solid manure (Housing Measure 12) (photograph: © Barbara Amon).

Acid scrubbers have demonstrated NH_3 removal efficiencies of more than 90 per cent, depending on their pH-set values. Scrubbers and biotrickling filters also reduce odour and PM by 75 per cent and 70 per cent, respectively (Guingand, 2009). Further information is needed on the suitability of these systems in Southern and Central Europe. Operational costs of both acid scrubbers and trickling filters are especially dependent on the extra energy use for water recirculation and to overcome increased back pressure on the fans. Optimization methods are available to minimize costs (Melse and others, 2012) and costs will be lower for large operations. The approach may also contribute to reducing N_2O and NO_x emissions, but more research is needed here.

Table IV.19: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 14

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category [a]	1	2	2	3[a]	3[a]	1
Magnitude of Effect	↓↓	↓	↓	_[a]	_[a]	↓↓[a]

[a] Although this measure does not directly reduce other NO_3^- and N_2 losses, where the recovered N_r contributes to replace inorganic fertilizer inputs from newly fixed N, it can contribute to increased system efficiency and circularity, reducing wider N_r and N_2 losses.

Housing Measure 15: Use of biological air-scrubbers (pigs)

207. Biological air-scrubbers operate with bacteria that remove ammonia and odours from the exhaust air. Ammonia captured in biological air-scrubbers typically undergoes nitrification and denitrification associated with increased emissions of N_2O, NO_x and N_2. Recovery of the collected N_r in bioscrubbers may help offset this increase by reducing the need for fresh N fixation and production of chemical fertilizers.

Table IV.20: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 15

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category [a]	1	2	2	3	3	1
Magnitude of Effect	↓↓	3[a]	↑[a]	-	↑[a]	↓

[a] Ammonia captured in biological air-scrubbers typically undergoes nitrification and denitrification associated with increased emissions of N_2O, NO_x and N_2. Recovery of the collected N_r in bioscrubbers may help offset this increase by reducing the need for fresh N fixation and production of chemical fertilizers.

3. Poultry housing

208. Designs to reduce NH_3 emissions from poultry housing systems have been described in detail in the document on BAT under the European Union Industrial Emissions

Directive[18] (Santonja and others, 2017), and apply the following principles:

(a) Reducing the open surface area of emitting manure;

(b) Removing the manure frequently from the poultry house to an external slurry store (for example, with belt removal systems);

(c) Quickly drying the manure to reduce hydrolysis of uric acid to ammonia;

(d) Using smooth, easy-to-clean surfaces;

(e) Treatment of exhaust air by acid scrubbers or biotrickling filters (for example, biological air-scrubbers);

(f) Lowering the indoor temperature and ventilation as animal welfare and/or production allow, reducing microbial processes that mobilize N_r losses.

209. Many of the measures listed for cattle and pigs are also applicable to poultry systems, especially Housing Measures 2 and 9 (Reduce emitting surface), 6 and 13 (Barn climatization to reduce indoor temperature and air flow) and 7 and 14 (acid air-scrubbers). This section therefore focuses on additional considerations for poultry housing. Further information can be found in the IPPC Best Available Techniques Reference document (Santonja and others, 2017) and the UNECE Ammonia Guidance Document (Bittman and others, 2014).

210. Where poultry houses are disconnected from the ground (for example, concrete base), emission-reduction measures for NH_3 are not directly expected to affect nitrate and other N_r leaching and run-off. For smaller farms, which are not required to comply with national legislation (for example, BAT) for layers, and for free-range poultry, pathways to the soil can also be anticipated. In such cases, NH_3 emission reduction including rapid drying and dry storage of poultry litter may also have benefits to reduce N_r leaching. In addition, expert observations have shown that downward-pointing air exhausts onto porous ground surfaces surrounding poultry houses can lead to localized increases of N_r leaching and run-off into groundwaters. Reduction of NH_3 emissions (and N_r-containing dusts) can therefore also contribute to reducing such hot spots of N_r leaching and run-off.

Laying hens

211. A wide range of regulations and minimum standards for protecting laying hens exist across the UNECE region. For example, in the European Union, regulations apply under Council Directive 1999/74/EC[19]. Under the Directive, the use of conventional cage systems has been prohibited since 2012. Instead, only enriched cages (also called "furniture cages"), or non-cage systems, such as litter (or deep litter) housing systems or aviary systems, are allowed.

Housing Measure 16: Rapid drying of poultry litter

212. Ammonia emissions from battery deep-pit or channel systems can be lowered by reducing the moisture content of the manure by ventilating the manure pit. The collection of manure on belts and the subsequent removal of manure to covered storage outside the building can also reduce NH_3 emissions, particularly if the manure has been dried on the belts through forced ventilation. The manure should be dried to 60–70 per cent DM to minimize the subsequent formation of NH_3. Manure collected from the belts into intensively ventilated drying tunnels, inside or outside the building, can reach 60–80 per cent DM content in less than 48 hours, but in this case exposure to air is increased, risking an increase in NH_3 emissions. Weekly removal from the manure belts to covered storages reduces emissions by 50 per cent compared with bi-weekly removal. In general, emissions from laying hen houses with manure belts will depend on:

(a) The length of time that the manure is present on the belts;

(b) The drying systems;

(c) The poultry breed;

(d) The ventilation rate at the belt (low rate = high emissions); and

(e) The feed composition.

213. Aviary systems with manure belts for frequent collection and removal of manure to closed storages reduce emission by more than 70 per cent compared with the deep litter housing system. While the primary drying poultry litter has been on reducing NH_3 emissions, keeping excreted N in the form of uric acid can also be expected to reduce N_2O, NO_x and N_2, since this will also reduce nitrification and denitrification. Dried poultry litter will therefore have a higher fertilizer value for farmers, which should be compensated by using reduced doses during land application (see chapter V), as compared with decomposed poultry litter.

Table IV.21: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 16

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category [a]	1	2[a]	2[a]	3[a]	2[a]	1
Magnitude of Effect	↓↓	~/↓[a]	~/↓[a]	~/↓[a]	~/↓[a]	↓↓

[a] Although this measure primarily focuses on NH_3 abatement, the stability of uric acid in dried poultry litter can help to increase system efficiency and circularity, decreasing wider N_r and N_2 losses, and reducing the need for fresh N_r production.

Housing Measure 17: Use of acid air-scrubbers (poultry)

214. Treatment of exhaust air by acid scrubbers has been successfully employed in several countries (Melse and Ogink, 2005; Ritz and others, 2006; Patterson and Adrizal,

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[18] Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 in industrial emissions (integrated pollution prevention and control), *Official Journal of the European Union*, L 334 (2010), pp. 17–119.

[19] Council Directive 1999/74/EC of 19 July 1999 laying down minimum standards for the protection of laying hens, *Official Journal of the European Communities*, L 203 (1999), pp. 53–57.

2005; Melse and others, 2012). In Germany, Hahne and others (2016) counted 179 installed air-scrubbers in poultry installations and 1,012 scrubbers installed in pig houses. The main difference between pig systems and poultry houses is that the latter (especially with dried litter) typically emit a much larger amount of dust. Acid scrubbers remove 70–90 per cent of NH_3, and also remove fine dust and odour. To deal with the high dust loads, multistage air-scrubbers with pre-filtering of coarse particles have been developed (Ogink and others, 2007; Melse and others, 2008). Yet some experts consider this technique as only category 2 because of the dust loading issue.

Table IV.22: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 17

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category[a]	1	2	2	3[a]	3[a]	1
Magnitude of Effect	↓↓	↓	↓	-[a]	-[a]	↓↓[a]

[a] Although this measure does not directly reduce other NO_3^- and N_2 losses, where the recovered N_r contributes to replace inorganic fertilizer inputs from newly fixed N, it can contribute to increased system efficiency and circularity, reducing wider N_r and N_2 losses.

Housing Measure 18: Use of biological air-scrubbers (poultry)

215. Treatment of exhaust air by use of biotrickling filters (biological air-scrubbers) has been successfully employed in several countries (Melse and Ogink, 2005; Ritz and others, 2006; Patterson and Adrizal, 2005; Melse, Hofschreuder and Ogink, 2012). Biological scrubbers have been found to reduce NH_3 emissions by 70 per cent of NH_3, also removing fine dust and odour. To deal with the high dust loads, multistage air-scrubbers with pre-filtering of coarse particles have been developed (Ogink and Bosma, 2007; Melse, Ogink and Bosma, 2008). Yet some experts consider this technique as only category 2 because of the dust loading issue and possible trade-offs with increases of other N_r losses.

Table IV.23: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 18

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category[a]	1	3[a]	3[a]	3	3[a]	1
Magnitude of Effect	↓↓	↑[a]	↑[a]	-	↑[a]	↓[a]

[a] Ammonia captured in biological air-scrubbers typically undergoes nitrification and denitrification, which is expected to increase emissions of N_2O, NO_x and N_2. Recovery of the collected N_r in bioscrubbers may help offset this increase by reducing the need for fresh N fixation and production of chemical fertilizers.

Broilers

216. To minimize NH_3 emission in broiler housing, it is important to keep the litter dry. Litter moisture and emissions are influenced by:

(a) Drinking-water design and function (leakage and spills);

(b) Animal weight and density, and duration of the growing period;

(c) Ventilation rate, use of in-house air purification and ambient weather;

(d) Use of floor insulation;

(e) Type and amount of litter;

(f) Feed.

217. Reducing spillage of water from the drinking system: A simple way to reduce spillage of water from the drinking system is by using "nipple drinkers" instead of "bell drinkers". This approach should be integrated into wider systems designed to keep poultry litter dry, as described under Housing Measure 16 (Rapid drying of poultry litter).

218. Air scrubber technology to remove NH_3 from ventilation air is highly effective, but not currently widely implemented because of high installation and running costs. Packed-bed filters and acid scrubbers currently available in

Image 9: Illustration of an ammonia scrubbing system in a poultry house, showing ducting, and air inlet immediately above the manure (Housing Measure 17). In the system shown, ammonia is recovered for use as a fertilizer (see Nutrient Recovery Measure 5) (photographs: © UVA, 2020; ammoniatrapping.com).

the Netherlands and Germany remove 70–90 per cent of NH_3 from exhaust air. Comprehensive measuring of air-scrubbers is done by the German Agricultural Association (DLG, 2020), based on a scientific standard testing frame. As with such systems for laying poultry, questions about long-term reliability due to high dust loads need to be further clarified. Various multi-pollutant scrubbers have been developed to also remove odour and PM (PM_{10} and $PM_{2.5}$) from the exhaust air (Zhao and others, 2011; Ritz and others, 2006; Patterson and Adrizal, 2005). Implementation of both acid air-scrubbers (Housing Measure 17) and biological air-scrubbers (Housing Measure 18) for broiler housing is largely similar to that for laying hens.

E Manure storage, treatment and processing

1. Principles of manure storage, treatment and processing

219. For livestock agriculture to become sustainable, an optimal and efficient use of manure nutrients and organic matter is essential. However, manure nitrogen may be easily lost via gaseous emissions (NH_3, N_2O, NO_x, N_2) and leaching of nitrate (NO_3^-) and other N_r compounds. Besides nitrogen losses, animal and manure emissions of methane (CH_4) to the atmosphere must be reduced as far as possible, to limit climate change impacts. Nitrate leaching and pollution of watercourses with N, P and organic compounds are possible if manures are not stored with impermeable barriers to prevent leakages of slurry or leachate from solid manures.

220. Significant N losses may occur during storage of either urine, faeces, or mixtures (slurries and farmyard manures/deep litters), and simple treatment (for example, solid-liquid separation) or more advanced processing (for example, anaerobic digestion, ultrafiltration) may enable more appropriate manure management with lower N losses.

221. The treatment of manures typically involves a one-step operation to improve the properties of the manure. Expected effects include: the improvement of the fluid properties (by adding water or by separating solids); the stabilization of volatile nutrients (by acidification); and a reduction in odour nuisance (for example, aeration). Single-stage treatment of manures is typically applied on farms in the proximity of livestock buildings. The mass and ingredients of manures are not, or are only slightly, changed by treatment systems.

222. The processing of manures generally describes more complex and multi-step processes, which are used specifically to produce new products. Such products may have higher nutrient content, lower water content, free of undesirable odours and hygienically safe. In most cases, manure processing is used to produce marketable products that can be used as fertilizers and soil conditioners, as well as secondary raw materials (for example, fibres). Manure processing technologies may either be located on farms or operated as central/decentral plants.

223. Manure treatment and processing always come at a cost, both in economic, energy and environmental terms, so the simplest option fulfilling the goal(s) should always be the priority option:

(a) Direct land application;

(b) Simple treatment;

(c) Advanced processing (with (a) first, according to local limitations, including those related to pollution).

224. Simple treatment and advanced processing are most relevant when conditions (for example, high regional livestock density, large manure N surplus relative to local crop demand) favour overall environmental benefits from treatment or processing. Such systems should be designed with awareness of the need to avoid pollution swapping (for example, reducing ammonia loss, but increasing nitrate leaching somewhere else and vice versa).

225. Animal slurry composition is typically not ideal with regard to low emission handling and crop fertilizing properties. In particular, the high dry matter and carbon content pose several problems during slurry storage, application and crop utilization (see table IV.24). This points to the opportunity for increased development of systems to collect and store urine and dung separately (Housing Measure 1), or to apply manure treatment by solid-liquid separation.

226. High slurry dry matter tends to result in crust formation on the slurry surface and/or in sedimentation on the bottom of the slurry tank. In order to achieve an even distribution of nutrients in the slurry, slurry must be mixed/homogenized prior to application. Homogenization of slurry with high dry matter content is energy consuming and increases NH_3 emissions, as a larger volume of the slurry comes into close contact with the atmosphere.

227. Slurry contains considerable amounts of easily degradable carbon that serves as substrate for microbes. During slurry storage, a continuous degradation of organic matter can be observed. Degradation intensity is strongly dependent on the slurry dry matter content. Amon and others (1995) investigated changes in slurry composition over a 200-day storage period for stored cattle, beef and pig slurry. Degradation of organic matter was found to be significantly greater with higher slurry dry matter content. Such slurry degradation will include mineralization to form of ammonium (NH_4^+) from organic matter. This points to an opportunity for increasing the immediate fertilizer value of the slurry, provided that storage is covered, thereby avoiding NH_3 emissions and benefiting from increased slurry NH_4^+ content.

228. As conditions in slurry are anaerobic, degradation of organic matter is always dominated by anaerobic pathways. This means that both CH_4 and CO_2 are formed as end products of the degradation process. It is thus to be assumed that high dry matter slurry bears a greater risk for CH_4 emissions, contributing significantly to climate change. This also points to the opportunity for CH_4 and CO_2 recovery;

for example, linked to anaerobic digestion for production of biogas (cf. Manure Measure 8).

229. Environmentally friendly slurry application in the field requires that the slurry be more evenly applied near or below the soil surface. It is much more complicated to fulfil this requirement when the slurry has a higher dry matter content, causing a higher viscosity and less easy flow through band-spreading hoses. Following application of slurry, NH_3 emissions can be substantial and are found to increase with an increase in slurry dry matter content, due to slower soil infiltration (Sommer and others, 2013; Bitmann and others 2014). This emphasizes the importance of maintaining low dry matter contents of slurries. By reducing NH_3 and other nitrogen losses, available N resources on farms are increased, decreasing the need for additional N to be bought as manufactured inorganic fertilizer.

230. The N availability to plants is difficult to calculate with high dry matter slurry, because a high dry matter content drives increased microbial immobilization right after application. The narrower the C/N-ratio, and the higher the NH_4^+-N content, the more slurry N is potentially available to plants, whereas with a wide C/N-ratio, part of the slurry N is immobilized in the soil N pool and becomes available only at a later stage, which is often unpredictable or even too late, causing increased risk of nitrate leaching. In addition, an increase in slurry dry matter and subsequent soil N content has the potential to increase rates of nitrification and denitrification, increasing subsequent N_2O, NO_x and N_2 losses (for example, Dosch 1996). It may thus be beneficial to reduce slurry dry matter and carbon content at an early stage of manure management. This leads to several manure treatment options, which can be evaluated in relation to the requirements listed in figure IV.4.

231. In line with the objectives of the European Union Circular Economy Action Plan[20], there is an opportunity to encourage the use of recycled nutrients that can replace nutrients otherwise obtained from primary raw materials. The main challenge is to use recycled nutrient resources with an environmental performance that is equal to, or better than, that of the primary nutrient resources they replace. Efforts are ongoing across the European Union to develop manure processing technologies that allow manure to be turned into a safe and agronomically valuable resource that can be used more widely[21].

232. Techniques for simple manure treatment can be classified as physical, chemical or biological (see figure IV.5; Bernal and others, 2015). Furthermore, a number of different options/technologies are available for further and more advanced processing of raw or treated manures for recovering and upgrading nutrients and organic matter from different manure types (see figure IV.6). For slurries or other liquid manures, such as digestate from anaerobic digestion of manure and other biowaste, all treatment steps start with mechanical separation into:

(a) A solid fraction that is relatively rich in organic N and P; and

(b) A liquid fraction, with low P, but relatively high mineral N and K contents.

233. Different simple techniques can be combined with each other. This allows a wide variety of by-products to be combined, resulting in highly variable distribution of organic nitrogen, ammoniacal nitrogen, phosphorus, carbon and

Table IV.24: Problems and benefits resulting from slurry high dry matter and carbon content and low nutrient content

	Problems
Storage	Natural crust formation and sedimentation of solids, giving heterogenousconcentration of nutrients High energy consumption per unit of nutrient for pumping and mixing Potentially higher emissions of NH_3, N_2O, N_2, CH_4, and odour
Field application	High potential risk of NH_3 losses due to slow infiltration Major technical effort required (at high economic cost) for even and low emission application Suffering of crop plants due to scorching by broadcasted slurry
Crop utilization	Less effective crop uptake of slurry N than from mineral fertilizer Increased temporary N immobilization in the soil, increasing risk of lower crop N effect Higher risk of denitrification and subsequent N_2O and N_2 emissions Crop N effect less predictable/more variable than from mineral fertilizer
	Benefits
Storage	Natural crust formation may serve as a natural barrier, inhibiting NH_3 transport to the atmosphere; furthermore, the crust may have significant capacity for CH_4 oxidation, due to its partial aerobic conditions and high microbial activity
Field/soil	High dry matter and carbon content contribute to maintenance of soil organic matter content and biologically active soil

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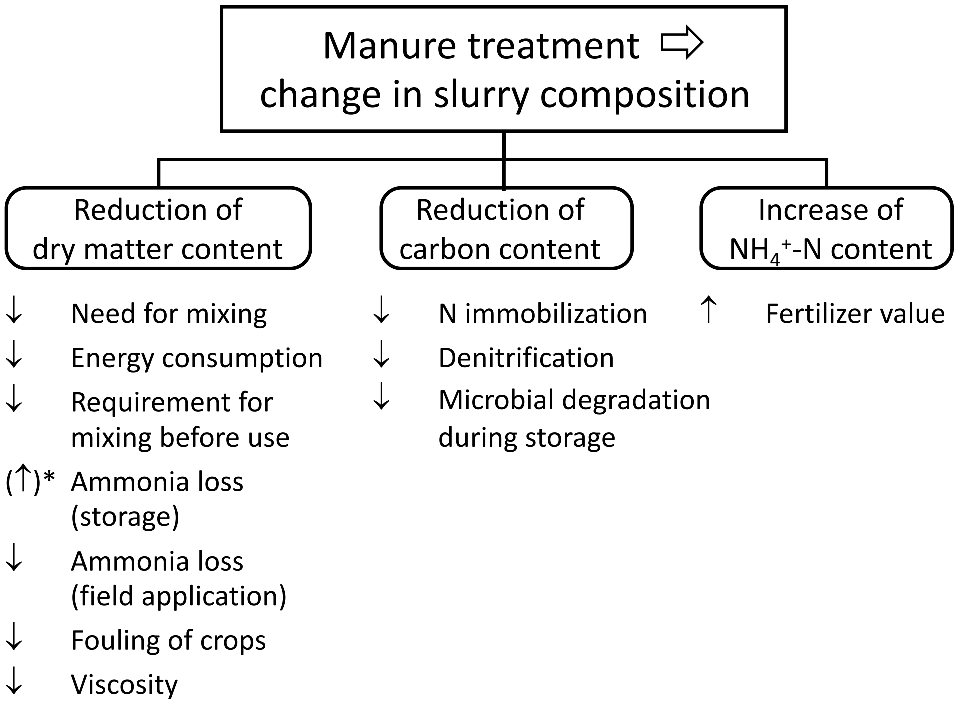
[20] See https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614.

[21] See https://ec.europa.eu/jrc/en/research-topic/waste-and-recycling.

Figure IV.4: Effect of changes in slurry composition achieved by manure treatment



Source: The figure was created for the current document.

Note: Arrows indicate decrease (↓) or increase (↑) in the listed property. *If depending on natural crusting of manure to reduce emissions rather than other types of cover.

other nutrients, which must be taken into account when managing the different fractions.

234. There may be additional possible treatments of the liquid phase. In order to save water without increasing the amount of nitrogen supplied to the soil, and to favour the circular economy of water, it is common to carry out successive treatments of the liquid phase, so that the resulting product can be used in fertigation. For example, in the south of Spain, wetlands are being constructed to allow the reuse of water for irrigation in areas of scarce availability. In addition to nitrogen, many other characteristics have an influence on the decision to choose a procedure, such as: the contribution of organic matter; the formation of methane and other greenhouse gases; the presence of other nutrients; type of agricultural systems; salinity; weather; and, importantly in the countries of Southern Europe, the water footprint.

235. Each of these processing pathways and resulting products (see figure IV.6) has certain advantages and disadvantages, and the net environmental benefits/impacts and economic costs/profits differ greatly. A number of factors must be considered when prioritizing the processing options (Jensen, 2013):

(a) The primary aim should be nutrient recycling, mainly N and P; N is consumed in the largest quantities, is expensive and has impacts on energy consumption and greenhouse gas (GHG) emissions, while P is a scarce and non-renewable resource, with the highest price;

(b) Splitting N and P into different fractions is generally beneficial, as this enables more flexible and balanced fertilization in accordance with the needs of many crops;

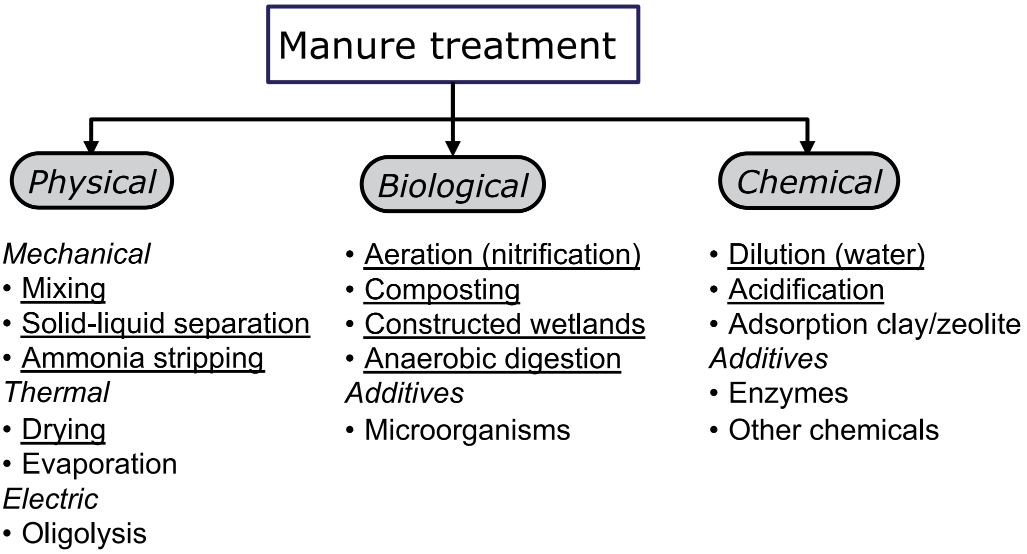
(c) The technology or combination of technologies applied should preferably also produce energy or consume relatively little energy, so net energy production should be taken into account for both environmental and economic reasons;

(d) Local solutions should be preferred, avoiding overly high transport cost and impacts; regional or more central solutions are therefore only justified if the economy of scale via higher efficiency outweighs the negative impacts of transporting the manure to a common facility;

(e) The quality of end-products and by-products is assessed differently depending on the user's perspective. For instance, a manure combustion ash, where the majority of the N has been lost, will not be appreciated by an organic farmer, while a compost is highly appreciated for its soil-ameliorating effect and slow release of N, even if some N is lost in the process;

(f) Biochars and compost may be valued highly by orchard and vineyard producers for their effects on soil-water holding capacity and nutrient retention, whereas conventional crop production farmers may value mineral concentrates and salts more highly. Production

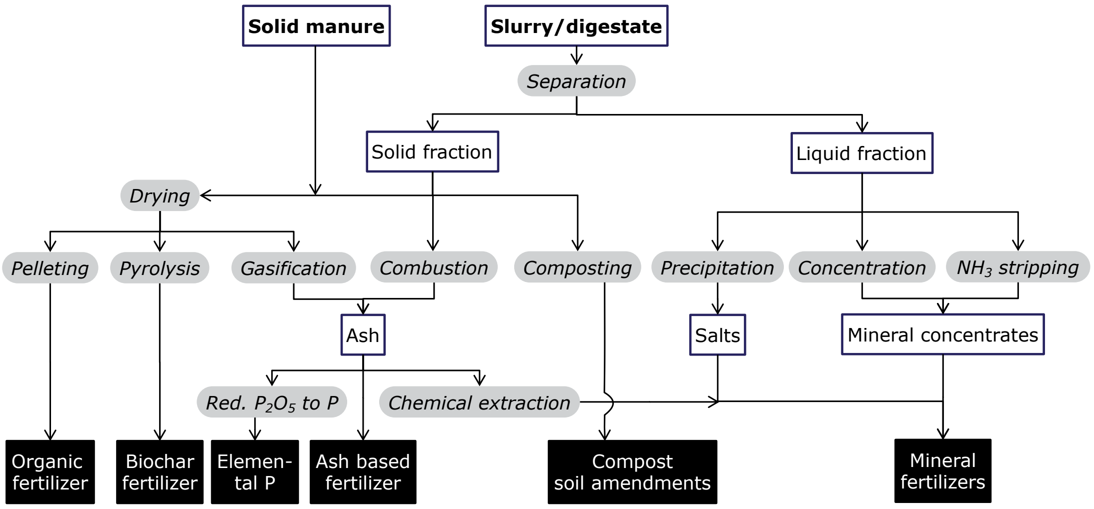
Figure IV.5: Options for simple manure treatment



Source: The figure was created for the current document.

Note: Underlined options are commonly applied in some regions in full scale on commercial farms (mainly pig farms); other options are applied either rarely or only in experimental/pilot scale – these are not dealt with further here, pending the availability of proof-of-concept and documentation.

Figure IV.6: Options for combining simple treatment with more advanced processing of manures to recover and upgrade nutrient and energy



Source: Modified from Jensen (2013).

Note: The options displayed result in widely different biobased fertilizers. Only a few are currently applied in full commercial scale; other are still at the experimental/pilot stage (and are therefore not dealt with further here).

of recovered, biobased fertilizer products should not be supply driven (trying to solve a waste problem), but rather demand driven (biobased fertilizers that the farmers want).

2. Abatement measures for manure storage, treatment and processing

Manure storage

Manure Measure 1: Covered storage of manure (solid cover and impermeable base)

236. A wide range of options are available for covered manure storage using solid covers, including use of metal or concrete tanks with solid lids, floating covers on lagoons, and use of slurry bags, most of which are associated with negligible ammonia emission if well operated (principle 15). Further details of such systems are provided by Bittman and others (2014). Less focus has been given to ensuring that solid manure (for example, farmyard manure and poultry manure) is covered; for example, through use of plastic sheeting. The reference system is taken as uncovered storage, including a permeable surface, which explains the benefit of using an impermeable base to reduce nitrate leaching (cf. Manure Measure 5).

Table IV.25: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 1

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE Category	1	3	3	1	3	1
Magnitude of Effect	↓↓	~	?	↓↓	↓↓	↓↓

Manure Measure 2: Covered storage of slurry (natural crust and impermeable base)

237. Where slurries have a high dry matter content, and stirring is minimized, these may form a natural crust during storage, which is associated with substantially reduced ammonia emission (Bittman and others, 2014). There is broad agreement that crusting has an impact on gas release in many ways:

(a) Enhanced resistance to mass transfer (Olesen and Sommer, 1993);

(b) Oxidation of NH_3 (Nielsen and others, 2010) and CH_4 (Petersen and others, 2005); and

(c) Formation of N_2O related to nitrification and denitrification occurring in liquid–air interfaces near air-filled pores present in crusts (Petersen and Miller, 2006).

238. Ammonia and CH_4 may be consumed due to microbial activity in the crust, leading to an emission reduction (Petersen and Ambus, 2006; Nielsen and others, 2010), while N_2O production may be enhanced (VanderZaag and others, 2009). A comprehensive assessment of the current knowledge on the effect of natural crusts can be found in Kupper and others (2020). The reference system is taken as uncovered storage, including a permeable surface, which explains the benefit of using an impermeable base to reduce nitrate leaching (cf. Manure Measure 5).

Table IV.26: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 2

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE Category	1-2	3	3	1	3	2
Magnitude of Effect	↓	↑?	?	↓↓	~	↓

Manure Measure 3: Covered storage of solid manure (dispersed coverings)

239. Ammonia emissions can be significantly reduced when covering solid organic fertilizers with dispersed coverings such as peat, clay, zeolite and phosphogypsum. The basis of the approach is to prevent contact of NH_3-emitting surfaces with the air, especially when covering them with ammonium-absorbing substances (principle 15). Lukin and others (2014) found that total NH_3 emissions from poultry manure amounted to 5.9 per cent when it was covered with peat, 4.7 per cent when it was covered with loam, 1.3 per cent when it was covered with zeolites, and 16.9 per cent when it was covered with phosphogypsum. These values are relative to NH_3 emissions in the reference system with no covering. Use of these simple materials to cover piles of organic fertilizers thereby substantially reduces NH_3 emissions into the

Image 10: Covered storage of liquid manure (Manure Measure 1) avoids contact with air and reduces both ammonia and odour emissions, while the containment provided also avoids aquatic nitrogen losses (photograph: © Stallkamp).

atmosphere (Lukin and others, 2014). Protocols are needed to specify minimum thickness of each type of covering material. Further testing is needed to assess the effect on N_2O, NO and N_2 emissions. Unless an impermeable base is used, the approach risks significant nitrate leaching. A combination of Manure Measures 3 and 5 can reduce both N_r emissions to air and leaching losses to water.

Table IV.27: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 3

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE Category	1	3	3	3	3	2
Magnitude of Effect	↓↓	?	?	~	?	↓

Manure Measure 4: Storage of solid manure under dry conditions

240. Simply storing manure in a dry place, out of the rain, can also reduce nitrogen emissions from a range of N_r compounds and N_2. This is even more important for dried poultry litter, where keeping manure dry and out of the rain helps to avoid hydrolysis of uric acid to form ammonia. However, poultry litter is hydroscopic and will emit some ammonia when in humid atmospheres, even when kept free of rain (for example, Elliot and Collins, 1982). Keeping solid manure dry during storage minimizes mineralization and denitrification, which can give rise to N_2O, NO_x and N_2 emissions, as well as reducing nitrate and other N_r leaching. The reference system is taken as uncovered storage, including a permeable surface, which explains the benefit of storing under dry conditions to reduce nitrate leaching (cf. Manure Measure 5).

Table IV.28: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 4

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE Category	2	2	2	2	2	1
Magnitude of Effect	↓	~/↑	↓	↓	↓	↓[a]

[a] Simple storage under dry conditions is most effective for dry poultry litter to avoid hydrolysis of uric acid and associated microbial processes.

Manure Measure 5: Storage of solid manure on a solid concrete base with walls

241. Investments in this approach have been motivated out of the need to reduce nitrate leaching and other N_r leaching by avoiding run-off and infiltration into the soil. The approach has the benefit of being low-cost, but risks substantial NH_3 emissions, while also being ineffective at avoiding nitrification and denitrification, which contribute to N_2O, NO_x and N_2 emissions. The reference system is taken as uncovered storage, including a permeable surface, which explains the benefit of using an impermeable base to reduce nitrate leaching. Storage of solid manure on concrete areas is considered good agricultural practice for nitrate pollution but makes no contribution to reducing NH_3 emissions

Table IV.29: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 5

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE Category	3	3	3	1	3	2
Magnitude of Effect	~	~	~	↓[a]	~	↓[a]

[a] The approach can be considered as preferable to open field storage of solid manure but risks substantial emissions of other N_r forms and N_2.

Simple Manure Treatment Measures

Manure Measure 6: Slurry mixing (during storage)

242. Slurry mixing in the storage is one of the most commonly applied manure treatment technologies. Slurry is thereby homogenized, typically shortly prior to field application, in order to achieve a more homogenous distribution of nutrients across the field(s) to which the volume of the slurry storage is applied. Apart from this, mixing does not offer any additional benefits compared to untreated slurry. Neither dry matter nor carbon content are reduced, and the C/N-ratio is not altered. No significant changes in N_2O or CH_4 emissions are expected, but NH_3 may tend to increase, depending on the extent and timing of mixing (mixing will tend to increase pH by promoting CO_2 loss from slurry), so mixing should only be done shortly before field application.

Table IV.30: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 6

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE Category	3	3	3	3	3	3
Magnitude of Effect	~/(↑)	~	~	~	~	~

Manure Measure 7: Adsorption of slurry ammonium

243. Slurry additives can act on a chemical, physical or biological basis. Clay/zeolite mineral additives have been shown to adsorb NH_4^+-N and can thus potentially reduce NH_3 losses. However, this can only be achieved effectively with high amounts of additives; for example, it has been shown that 25 kg of Zeolite per m^3 slurry are needed to adsorb 55 per cent of NH_4^+-N (Kocatürk and others, 2017, 2019). On most commercial farms, it is neither logistically possible nor economically profitable to add such high amounts of slurry additives. Addition of biochar may also reduce NH_3 emissions from stored manure.

Image 11: Open storage of solid manure on a solid concrete base with walls (**A**, **B**; Manure Measure 5) helps reduce nitrate and other nitrogen leaching and run-off, but risks substantial ammonia emissions to the atmosphere (photographs: © Sergei Lukin).

Table IV.31: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 7

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	2	3	3	3	3	2
Magnitude of Effect	↓	?[a]	?[a]	?[a]	?[a]	↓

[a] The effect of ammonium adsorbing additives for stored slurry on losses of N_2O, NO_x, NO_3^- and N_2 remains uncertain.

Manure Measure 8: Slurry acidification (manure storage)

244. An obvious way to minimize ammonia emissions from stored slurry is to decrease pH by adding strong acids or other acidifying substances. This can also be done in the animal house (Housing Measure 8). Care must be taken to ensure that a low pH is maintained to get the full benefit of this measure. Slurry with a sufficiently reduced pH will also emit less methane. This solution has been used commercially since 2010 in countries such as Denmark (by 2018, around 15–20 per cent of all slurry applied in Denmark was acidified; Birkmose, personal communication), and its high efficiency for minimizing NH_3 emissions has been documented in many studies (see review by Fangueiro and others, 2015), with emission reductions by >80 per cent possible. It is most typical to acidify slurry using sulphuric acid (cheapest industrial acid; also, the sulfate added serves as a relevant plant nutrient source), although use of other acids is also possible. Acidification also reduces methane formation very effectively, by up to 67–87 per cent (Petersen and others, 2012). Reduced nitrification and denitrification decrease the potential for N_2O and N_2 emissions, though further studies are required to demonstrate efficiency for this. In one novel variant of this method, electricity is used to produce a plasma that oxidizes N_2 to NO and thence to nitrogen dioxide (NO_2), which converts in slurry to produce nitric acid (HNO_3). In this way, slurry acidification is achieved while augmenting the nutrient value of the manure (Graves and others, 2019). More research is needed to assess this option fully.

245. Costs for in-house acidification systems can be higher than acidification during field application (Manure Measure 9), but are counteracted by additional benefits including: improved in-house air quality benefiting animal and staff, which may influence productivity; retention of more slurry N throughout the manure management chain; and associated savings in fertilizer costs.

Table IV.32: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 8

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	1	2	2	3[a]	2	1[a]
Magnitude of Effect	↓↓	↓	~/↓?	~[a]	↓	↓↓[a]

[a] Although this measure is not known to reduce NO_3^- directly, where NH_3-saving contributes to replace inorganic fertilizer inputs from newly fixed N (for example, when fertilizer regulations require the improved fertilizer value to be taken into account), it can contribute to increased system efficiency and circularity, reducing wider N_r and N_2 losses.

Manure Measure 9: Slurry aeration

246. Slurry aeration introduces oxygen into the slurry rapidly in order to allow aerobic microbes to develop. Oxidation of organic matter to CO_2 and H_2O increases, and thus CH_4^- production and emission is reduced. Odorous compounds are degraded. Slurry dry matter content decreases. Thus, less mixing is needed and technical properties of slurry are often improved. However, successful aeration requires 200 m^{-3} oxygen per ton of slurry (Burton 1998).

247. Slurry aeration increases NH_3 emissions and in energy consumption. The potential for NO_x emissions is also expected to increase, as increased oxygen availability promotes nitrification, while subsequently higher levels of nitrate availability may increase other oxidized N_r losses and denitrification. Only a few studies have quantified the extent of these increases (Amon and others, 2006) and more

research is necessary to allow a complete evaluation. In the present context, an increase in denitrification to form N_2 is considered a waste of available N_r resources.

Table IV.33: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 9

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	3	3	3	3	3	3
Magnitude of Effect	↑↑	↑↑	↑?	?	?	↑↑

Manure Measure 10: Mechanical solid-liquid separation of slurry fractions

248. During slurry separation, solids and liquids are mechanically separated from each other. This results in two fractions: a liquid slurry fraction, with relatively low dry matter content compared with the slurry; and a solid fraction that can be stored in heaps. Energy consumption for slurry separation is relatively low but depends on the technology used for separation. Dry matter content in the liquid fraction is reduced by 40–45 per cent, and vice versa for the solid. Carbon content in the liquid is typically reduced by 45–50 per cent, with the C/N-ratio of the liquid decreasing from about 10:1 to about 5:1 (Amon 1995; Sommer and others, 2013). As carbon is removed from the slurry, microbial degradation of organic matter during slurry storage is reduced. However, the opposite may be the case for the solid fraction, depending on storage conditions.

249. The removal of solids reduces crust formation and sedimentation of the liquid fraction in comparison with raw slurry. Thus, less intensive mixing is necessary to homogenize the slurry prior to application. Conversely, the potential for ammonia losses is increased if slurry is stored without a cover. Therefore, other emission-reduction measures during storage of the liquid fraction need to be applied (Manure Measures 1, 2 or 8). Efforts for low-emission application techniques are also reduced as separated slurry has a lower viscosity and flows more easily through band-spreading hoses (Owusu-Twuma and others, 2017). Slurries with very low dry matter content can be spread with simple nozzle-beam-dischargers that can be operated on slopes >10 per cent, which is not possible with other band-spreading techniques. Furthermore, separated slurry liquid fraction has a low viscosity and infiltrates rapidly into the soil. Thus, plants get less dirty, and ammonia emissions after liquid fraction spreading are typically reduced. A substantial reduction of ammonia emissions by slurry separation is therefore possible for the liquid phase, especially following land application (for example, Amon and others, 2006).

250. The liquid fraction of separated slurry has a narrow C/N-ratio, which reduces the potential for both microbial N immobilization in the soil and N_2O emissions. Crop N availability of the liquid fraction is therefore more predictable and can be better calculated in order to match nutrient requirements of crops to actual fertilization. Dosch (1996) investigated fertilization with untreated and separated slurries and found significantly higher denitrification rates with untreated slurry. Separated slurry liquid fraction on the other hand resulted in significantly higher crop yield. However, the solid fraction needs to be handled with care during storage to avoid elevated ammonia emissions. Furthermore, the solid fraction may become a source of methane emissions, if not properly treated. Alternatively, if the solid fraction is used as feedstock for biogas production, this methane potential may be recovered and utilized as renewable energy source. After application, the solid fraction serves mainly as soil improvement and slow-release N fertilizer.

251. Slurry separation fulfils most requirements of appropriate manure treatment. Costs could be further reduced if the technology were more widespread and more separators were on the market and available to farmers. As the fertilizer value of the liquid fraction from separated slurry is improved, mineral N fertilizer input can be reduced. The slurry liquid fraction can be applied at the soil surface in a growing crop with very simple low-cost slurry band spreaders (for example, trailing hose, see chapter V) with a high uptake efficiency and fertilizer replacement value. The main caveat to the method is the difficulty of appropriate storage, handling and utilization of the solid fraction; this needs to be low emission (for example, Field Measure 11), in order not to compromise benefits of the liquid fraction. An alternative is to use the solid fraction as a feedstock in nutrient anaerobic digestion (Manure Measure 11) with nutrient recovery.

Table IV.34: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 10

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	1-2	2	3	3	2	2[b]
Magnitude of Effect	↓↓	↓	?[a]	?[a]	↓	↓[a]

[a] Although this measure is not known to reduce NO_x and NO_3^- directly, where NH_3-saving contributes to replace inorganic fertilizer inputs from newly fixed N, it can contribute to increased system efficiency and circularity, reducing wider N_r and N_2 losses.

[b] The main emphasis of this approach is on reducing emissions from the liquid fraction, which contains most of the ammoniacal nitrogen, therefore implying: (a) the need to cover or acidify the liquid fraction during storage; and (b) the opportunity to reduce NH_3 emissions during spreading of the liquid fraction (chapter V). Maximum effectiveness of this approach also requires appropriate storage and use of the solid fraction (for example, by covered storage, direct incorporation into soil, or anaerobic digestion).

Manure Measure 11: Anaerobic Digestion

252. Anaerobic digestion of animal manures is mainly implemented at present for bioenergy production reasons. Improvement of manure quality is therefore typically considered to be a "by-product" of anaerobic digestion. However, when combined with nutrient recovery methods (see figure IV.6; for example, Nutrient Recovery Measures

3–5), nutrient management can be considered as fully integrated as a key goal in implementation of anaerobic digestion. The value of products from anaerobic digestion (biogas produced, available nutrients) can help provide an extra income to farmers, enabling them to make investments (for example, for adequate manure storage and application technology).

253. Biogas production from animal manures through anaerobic digestion aims at maximizing the biomethane yield. Where no biogas recovery system is available, unintended anaerobic degradation of organic substances into methane during manure storage should be limited as far as possible, to prevent emission to the atmosphere of this strong GHG. This also maximizes the resource availability for subsequent biogas production when facilities are available. Anaerobic digestion can include heating of the manure to promote digestion, leading to increased methane production, which may be used in a variety of systems (for example, in combined heat and power production). Anaerobic digestion not only reduces methane emissions from subsequent storage of the manure digestate, but the energy produced typically substitutes consumption of use of fossil energy. Both effects reduce anthropogenic greenhouse gas emissions.

254. Anaerobic digestion reduces manure carbon and dry matter content by about 50 per cent (Amon and Boxberger 2000). Ammonium content and pH in digested slurry are higher than in untreated slurry. Thus, the potential for NH_3 emissions during subsequent slurry storage is increased. Digested slurry therefore has to be stored in covered slurry stores. These should be connected to the gas-bearing system of the biogas plant, because methane is still formed after the main digestion phase has taken place in the heated digester.

Due to the reduced dry matter content, biogas slurry can infiltrate more rapidly into the soil, which tends to reduce ammonia emissions after slurry application. However, the increased NH_4^+ content and pH give rise to higher potential for ammonia loss, especially after surface application. It is therefore strongly recommended to apply biogas slurry with low-emission techniques near or below the soil surface (for example, band application or injection, chapter V).

255. It should be noted that the process of anaerobic digestion itself does not reduce NH_3 emission, but rather provides the opportunity to reduce NH_3 emission by virtue of the requirement for a closed system. Similarly, anaerobic digestion produces a digestate with high TAN content and low dry matter content, which is more easily manageable to increase crop nitrogen use efficiency than slurry or solid manure with a high carbon content. These points mean that, while anaerobic digestion increases the opportunity to reduce NH_3 emissions, achieving this will depend on the deployment of an appropriate package of measures. The combined implementation of anaerobic digestion (reducing dry matter content, increased NH_4^+ and pH), covered storage prior to use, and low-emission application to land (for example, trailing hose, injection) therefore considerably reduces NH_3 emissions. In addition, N immobilization and N_2O losses are likely to be smaller than from untreated slurry, due to the removal of easily degradable organic substances during the anaerobic digestion process. Energy consumption for pumping and mixing is considerably reduced due to the reduced dry matter content. When combined with appropriate methods for low-emission land-spreading of the digestate, anaerobic digestion therefore has multiple benefits. In addition, it provides the opportunity for further processing for more advanced forms of nutrient recovery, including nutrient precipitation, concentration and ammonia stripping (see figure IV.6; Nutrient Recovery Measures 3–5).

Table IV.35: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 11

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	1[a]	2[a]	3	1[a]	2[a]	1
Magnitude of Effect	↓↓[a]	↓[a]	?[b]	↓↓[b]	↓[a]	↓↓

[a] UNECE category and magnitude are given on the basis of anaerobic digestion being implemented in combination with low-emission land application of the digestate (for example, band-spreading, injection, chapter V). Due to the high pH of anaerobic digestate, ammonia emissions may otherwise increase (↑↑).

[b] Although this measure is not known to reduce NO_x directly, where NH_3 and N_2 saving contribute to replace inorganic fertilizer inputs from newly fixed N, it can contribute to increased system efficiency and circularity, reducing wider Nr losses.
The requirement for an impermeable base implies less nitrate leaching than storage/treatment of manure on a permeable surface.

Manure Measure 12: Manure Composting

256. Composting of manure is done in order to create a stable and odourless biobased fertilizer product, with lower moisture content, while containing most of the initial nutrients, free of pathogens and seeds (Jensen, 2013). Composting significantly reduces mass (as a result of water evaporation and volatile solids decomposition to release CO_2) and hence transport costs. However, it is difficult to avoid some loss of manure N in the form of NH_3 and the process also emits greenhouse gases, with potential for increased N_2O and CH_4 emissions, in addition to NO_x and N_2 (Chowdhury and others, 2014). The N fertilizer value of composts is often significantly lower than the N-rich manure components it is made from, which is largely a result of associated NH_3 and N_2 emissions (Jensen, 2013). Composting on porous soil surfaces may also be associated with significant leachate, including NH_4^+, NO_3^- and other N_r compounds. Composting is typically a low-cost technology but implies space requirements and energy consumption. Overall, it is not therefore usually recommended to mitigate nitrogen losses but may be preferred on other criteria (for example, volume and weight reduction, compost product stability, reduced odour, improved marketability and soil amelioration).

Table IV.36: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 12

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE Category	3	3	3	3(2)	3	2
Magnitude of Effect	↑	~/↑	↑	↑(↓[a])	↑	~[b]

[a] If conducted on an impervious surface with recovery of composting leachate.

[b] A more favourable overall assessment for N_r may be achieved for "closed vessel composting" combined with acid scrubbing of exhaust air (cf. see Nutrient Recovery Measures), which may be used in certain contexts to manage biohazards, though significantly increasing implementation costs.

257. In addition to these simple manure treatment options, constructed wetlands have also been used to treat liquid manure (see Landscape Measure 5).

Advanced Manure Processing and Nutrient Recovery

Nutrient Recovery Measure 1: Drying and pelletizing of manure solids

258. Drying and pelletizing of solid manures, slurry or digestate solids can be done to create a more stable and odourless biobased fertilizer product. Drying is energy intensive and thereby relatively expensive, unless excess energy (for example, from the combined heat and power plant engine on a biogas plant) is freely or cheaply available. Increased ammonia loss is inevitable in the process, unless exhaust filtering or scrubbing and recovery is applied, or the solids are acidified prior to drying. Drying is usually combined

Image 12: Two examples of on-farm anaerobic digestion facilities, which provide an opportunity to recover biogas and nitrogen rich digestate (Manure Measure 11). The approach should be integrated with low emission spreading, ammonia stripping or other nutrient recovery to avoid subsequent ammonia losses. (**A**, Digestion for a pig farm Russia, photograph © Sergei Lukin; **B**, System combined with photovoltaics in Germany, photograph © Shutterstock, www.shutterstock.com, ID: 430844485).

with a pelletizing process to facilitate handling. The pelleted material can be marketed as an organic matter and P-rich soil amendment; if acidified prior to drying, the resulting product may also be rich in plant-available N (Pantelopoulos and others, 2017).

Table IV.37: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Nutrient Recovery Measure 1

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	3(1^a)	3	3	2	3	2
Magnitude of Effect	↑(↓^{a})	~?	~?	~?	~?	~↑(↓^{a})

[a] The method increases NH_3 emissions unless combined with acidification of slurry or scrubbing/stripping (Nutrient Recovery Measures 4 and 5) of the exhaust air.

Nutrient Recovery Measure 2: Combustion, gasification or pyrolysis

259. Combustion, thermal gasification or pyrolysis of manure and digestate solids can be used to generate a net energy output for heat and/or electricity production. However, at present, the method leads to an almost complete loss of the manure N, which is converted into gaseous N_2, NO_x and NH_3. Available advanced technologies (for example, selective non-catalytic reduction, focus on denitrifying these N_r gases to N_2. In the absence of systems to minimize N_2 formation and recover the N_r gases, this measure cannot be considered appropriate for abating overall N loss (category 3). Systems currently under development to recover N_r gases can be considered as having high potential (category 2).

260. At the same time, the approach produces ash or biochar residuals. These ashes contain the non-volatile nutrients, concentrated relative to the solids. They can be used as an ash-based, P- and K-rich soil amendment or biobased fertilizer. The availability of the remaining nutrients in the ash is generally much lower than for the raw manure, whereas for biochar it is in between ash and raw manure. Organic compounds in the biochar that are produced are very recalcitrant to biological decay and have a very large specific surface area, being potentially charged. This means that such biochar may be used for soil amendment, ameliorating soil pH and organic matter positively.

Image 13: Example of pelletized manure (Nutrient Recovery Measure 1) (photograph: © Sergei Lukin).

Table IV.38: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Nutrient Recovery Measure 2

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	3(2^a)	3	2-3	3	3	3(2^a)
Magnitude of Effect	↑(↓^{a})	↑(↓^{a})	↑(↓^{a})	-	↑↑	↑↑

[a] Values in brackets reflect the benefit of additional process controls (for example, selective (non-) catalytic reduction), which work to minimize the NO_x and NH_3 emissions. However, current methods still increase N_2 emission, so that the N_r resource is effectively wasted. This approach therefore tends to reduce system-wide nitrogen use efficiency and contributes to preventing progress towards a nitrogen circular economy. Further development is required to couple minimization of N_2 formation with effective recovery of N_r gases (Sutton and others, 2013).

Nutrient Recovery Measure 3: Precipitation of nitrogen salts

261. Struvite ($MgNH_4PO_4{\cdot}6H_2O$) can be precipitated from liquid manures, provided that the appropriate conditions are present (pH ~9, a molar ratio 1:1:1 of Mg^{2+} : NH_4^+ : PO_4^{3-}, conducive physical settling conditions). As such, the precipitation of struvite is a method for removal and recovery of both N and P from liquid manures. The method has been developed for wastewater treatment, where P removal can easily reach more than 70 per cent and it is commercially available for sewage treatment plants, although not yet widely applied. For manures, the struvite technique is particularly relevant for anaerobically digested slurries and the liquid fraction from digestate separation; hence, it has been the subject of massive research in the past decade and quite high removal efficiencies have been achieved (56–93 per cent; see further review in Jensen, 2013). However, it only works for the N already present as NH_4^+ and further development is needed for appropriate application to liquid manures and digestates. So far, only a few commercial-scale plants are in operation worldwide. The main advantage of struvite is its high concentration and similarity in physical-chemical properties to conventional mineral N fertilizer.

Table IV.39: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Nutrient Recovery Measure 3

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	2	3	3	2	2	2
Magnitude of Effect	↓^{a}	?^{a}	?^{a}	↓^{a}	↓^{a}	↓^{a}

[a] The table refers to precipitation of struvite only. As the approach recaptures N_r for reuse, system-wide reductions in the main losses of NH_3, NO_3^- and N_2 can be expected. However, the actual efficiencies remain to be demonstrated. This can be considered as an enabling measure to reduce overall N_r and N_2 losses, by mobilizing recovery and reuse of available N_r resources.

Nutrient Recovery Measure 4: Concentration of nitrogen salts and solutions

262. Mineral concentrates are highly nutrient-rich solutions that may be obtained via ultrafiltration, evaporation or reverse osmosis of the liquid fraction from separation of slurry or digestate. These mineral concentrates (the retentate) may be directly applied to agricultural land, while the by-product water, which is low in nutrients (the permeate), may be directly discharged to surface waters or the sewage system. The greatest wealth of experience with these technologies in Europe can be found in the livestock regions of the Netherlands and Belgium, where a number of centralized and large-scale manure processing plants utilize a range of technologies in combination (for example, anaerobic digestion, solid-liquid separation, ultrafiltration/reverse osmosis/solids drying). Provided that the losses can be kept to a minimum, the mineral fertilizer replacement value of the mineral concentrates can be relatively high, as they resemble commercial liquid fertilizers, with nearly all the nutrients in a mineral, plant-available form. However, to avoid gaseous NH_3 losses, this may require prior acidification or injection of the concentrate into the soil (Jensen, 2013). At present, such approaches have significant energy requirements, so the challenge for the future must include improving energy efficiency, with lower energy requirements per kg of recovered nitrogen and other nutrients. As these technologies are still under investigation, the UNECE categories are currently uncertain (for example, category 2-3, pending further assessment).

Nutrient Recovery Measure 5: Ammonia stripping and recovery

263. Air stripping of NH_3 is a process whereby the liquid fraction after manure separation is brought into contact with air, upon which NH_3 evaporates and is carried away by the gas. Instead of ambient air, "'steam stripping" can be used whereby steam replaces air as the ammonia carrier. Since evaporation occurs from the liquid surface, it is advantageous to ensure that the liquid has a large surface area. This can be achieved in a stripping column with structured packing, where it spreads over the packing material in a thin film and therefore has a considerably larger surface. The mass transport also increases with the concentration of NH_3 (aq) in the liquid phase; hence, if pH and/or temperature is increased, an increasing part of total ammoniacal nitrogen is in NH_3 (aq) form and the mass transport of NH_3 increases (Sommer and others, 2013). Altogether, this makes the technology relatively energy demanding and costly, although cheap/free surplus energy from, for example, a biogas- combined heat and power plant may reduce energy costs. Alternatively, using selectively permeable membrane contact systems at lower temperatures may offer a cheaper solution, if membrane fouling can be avoided.

264. Ammonia released from an NH_3 stripping column or from a manure drying facility can be collected using wet scrubbing with an acid solution, typically sulphuric acid, to make ammonium sulfate (which is most common). Application of the approach using nitric acid to make ammonium nitrate has also been reported. Both compounds can serve as raw materials for mineral fertilizers, and thus provide the opportunity for circular economy development as part of the fertilizer industry's commitment to include recovered and recycled N_r. In general, this is a well-known, and generally effective technology. The main barriers are: the relatively low N concentrations achievable in the scrubber-liquid (and thus high logistic costs); and the quality requirements for introduction of the scrubber-liquid into the raw materials market for the fertilizer industry.

Table IV.40: Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Nutrient Recovery Measure 5

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE Category	1[a]	1[a]	1[a]	1[a]	1[a]	1[a]
Magnitude of Effect	↓[a]	↓[a]	↓[a]	↓[a]	↓[a]	↓↓[a]

[a] This can be considered as an enabling measure to reduce overall N_r and N_2 losses, by mobilizing recovery and reuse of available N_r resources. In this way, recovered N_r contributes to replace inorganic fertilizer inputs from newly fixed N, thereby increasing system efficiency and circularity.

F. Best practices and priority measures

265. Best practices and priorities for the selection of abatement/mitigation measures must be based on the following criteria:

(a) Ease with which approaches can be implemented;
(b) Effectiveness;
(c) Impact on environmental emissions;
(d) Secondary effects;
(e) Controllability;
(f) Cost efficiency.

266. Based on these criteria, we suggest the priority measures listed below.

Livestock feeding

267. The following priorities through livestock feeding help to reduce nitrogen losses:

(a) Avoid N surplus from the very beginning of the manure management continuum;

(b) Adjust animal diet to animal performance (in line with existing guidance in the UNECE Ammonia Framework Code, Bittman and others, 2014);

(c) Adapt animal diet to shift N excretion from urine to faecal excreta;

(d) Dairy cattle:

  (i) Reduction of crude protein content in the diet;

  (ii) Adapt diet and dairy production system to site-specific conditions;

  (iii) Increase milk yield with moderate level of concentrates;

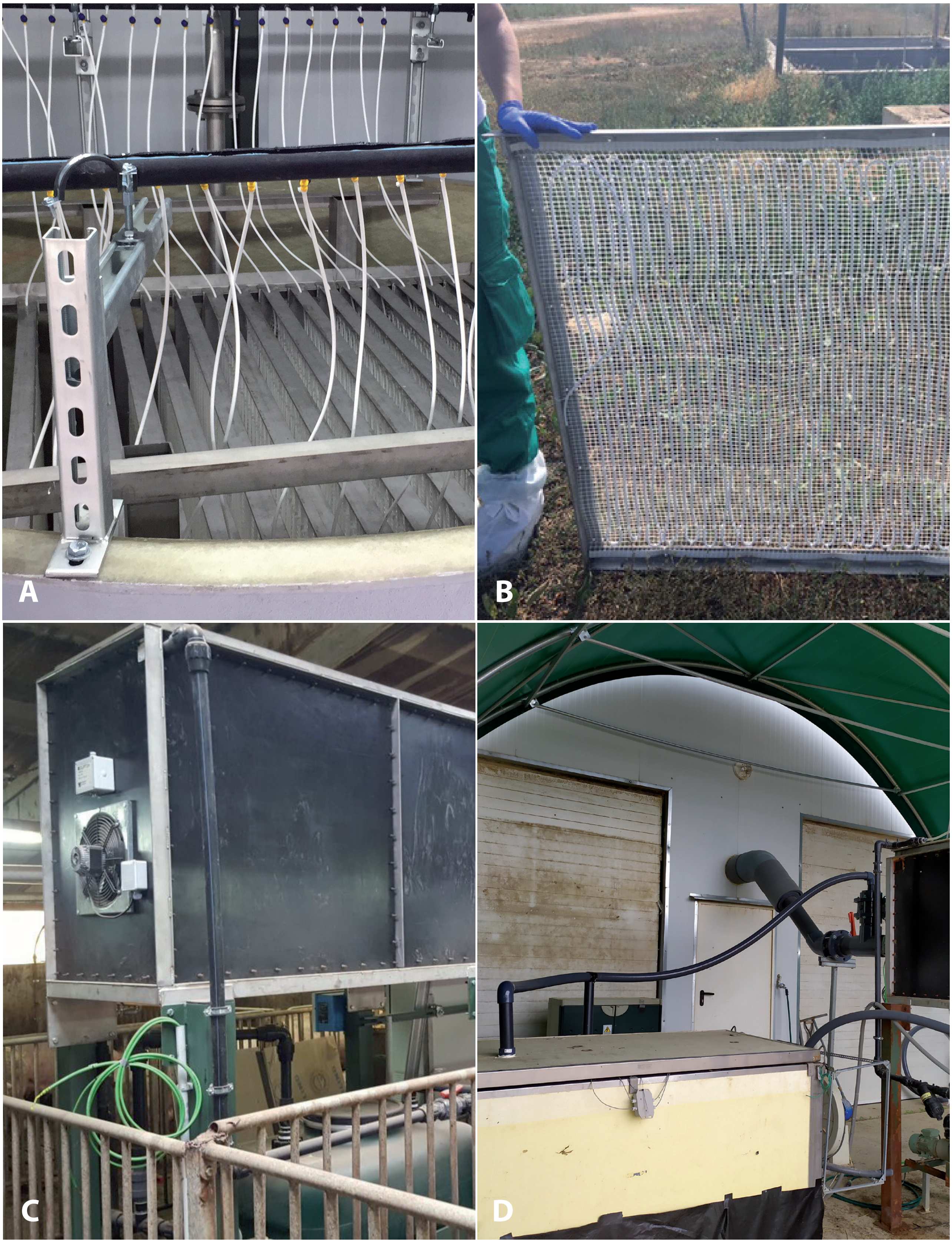


Image 14: Illustration of an ammonia stripping system gas permeable membrane technology (Nutrient Recovery Measure 5). (**A**), Membranes in a slurry tank to trap ammonia from aqueous solution; (**B**), Detail of each membrane frame, thought which dilute sulfuric acid is re-circulated; (**C**), Installation of membranes for gaseous ammonia recovery from a pig house; (**D**), Recovery outside a free-range laying hen building. This system was estimated to recover nitrogen at €2.07 per kg (photographs **A**, **B**: @Itacyl, 2020; photographs **C**, **D**: © UVA, 2020; https://doi.org/10.3390/membranes10100270; ammoniatrapping.com).

    (iv) Increase production cycles per cow.

(e) Pigs:

    (i) Reduction of crude protein content in the diet;

    (ii) Multiphase feeding;

    (iii) More use of food wastes (including from processing and retail) as a way to reduce upstream and downstream emissions.

Livestock housing

268. The following priorities help to reduce nitrogen losses from livestock housing:

(a) Reduction of indoor temperature;

(b) Reduction of emitting surfaces, reduction of soiled areas;

(c) Reduction of air flow over soiled surfaces;

(d) Use of additives (for example, acidification);

(e) Frequent removal of slurry to an outside store;

(f) In the longer term: smart barns with optimized ventilation (open housing) or ventilation air scrubbing (closed housing), immediate segregation of urine and faeces components, in-house acidification of slurry (pigs and cattle).

Manure storage, treatment and processing

269. The following priorities help to reduce nitrogen loses and to mobilize nitrogen recovery and reuse from manure storage, treatment and processing:

(a) Store solid manures outside the barn on a solid concrete base in a dry/covered location;

(b) Ensure tight slurry stores, and cover either by a solid cover, or by ensuring sufficient natural crust formation;

(c) Use manure treatment where relevant to:

    (i) Homogenize nutrient content for more even field spreading to ensure that all available nutrient resources are used effectively for crop growth;

    (ii) Reduce slurry dry matter content, for example, by solid-liquid separation, to enhance soil infiltration and limit NH_3 loss;

    (iii) Increase slurry NH_4^+ content to maximize crop N availability;

    (iv) Lower pH by acidification to reduce NH_3 volatilization and enhance fertilizer value;

    (v) Apply manure treatment methods to enable combined energy and nutrient recovery, for example, anaerobic digestion, where relevant.

270. The use of manure advanced processing for N recapture and production of value-added nutrient products from recycled manure N resources should be focused on situations where other effective options are not available, for example, high-tech separation by filtration, reverse osmosis and NH_3 scrubbing, drying of manure and digestate solids for organic fertilizer production. Ideally, production of recovered, biobased fertilizer products should not be supply driven (trying to solve a waste problem), but rather demand driven (biobased fertilizers that farmers want). However, this implies the need to also address regional manure surpluses that can result from large-scale livestock feeding operations.

G. Conclusions and research questions

271. It is clear that manure management has an impact on quantities of N_r emissions (NH_3, direct and indirect N_2O emissions, NO_x emissions, NO_3^- leaching) and N_2 emissions, as well as emissions of CH_4 and CO_2. This applies at each stage of the manure management continuum (Chadwick and others, 2011). Since production of these gases, as well as of leachable N_r, is of microbial origin, the dry matter (DM) content and temperature of manure and soil are key factors for farm manure management decisions that influence the magnitude of N and greenhouse gas losses. There remains a degree of uncertainty in emission rates of N and greenhouse gases from different stages of manure management, and researchers continue to investigate interactions of the management and environmental factors that control emissions. Some specific approaches to reducing N and greenhouse gas emissions from livestock housing and manure storage include: optimizing diet formulation; low-emission housing technologies; manure processing; and nutrient recovery. The technologies include: air-scrubbers; covered manure storage; slurry separation and anaerobic digestion; nitrogen concentration; and stripping methods.

272. Existing legislation across the UNECE region offers opportunities to find "win–win" scenarios, with benefits in reducing multiple forms of pollution. One example is the European Union Nitrates Directive[22], which has led to development of Nitrate Vulnerable Zone action plans to prevent application of animal manure, slurry and poultry manure (with high available N content) in autumn, a practice that reduces N losses, as well as direct and indirect N_2O losses. Care is needed to ensure that legislation does not lead to potential "pollution swapping" (for example, unadjusted use of slurry injection to reduce NH_3 emissions at the expense of an increase in N_2O emissions, with no modification of N inputs. A core principle (chapter III, principle 6) is that measures that reduce one form of N loss need to be accompanied by either a reduction of fresh nitrogen inputs, or an increase in harvested products, to maintain mass consistency. In this way, what may at first seem a trade-off at the field scale, can be seen at the landscape and regional scales as an opportunity to move towards a more circular system with lower overall N losses.

273. The nature of the N cycle and its interaction with the C, P and other nutrient cycles demands a holistic approach to addressing N and greenhouse gas emissions and mitigation research at a process level of understanding. Systems-based modelling must play a key role in integrating the complexity of management and environmental controls on emissions. Progress has been made to this end (Sommer and others,

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[22] Council Directive of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources, *Official Journal of the European Communities*, L 375 (1991), pp. 1–8.

2009), with some studies producing whole farm models encompassing livestock production (del Prado and others, 2010).

Addressing environmental needs

274. Concepts for best practices to reduce adverse environmental impacts depend on the following integrated concepts:

(a) Relationship between nitrogen and greenhouse gas emissions;

(b) Influence of climate change on nitrogen emissions;

(c) Interaction between abatement/mitigation and adaptation measures;

(d) Interaction between nitrogen emissions and animal welfare;

(e) Integrated assessment of the whole manure management continuum;

(f) Integrated assessment considering the three pillars of sustainability: economy; environment; society;

(g) Interaction between consumer demand and nitrogen emissions;

(h) Development of region-specific concepts for sustainable intensification;

(i) Modelling of livestock production at the regional, national and global scales;

(j) Economic impact of both the cost of the techniques and the benefit to the farmer of reducing emissions and retaining nitrogen as a fertilizer.

275. Concepts to reduce adverse environmental impacts depend on the understanding at a process level of the following:

(a) Assessment of emissions from naturally ventilated barns;

(b) Assessment of emissions from new, animal-friendly housing systems;

(c) Development of abatement/mitigation measures, especially for naturally ventilated dairy barns (for example, targeted ventilation and air-scrubbers, manure acidification);

(d) Interaction between climate change and heat stress/ animal behaviour/emissions;

(e) Interaction between low-protein diets and N and greenhouse gas emissions;

(f) Interactions between N and greenhouse gas emissions during housing, storage and application to field;

(g) Life-cycle assessment: for example, grass-based dairy feeding versus low-protein dairy feeding;

(h) Feed and manure additives for improved N use efficiency;

(i) Manure treatment for higher N use efficiency (increase of nutrient availability, decrease of emissions) and potential of processing to recover manure N into biobased fertilizers in a circular economy.

276. Concepts to reduce adverse environmental impacts depend on the development of flexible concepts for environmental improvement:

(a) Climate and site-specific conditions vary across the UNECE region and globally;

(b) All three columns of sustainability must be considered: economic, environmental and social sustainability;

(c) Conflicts of interest must be addressed;

(d) Targeted approaches should be used according to the needs of different regions.

277. Concepts to reduce adverse environmental impacts depend on effective communication and interaction:

(a) Establishing networks to exchange manure management information, connect people, and forge partnerships;

(b) Launching an online knowledge hub on best practices for livestock housing and manure management;

(c) Establishing a roster of experts to provide targeted technical assistance and training, analysis and practical implementation and policy support, relying heavily on co-financing and in-kind resources from partners;

(d) The development of best practice concepts is challenging. Climate and site-specific conditions are highly variable. It is essential to consider the three columns of sustainability – economy, environment and society – and to address synergies and potential conflicts of interest. This inevitably leads to the conclusion that there will be no "one-size fits all solution". Best-practice concepts provide a basis that offers guidance on the development of flexible measures targeted for each specific region and context.

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