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Executive Body for the Convention on Long-range Transboundary Air Pollution

United Nations Economic Commission for Europe Framework Code for Good Agricultural Practice for Reducing Ammonia Emissions

Summary

At its thirty-third session (Geneva, 8–11 December 2014), the Executive Body to the Convention on Long-range Transboundary Air Pollution adopted the United Nations Economic Commission for Europe Framework Code for Good Agricultural Practice for Reducing Ammonia Emissions (Ammonia Framework Code) and mandated the secretariat to issue its final version in the three official languages of the Commission.

The Ammonia Framework Code contained herein replaces an earlier version of the Code (EB.AIR/WG.5/2001/7) and takes account of the latest scientific knowledge and experience in ammonia abatement, as described in the recent update of the guidance document on preventing and abating ammonia emissions from agricultural sources (ECE/EB.AIR/120). Its purpose is to provide the Convention's Parties with easily understandable information on the good practices that are necessary to reduce ammonia emissions from agricultural sources.

The document is for guidance only, and it is not a prescriptive set of measures for full adoption; alternative and novel measures and technologies can be considered by countries if evidence can be provided. The Ammonia Framework Code is designed to support Parties in establishing or updating their national advisory codes of good agricultural practice to control ammonia emissions, as required by annex IX to the 1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone, and its 2012 amendment.

The document was prepared by the Task Force on Reactive Nitrogen through its Expert Panel on Mitigation of Agricultural Nitrogen.

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I. Nitrogen management, taking account of the whole nitrogen cycle

A. Introduction

1. Nitrogen (N), together with other plant nutrients, is essential for plant growth and sufficient amounts need to be available for plants to achieve optimum crop yields. Nitrogen is readily lost from agriculture through a number of pathways including leaching and run-off of nitrate and organic N to water and gaseous emissions to air. From the perspective of agriculture's role in air pollution, ammonia (NH_3) and the greenhouse gas nitrous oxide (N_2O) are of the most concern. Although this Framework Code is mainly about NH_3 emission, there are interactions between this and other nitrogen transformations, losses and crop uptake which should be considered together. It is, therefore, important to consider the whole N cycle in devising effective strategies for:

(a) Minimizing both water and atmospheric pollution;

(b) Optimizing N use for crop production;

(c) Taking into account the effects of NH_3 abatement on other N losses.

2. Most of the plant-available N in manure or slurry is in the form of ammonium nitrogen, which can substitute directly for mineral fertilizers. NH_3 emissions from organic and inorganic fertilizers represent a loss of valuable N and thus increase the requirement for commercial fertilizers to optimize crop yields. For this reason, the basic obligations and annex IX to the 1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (Gothenburg Protocol) to the Convention on Long-range Transboundary Air Pollution request each Party take due account of the need to reduce NH_3 losses from the whole N cycle. In agriculture, this applies especially in livestock, crop and mixed farming systems. In particular, the Protocol provides guidance to the Parties in identifying the best available options for reducing the release of NH_3 from agriculture in the guidance document on preventing and abating ammonia emissions from agricultural sources (Ammonia Guidance Document) (ECE/EB.AIR/120).

3. NH_3 emissions originate mainly from manures produced by housed livestock as slurries or solid manures and from applied mineral N fertilizers, and to a lesser extent from urine excreted by grazing animals and directly from crops. Emissions from manures occur sequentially from livestock buildings, manure stores and following application to land. Because the losses are sequential, the percentage of savings of NH_3 from measures employed at each production stage are compounded rather than additive. This also means that measures to reduce NH_3 emissions at an early stage (i.e., during housing and storage) should be followed by measures at a later stage (i.e., during manure spreading) to fully profit from the early savings if early savings are not to be lost. In many circumstances, optimized land application of slurry and livestock feeding strategies offer the greatest and most cost-effective opportunities for reducing emissions.

B. Elements of good nitrogen management

4. Nitrogen management varies greatly across the United Nations Economic Commission for Europe (ECE) region, and NH_3 emissions vary accordingly. In general, emissions of nitrogen tend to decrease when:

(a) All nitrogen sources on the farm are managed considering fully the "whole farm" and "whole nitrogen cycle" perspectives;

(b) Amounts of nitrogen used are matched to the needs of growing plants and animals, including considerations of local breeds/varieties, soil conditions, climate, etc.;

(c) As aspects of good husbandry to achieve high production, other limitations to production (such as other nutrient limitations, pests, stress) are minimized to the extent practical;

(d) Nitrogen sources are stored effectively, then used in a timely manner and applied with appropriate techniques, in the appropriate amounts, and in the appropriate places;

(e) All important nitrogen loss pathways are considered in a coherent manner to ensure that measures do not have unintended side effects.

5. All N sources used on the farm should be carefully planned, and the amount of N used should not exceed crop or livestock requirements. All N-loss pathways should be taken into account: for example, conserving NH_3 from land-applied manure may increase leaching if the optimum rate of N for the crop has been exceeded. Application rates and losses may be reduced if N excretion is reduced by better matching feed N to animal requirements. Adopting measures to reduce NH_3 emission following manure and fertilizer application will also directly contribute to better management by conserving N for crop uptake. In countries that limit annual N applications, NH_3 abatement from both manure and fertilizer will also improve crop yields and protein concentration.

C. Aids to optimize nitrogen management

6. Good N management on farms is a challenging task that requires knowledge, technology, experience, planning and monitoring. Tools for predicting optimum fertilizer rates and tools to calculate the N balance and N-use efficiency (NUE) are valuable aids for managing N on farms. While the detailed approaches adopted should be consistent with the size of the farm business concerned, there are suitable actions available for all farm types.

7. Fertilizer recommendations based on soil and crop testing provide indicative values on the nutrient requirements of crops and grassland to safeguard against over-application, which would contribute to emissions. Techniques like fertigation (fertilizer applied in irrigation) may also reduce emissions by potentially reducing application rates. Fertilizer recommendations are calibrated for local conditions and economic considerations and are therefore provided at the national or regional level in most countries. This helps farmers to dose their crops appropriately with manure, other organic amendments and mineral fertilizer to optimize yields and avoid nutrient surplus. However, this technology is still inexact and an active area of research in many countries. On-farm testing can be very helpful.

8. N-balance tools compare N inputs with N outputs. The “N input-output balance” (also referred to as the “farm-gate” balance) is the total, at the farm level, of all nitrogen inputs coming into the farm (fertilizer, feed, bedding, animals, as well as N fixation by legumes and atmospheric N deposition) minus all nitrogen outputs in products (crops, animals products, manure) leaving the farms. The “field balance” is the total of field nitrogen inputs including manure and fertilizer (including N fixations, deposition and irrigation), minus harvested products such as grain, fodder or fruit. In all nitrogen balances, the difference between nitrogen inputs and nitrogen outputs may be positive (surplus) or negative (deficit). An “Nsurplus” is an indicator for pressure on the environment while a deficit indicates nutrient depletion; both are expressed in terms of kilograms (kg) of nitrogen per hectare (ha) per year.

9. The total nitrogen outputs divided by total nitrogen inputs is a measure of NUE (amount of exported nitrogen per nitrogen input, expressed as kg per kg). Note that crop or

animal yield per nitrogen input provides another important measure of NUE. In addition to using this measure, total N losses from agricultural systems must be carefully considered with respect to their impact on the environment.

10. Decreases in nitrogen surplus and increases in NUE over a period of years indicate improvement in nitrogen management. For this purpose, it is recommended that five years represents a suitable evaluation period. Nitrogen management can be improved until a “best management practice” level is approached. Both nitrogen surplus and NUE values can be used to assess farms relative to one another or for comparison with model farms. However, different farm types vary in their characteristic NUE and Nsurpluses. Tools to calculate the nitrogen balance and NUE are available in many countries.

11. A wide range of options to reduce NH_3 emission are presented in the following sections, where the effectiveness is mainly described as a percentage reduction compared with a reference method. In general, while all emission reductions represent helpful contributions, achievement of a 30% reduction in emissions from a component source can be considered as a suitable performance benchmark for good practice. Many methods are available that offer more ambitious reduction opportunities.

II. Livestock feeding strategies

A. Introduction

12. Reducing emissions from feed inputs requires good animal husbandry, such as:

(a) Diet correctly balanced to animal needs;

(b) Good animal health and welfare;

(c) Good management of the animals’ environment;

(d) Good stockmanship skills;

(e) Appropriate genetics.

13. Ensuring that farm livestock are not fed more protein than required for the target level of production can reduce the N excretion per livestock unit and per unit of production. This should include maximizing the fraction of protein in the diet that can be metabolized and minimizing the fraction that cannot be metabolized. Decreasing the amount of N in manure will not only abate NH_3 emissions at all manure stages, but also other potential N losses (leaching, denitrification). N excretion by different livestock categories is strongly dependent on the production system. Hence, standard excretion values should be calculated on a national or regional level.

14. Protein surplus in livestock rations is primarily excreted in the form of urea (or as uric acid in the case of poultry manure). These compounds are rapidly degraded to NH_3 and ammonium that have a high emission potential. Reducing protein in feed will reduce the amount of N in the excreta and the proportion of inorganic N, thereby affecting the total amount of inorganic N excreted (i.e. as total ammoniacal nitrogen in excreta). Since dietary optimization alters the total input to this flow of nitrogen, it offers a promising option for reducing ammonia emission. Furthermore, the consequent emission abatement is effective at all stages of manure management (houses, storage, treatment, application).

15. Even under optimal conditions, animals excrete more than half the protein intake in feed in the form of different N compounds. There are often excesses in the protein supply for almost all livestock classes and production systems, the reduction of which can therefore reduce N excretion.

B. Methods for decreasing nitrogen excretion

16. The following general methods can be used to decrease the amount of N excreted by livestock:

(a) Reducing excesses in the protein supply by ensuring that it does not exceed current feeding recommendations. Table 1 gives indicative target levels for the crude protein (CP) content of the diet of different livestock species and production stages;

(b) Better adjustment of the composition of the diet to the requirements of the individual animal, e.g., according to lactation stage, age and weight of animals, etc.;

(c) Reducing the CP content of the ration by optimization of the amino acid supply. For monogastric animals, the required amino acid supply can be controlled by addition of pure amino acids to the diet or by using a combination of different protein feeds in the diet;

(d) Increasing the NUE by improving animal performance (milk yield, growth rate, feed conversion efficiency, etc.), so that a diminishing proportion of the total protein requirement is used for maintenance.

C. Pigs and poultry

17. For pigs, N excretion can be reduced by matching more accurately the diet to the specific requirements of the different growth and production stages. This can be achieved by:

(a) Ensuring that the protein content of the feed or ration is not higher than the recommended level;

(b) Using different diets for lactating and gestating sows;

(c) Using different diets for different growth stages of fattening pigs (phase feeding).

(d) Considering the within- and between-feed variability of the precaecal (or “ileal”) digestibility of CP and individual amino acids.

18. In addition to the above options, the protein level of pig diets can be lowered without impacting production by optimizing the essential amino acid content rather than the CP content. This can be achieved by adding pure amino acids, especially lysine, methionine and threonine, to the diet. Even though such strategies will result in somewhat higher feed prices, they are some of the cheapest measures to reduce NH_3 emissions.

19. For poultry, the strategies to reduce N excretion are basically the same as for pigs.

D. Ruminants

20. For ruminants, protein surplus and N excretion strongly depend on the proportion of grass, grass silage, hay, grain and concentrates in the ration and the CP content of these feeds. The CP surplus and the resulting N excretion and NH_3 losses will be highest for grass-only summer rations with young, intensively fertilized grass or grass-legume mixtures. In such cases, a ration matched to the energy demand of the animals will always result in a high protein surplus. The following strategies can improve this situation:

(a) Ensuring that N-fertilizer application rate on the grassland is not excessive;

(b) Improving the energy/protein equilibrium by:

(i) Substituting some of the fresh grass with a feed of lesser protein content (maize silage, hay harvested at advanced stages of maturity, straw, etc.);

(ii) Using more mature grass (wider cutting intervals) or rationed amounts of grass and more high-energy concentrates and providing the appropriate amount of rumen-by-pass protein. Nevertheless, for livestock production systems predominantly based on grassland, the feasibility of this strategy is often limited because a full use of the grass production would no longer be guaranteed (under conditions of limited production, e.g., milk quotas) and the nutrient balance of the farms would not be in equilibrium.

21. A reduction of NH_3 emissions from ruminants can also be achieved by increasing the proportion of time that the animals spend grazing. This is because much of the urine infiltrates into the soil before urea is degraded and lost as ammonia. Nevertheless, the total N efficiency of grazing systems tends to be lower than that of cut grassland due the uneven distribution of the excreta. The extent of grazing is typically limited by climatic and soil conditions as well as farm structure. A minimum period of grazing per year may be required in some countries for animal welfare reasons.

22. One strategy for reducing N excretion and losses per unit product is the improvement of the feed conversion efficiency through higher yields. Increasing the number of lactations per cow may also decrease NH_3 emission per unit of milk production over the life of the animal.

23. The conversion of grass and legume N into ruminant protein could be improved by maintaining the quality of CP when making silage for winter feeding. Minimizing degradation of true protein in grass silage can be achieved by:

(a) Ensiling grass as fast as possible after cutting;

(b) Excluding oxygen from the silo quickly after filling;

(c) Avoiding heat damage.

Table 1
Indicative target protein levels (%) of dry feed with a standard dry matter (DM) content of 88% for housed animals as a function of animal category

Species	*Category*	*Production phase*	*Mean CP content of the animal feed*
Cattle	Dairy cows	Early lactation	15–16
	Dairy cows	Late lactation	12–14
	Replacement (heifers)		12–13
	Fattening	Calf (veal production)	17–19
		Beef < 3 months	15–16
		Beef > 6 months	12
Pigs	Piglets	< 10 kg	19–21
		< 25 kg	17–19

Species	*Category*	*Production phase*	*Mean CP content of the animal feed*
	Fattening pigs	25–50 kg	15–17
		50–110 kg	14–15
		110-170 kg	11–12 (with specific amino acids such as lysine and tryptophan)
			13–14 (without specific amino acids)
	Sows	Gestation	13–15
		Lactation	15–17
Poultry	Broilers	Starter	20–22
		Grower	19–21
		Finisher	18–20
	Layers	18–40 weeks	15.5–16.5
		40+ weeks	14.5–15.5
	Turkeys	< 4 weeks	24–27
		5–8 weeks	22–24
		9–12 weeks	19–21
		13+ weeks	16–19
		16+ weeks	14–17

III. Low-emission animal housing systems

A. Introduction

24. Livestock housing, together with the application of manures to land, is one of the largest sources of NH_3 emission from agriculture. For all types of housing, it is necessary to take into account the requirements of animal welfare codes in deciding stocking density, etc. Appropriate husbandry of the farm area can contribute to the reduction of NH_3 emissions and other forms of pollution. The rebuilding of livestock housing systems to meet animal welfare requirements can lead to increased NH_3 emissions (linked to increasing space per animal). Because of the opportunity for cost-sharing, such rebuilding operations provide a key opportunity for introducing low-emission techniques for ammonia, allowing lower costs than retrofitting such technologies. Such an approach may thereby ensure that animal welfare measures do not increase NH_3 emissions.

25. A range of emission abatement methods are available which vary from high to negligible cost and in their applicability to different housing systems.

26. Several general principles should be adhered to for the housing of livestock in order to reduce NH_3 emissions:

(a) Keep all areas (activity, lying, exercise area) inside and outside the animal house dry and clean;

(b) Keep manure surfaces in pits as small as possible (for instance with partly slatted floors, sloped pit walls);

(c) Rapidly separate and remove faeces and urine, which can help reduce ammonia emissions;

(d) Keep air velocity and temperature of air over surfaces that are fouled with excreta as low as possible (without reducing overall ventilation), except where manure is being dried, e.g., by cooling incoming air or, in the case of natural ventilation, considering prevailing wind direction;

(e) Offer the animals functional areas for lying/sitting, feeding, defecating, exercising, (applies to pigs only);

(f) Clean the exhaust air in the case of artificially ventilated buildings.

B. Low-emission systems for cattle buildings

27. The cubicle house is the most common housing system and considered to be the reference. In some countries dairy cattle are still held in tied stalls; however, they are not recommended in consideration of animal welfare and health, unless daily exercise is applied.

28. It is difficult to reduce NH_3 emissions from naturally ventilated buildings that house cattle. Modifying the diet, as outlined in section II, offers some possibilities. Systems for frequently cleaning, by scraping or flushing, may be possible in some buildings. Using water for cleaning reduces emissions, but increases the volume of slurry that needs to be stored and managed. There is some ongoing research on the possibilities to reduce emissions from naturally ventilated buildings by reducing the air velocity over emitting surfaces (through changes in the openings, application of wind shielding nets, etc.) without affecting overall ventilation, but this work is just starting and no recommendations are available so far.

29. In houses with traditional slats, optimal barn climatization with roof insulation and/or automatically controlled natural ventilation can achieve a moderate emission reduction (20% compared with a conventional system), due to the decreased temperature (especially in summer) and reduced air velocities.

30. For loose-housed cattle bedded on straw, increasing the amount of straw used per animal can reduce NH_3 emissions from the building and during manure storage. The appropriate amount of straw depends on breed, feeding system, housing system and climate conditions.

31. There is no evidence of significantly higher losses from houses with well-managed straw systems compared with slurry systems, provided that the floor space per animal is similar. More research is needed on relative emissions between these systems. Management of straw systems takes more effort than slurry-based systems.

32. The following approaches can be used to reduce NH_3 emissions from dairy and beef cattle housing, but may need further assessments as indicated below:

(a) Good husbandry, e.g., keeping passageways and yards used by cattle as clean as possible, can contribute to lower NH_3 emissions on most farms;

(b) 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. An NH_3 emission reduction of 25% to over 40% can be achieved relative to a conventional system, so long as the frequency of the scraping is sufficiently regular;

(c) Adding acid to the flushing water can significantly reduce NH_3 emissions from buildings. Further assessment is necessary.

C. Slurry-based pig buildings

33. For slatted floor systems, the following techniques can contribute to emission abatement:

(a) *Reduce the surface area of the slatted area*, e.g., by using partially slatted floors. Slat design should facilitate maximum transfer of dung and urine to the channels. Solid floor areas should have provisions (e.g., a slight slope) for urine to drain to the channels. Channels should be emptied frequently to a suitable store outside the house. This can be achieved by the use of scrapers or of a vacuum system, by flushing with water, untreated liquid manure (under 5% DM) or separated slurry. Partly slatted floors covering 50% of floor area generally emit 15%–20% less NH_3 than fully slatted floors, particularly if the slats are less sticky for manure than concrete (e.g., metal or plastic-coated slats);

(b) *Reduce the exposed surface of the slurry beneath the slats*, e.g., by constructing channels with inwardly sloping walls so that the channel is narrower at the bottom than at the top. The walls should be made of a smooth material to avoid manure sticking to them. 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%–65%, depending on 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. For lactating sows, emission reduction of up to 65% can be achieved by reducing the emitting area by means of constructing a pan under the slatted floor of the pen. The pan is a sloped subfloor (at least 3°) with manure drainage at the lowest point;

(c) *Lower slurry temperature*. For existing houses, the temperature of the slurry in the channels can be lowered by pumping a coolant (e.g., groundwater) through a series of fins floating on the slurry (recycling groundwater may not be permitted in some countries or regions). Surface cooling of manure with fins using a closed heat-exchange system can reduce emissions by 45%–75% depending on animal category. This technique is most economical if the collected heat can be exchanged to warm other facilities, such as weaner houses;

(d) *Acidifying slurry*. NH_3 emission reduction can be achieved by acidifying the slurry to shift the chemical balance from NH_3 to NH_4^+. The manure (especially the liquid fraction) is collected into a tank with acidified liquid (usually sulphuric acid, but organic acids can be used as well) maintaining a pH of less than 6. In piglet housing an emission reduction of 60% has been observed. However, the use of chemicals in housing must not be carried out unless it is fully compliant with all health and safety regulations;

(e) *Improve animal behaviour and design of pens*. Animal behaviour may be improved by offering pigs functional areas for different activities. For example, pens with partially slatted floors should be designed so that pigs can distinguish separate functional areas for lying, eating, dunging and exercising. The aim is to keep the solid part of the floor as free from dung and urine as possible to reduce NH_3 emissions. This can be done by using the nature of the pig to avoid dunging in eating and lying areas by optimizing pen layout and climatic control. For example, longer narrow pens with feeders in the front of the pen and drinkers at the back above the slatted part of the floor can avoid dunging on the solid floor. High room temperatures encourage pigs to lie down on the slatted portion of the floor (the dunging area) rather than on the solid area. This can lead to a dirty solid floor area and an increase in emissions that make it necessary to take additional steps to achieve good abatement (e.g., improved ventilation, controlling the temperature of the solid floor to encourage pigs to lie on it or installation of automatic sprinklers for cooling during hot summer periods). Detailed design and management will vary from country to country and from region to region. In general it is more difficult to control the behaviour of the pigs in warmer climates;

(f) *Avoid ventilation directly above the surface of the slurry in the channels*. The higher air velocity will increase NH_3 emission from the manure surface. In pig houses where this is unavoidable, the gap between the slats and the manure surface should be sufficiently large to minimize air velocity;

(g) *Clean the air from NH_3 with acid scrubbers or biotrickling filters*. Although more expensive, such scrubbing approaches offer the highest potential (reduction of 70%–90%) for mitigation of artificially ventilated buildings and may be considered appropriate where there is a strong national, regional or local imperative to reduce NH_3 emissions (e.g., in the European Union when in the vicinity of an adversely affected Special Area of Conservation).

34. In principle, many of the methods for reducing NH_3 emissions from slurry-based pig buildings could also be applied to slurry-based cattle houses. Although these are generally naturally ventilated, preventing the easy application of scrubbers to clean exhaust air, strategies to reduce exposed surfaces, lower slurry temperature, acidify slurry and minimize ventilation over the slurry surface are all applicable.

D. Straw-based pig systems

35. In straw-based pig systems, use fresh, clean, dry and hygienic bedding material. There should be sufficient bedding material to allow complete adsorption of urine. Changing bedding frequently helps absorb urine. If complete adsorption of urine is not possible, sloped floors and gutters should allow rapid drainage and removal of urine. Leakages of drinking systems should be avoided at any time in order to avoid additional moistening of the bedding.

36. Straw-based systems are better for animal welfare than slurry-based systems. There is no evidence of significantly higher losses from houses with well-managed straw systems than those with slurry, provided that the floor space per animal is similar. For animal welfare and environmental reasons, systems should be used where the pigs differentiate a lying and a dunging area. This is according to the pigs’ natural behaviour and at the same time reduces emissions. Management of straw systems takes more effort than slurry-based systems.

37. Kennel houses combine free ventilation systems and the realization of functional areas. NH_3 emissions may be reduced by 20%. More space is needed compared with forced ventilated buildings. Building costs are similar.

E. Low-emission systems for poultry buildings

38. NH_3 emissions are minimal when the DM content of poultry manure or litter is 60% or above. Under these conditions insufficient moisture is available to allow the breakdown of uric acid to liberate ammonia. This means that further drying will not increase NH_3 emissions. By contrast, drying of poultry manure that has already become wet, and in which

uric acid breakdown has already occurred, will lead to increased NH_3 emissions. For poultry litter and manure, abatement techniques should therefore aim to increase the DM content by preventing spillage of water and, in new buildings, by providing a drying mechanism that maintains litter DM content above 60%.

39. In buildings for laying hens, NH_3 emissions from battery deep-pit or channel systems can be lowered by reducing the moisture content of the manure by ventilating the manure pit. Other emission abatement options for laying-hen buildings include:

(a) *Belt systems in cage housing systems (cage battery, enriched cage)*: The collection of manure on belts and the subsequent removal of manure to covered storage outside the building can reduce NH_3 emissions, particularly if the manure has been dried on the belts through forced ventilation. Manure collected from the belts into intensively ventilated drying tunnels, inside or outside the building, can reach 60%–80% DM content in less than 48 hours. Belt drying would be expected to prevent substantial hydrolysis, but heating up manure that is only infrequently removed, and allowed to become wet, should be avoided. An increase of the removal frequency from once per week to two or three times per week reduces NH_3 emissions;

(b) *Aviary systems (non-cage housing system) with manure belts* for frequent collection and removal of manure to closed storages reduce emission by more than 70% compared with a deep-litter housing system.

40. Exhaust air from poultry houses can be cleaned of NH_3 with acid scrubbers or biotrickling filters (with a reduction efficiency of 70%–90%). Because air from poultry barns contains much large dust particles that can clog the scrubber, a multistage scrubber is recommended which removes the large particles in the first stage. Such multistage scrubbers offer co-benefits in reducing NH_3 and other particulate matter emission, which also contains substantial amounts of phosphorus and other elements, allowing these to be recycled as plant nutrients.

41. In broiler and turkey buildings the quality of the litter is the main factor affecting NH_3 emissions, as in other poultry systems, since this affects the extent of uric acid breakdown. In new buildings, ventilation systems should be designed to remove moisture under all weather and seasonal conditions and the house should be well insulated. In new and existing houses measures to avoid condensation (insulation) should be taken and nipple-type drinkers, which are less prone to spillage, should be provided for broilers.

IV. Low-emission manure storage systems

A. Introduction

42. NH_3 losses from buildings and after spreading livestock manures are usually the most important emission sources; however, losses from stored slurries and solid manures can also make a significant contribution to the total emission of ammonia. Storage enables manures to be spread onto land at times of the year when there is a crop nutrient requirement and the risk of water pollution is low.

B. Storage of slurry and other liquid manures

43. After removal from livestock buildings, slurry is stored either in concrete, steel or wooden tanks (or silos), in lagoons or in bags. Lagoons have a larger area per unit volume and thus a greater potential for NH_3 emissions. There may be national or regional regulations controlling the design, construction and management of manure stores.

44. Techniques for reducing NH_3 emissions from manure stores include:

(a) *Design of the store*:

(i) *Size*: The store should be of sufficient size to avoid spreading on land at times of the year when there is a risk of water pollution (e.g., through nitrate leaching) and to allow application at the best time with regard to crop nitrogen demand;

(ii) *Surface area*: Reduce the surface area (or emitting surface) of the store. For example, the surface area of a 1,000-cubic-metre (m^3) slurry store can be reduced by more than one third if the height of the sides is increased by 2 metres, from 3 to 5 metres. Generally, for practical (mixing, reducing required volume for precipitation) and abatement reasons, the height of the store should be at least 3 metres where feasible;

(b) *Covers for slurry tanks or silos:* Covers on slurry stores are an effective means of reducing NH_3 emissions. The options for covering tanks or silos are summarized in table 2. They include:

(i) *Solid covers*: These are the most effective for reducing NH_3 emissions, but also the most expensive. While it is important to guarantee that covers are well sealed to minimize air exchange, there need to be small openings or a facility for venting to prevent the accumulation of inflammable methane (CH_4) gas, especially with tent structures. In areas with heavy rainfall solid covers have the advantage of preventing rain from entering the store and thus avoid an increase in transport volume from rainwater;

(ii) *Floating covers*: These are usually made from plastic sheets and are less effective than roofs, and also usually less expensive. Double sheets with shrink-wrapped polystyrene are often used to avoid gas bubbles and sinking of parts of the sheet. The floating cover should be fixed to vertical ropes fastened to the store wall. This prevents the cover from turning during manure mixing and being lifted off by wind. Some floating covers also exclude rainfall from the store and so increase the volume of slurry that can be stored;

(iii) *Floating geometrical plastic bodies*: Floating geometrical plastic bodies form a closed floating cover on the slurry surface. The vertical ribs in the bodies prevent the elements from being pushed one on top of the other. They may be used only in pig slurry or other liquid manures without natural crust. They are not suitable for slurries rich in organic matter, because they will become part of a crust which will be difficult to break;

(iv) *Natural crusts*: Cattle slurries and in some cases also pig slurries normally build up a natural crust of floating organic materials. The crust will only form if the DM is high enough (> 7%) and stirring can be minimized. The crust should cover the whole of the surface area of the manure. The store should be filled from below the crust to avoid breaking it up. Efficiency of crusts depends on how fully they cover the manure surface, which depends on their thickness, completeness and duration. Note that time is needed for crust formation;

(v) *Floating crusts*: The introduction of straw, granulates or other floating material on the slurry surface in tanks or lagoons can reduce emissions by creating an artificial crust:

a. *Clay granulates*: The introduction of granulates can be done very easily. It is more expensive than straw, but only about one third as costly as compared with a tent structure. About 10% of the material is usually lost yearly from emptying the store. Agitating one day before spreading and briefly just beforehand can help to reduce losses;

b. *Straw:* The most effective way is to use a self-propelled field chopper (forage harvester) to introduce chopped straw of about 4 cm in length. About 4 kg straw/m^2 should be blown into either the emptied or the filled tank by a well-instructed and experienced driver. Straw covers are likely to increase CH_4 and N_2O emissions because of the increased carbon added. The slurry DM is also increased which as a consequence raises NH_3 emissions after slurry application.

45. The use of oil and peat is not recommended because of practical difficulties in their use and the lack of experience under farm conditions and because it is likely to lead to a strong increase in CH_4 emissions.

46. It is more difficult to reduce NH_3 emissions from lagoons than from tanks. The replacement of existing lagoons with tanks can be considered to be an abatement technique. The construction of new lagoons should be discouraged in favour of tanks or other low-emission solutions (see below) unless effective mitigation methods for reducing emissions can be implemented and validated. There are technologies, including floating booms, that partition the surface and may facilitate the use of floating covers, such as clay granulates and straw, and the formation of crusts in large lagoons even under windy conditions.

47. Storage bags are suitable for reducing emissions from slurry. Interest in this approach is growing because such systems can be implemented at significantly lower cost than building an elevated slurry store with a solid roof. There may, however, be a risk of water pollution if not correctly maintained and this technique may not be suitable for large volumes or for slurry with a high DM concentration.

Table 2
Effectiveness and applicability of ammonia abatement techniques for slurry stores

Abatement measure	*Livestock class*	*Emission reduction (%)*	*Applicability*	*Remarks*
Rigid lid or roof	All	80	Tanks and silos only	No additional capacity for rainwater needed; limitation through static requirements
Flexible cover (e.g., tent structure)	All	80	Tanks and silos only	Limitation through static requirements
Floating foil	All	60		—
Floating plastic bodies	All	circa 60	Not on crusting manures	Further data on emission reduction needed
Natural crust	Cattle, pig slurries with more than 7% DM	40	Not on farms with frequent spreading	—
Artificial crusts: straw	Pig and cattle slurry	40	Not practicable on thin liquid manures, or on farms with frequent spreading	May lead to increased N_2O and CH_4 emissions

Abatement measure	*Livestock class*	*Emission reduction (%)*	*Applicability*	*Remarks*
Artificial crusts: clay granulates, etc.	Pig slurry, liquid manures	60	Also on thin liquid manures; not on farms with frequent spreading	Loss of some of the clay granulate material through pumping
Replacement of lagoons with covered/open tanks	All	30–60	—	The reference in this situation reflects the higher emission rate from open lagoons.
Storage bag	All	100	Applicability is rapidly increasing as experience increases	Most experience so far with small pig farms, but has also been used in larger dairy farms.

48. Further aspects to consider:

(a) Frequent mixing and emptying should be avoided wherever possible because these operations increase NH_3 emissions. However, mixing and removal of slurry for spreading is likely to be more frequent on grass than on arable farms to ensure effective utilization of the slurry;

(b) Reduction in the air velocity on the slurry surface can be achieved by a sufficiently high freeboard and by planting a tree shelterbelt;

(c) Both below-ground tanks outdoors and shadowing of stores may reduce the temperature of the slurry in the storage tank and thus result in a significant reduction of NH_3 (and CH_4) emissions.

Storage of solid manure

49. At present there are few options for reducing NH_3 emissions from stored solid manures. Clear good-practice guidelines nevertheless apply. After removal from animal houses, solid manure may be stacked on a concrete area, sometimes with walls, usually with drainage and a pit for collecting leachate. In some countries, it is permitted to store manure in stacks on the soil in fields — at least over a limited period. However this can lead to significant losses through NH_3 emissions, denitrification and leaching. Litter and manure from poultry, especially air-dried dung from laying hens, is increasingly stored in bunkers. Management guidelines for limiting NH_3 emissions are as follows:

(a) *Cover solid manure stores*. While the use of solid covers may not always be practical, the use of plastic sheeting has been shown to reduce NH_3 emissions substantially without significantly increasing CH_4 or N_2O emissions. As with reduced emission storage of slurry, it is important that covered storage of solid manure is followed by low-emission spreading techniques (i.e., immediate incorporation), otherwise the nitrogen savings may be lost at this later stage;

(b) *Add an increased amount of straw to the manure*. This approach can be considered as less effective than covering solid manure, with variable performance depending on the type of manure, conditions and possible increase in N_2O and CH_4 emissions;

(c) *Make the surface area of the stack as small as possible* (e.g., by constructing walls to increase the height). This approach can also be considered as less effective than covering manure;

(d) *Keep the manure as dry as possible*. This is particularly important for poultry litter (broilers and laying hens) and belt-dried poultry manure, where the availability of moisture allows uric acid to break down to produce ammonia. Measures to keep poultry manure dry include:

(i) Covering with a sheet;

(ii) Storing under a roof, preferably on a concrete base;

(iii) If it is not possible to cover poultry manure, storage in narrow, A-shaped heaps may help shed water more readily, although the extent of benefits from this approach remain poorly quantified.

50. Air-dried laying-hen excreta collected on manure belts that have a DM content of at least 60% to 70% emit very little ammonia. These manures should be kept dry and prevented from remoistening. Therefore storing under a roof is the most appropriate option.

51. Excreta from deep-pit battery-laying hen houses, which are often stored for a year beneath the surface of the house, emit high rates of NH_3 due to their low DM content (i.e., high moisture content). To reduce NH_3 emission, the DM content may be increased by passing exhaust air from the building over the manure heap.

52. Other techniques include maintaining the temperature of the heap below $50^{o}C$ or increasing the C:N ratio to > 25, e.g., by increasing the amount of straw or other bedding material used.

53. It is essential to take national or regional regulations concerning the avoidance of water pollution into account if locating manure stacks directly on the soil in fields, given the significant risks of leaching and run-off associated with this practice.

V. Low-emission manure spreading techniques

A. Introduction

54. NH_3 emissions from the application of manures (slurries and solid manures such as farmyard manure and broiler litter) account for a large proportion of NH_3 emissions from agriculture. It is very important to minimize losses at this stage of management because any NH_3 saved earlier, from livestock housing or manure storage, might be lost if it is not controlled by an appropriate field application technique. Reducing NH_3 loss means that more nitrogen is potentially available for crop uptake. To gain the maximum agronomic benefit from manures, and to avoid increasing the risk of nitrate leaching, attention should be paid to the N content of the manure so that the rate, method and time of application is matched to crop requirements, taking account of the amount of N saved when using low-emission practices.

55. The techniques summarized below reduce emissions of NH_3 by reducing exposure of the manure to the atmosphere. Hence the methods are effective for all climates. Although absolute NH_3 emissions will be influenced by climate, tending to increase with increasing temperature, the proportion of the NH_3 emission abated by reduced-emission techniques has not been found to depend on climate. Emission reductions are shown in table 3.

B. Reduced-emission techniques for slurries and other liquid manures

56. The most effective means of reducing NH_3 emissions from slurry application is to employ an appropriate application technique such as an injector or band spreader. Such approaches also have the agronomic benefit of a more consistent application of slurry, with a more precise placement that can reduce the risk of slurry run-off (see box).

Slurry application techniques: injectors and band spreaders

Injectors: These reduce NH_3 emissions by placing the manure beneath the soil surface, thus decreasing the manure surface area exposed to the air and increasing infiltration into the soil. They are generally more effective for reduction of NH_3 emission than band spreaders. There are three types:

(a) *Shallow (or slot) injectors*: these cut narrow slots (typically 4–6 centimetres (cm) deep and 25–30 cm apart) in the soil that are filled with slurry or liquid manure. They are most commonly used on grassland. Different abatement results are achieved depending on whether open- or closed-slot injectors are used. Application volumes may be limited by the volume of the slots;

(b) *Deep injectors*: these apply slurry or liquid manure to a depth of 10–30 cm in the soil using injector tines spaced about 50 cm or even 75 cm apart. The tines are often fitted with lateral wings to aid dispersion in the soil and to achieve high application rates. They are most suited for use on arable land because of the risk of mechanical damage to grass swards;

(c) *Arable injectors*: these are based on spring or rigid-tine cultivators and are for use on arable land only.

Band spreaders: These reduce emissions of NH_3 from slurries and liquid manures through decreasing the manure surface area exposed to the air and decreasing exposure to the air flow over it. The efficiency of these machines can vary depending on the height of the crop. There are two main types of machine:

(a) *Trailing hoses*: slurry is discharged at ground level to grass or arable land through a series of flexible hoses. Application between the rows of a growing arable crop is feasible;

(b) *Trailing shoes (or feet)*: slurry is normally discharged through rigid pipes which terminate in metal "shoes" designed to ride along the soil surface, parting the crop so that slurry is applied directly to the soil surface and below the crop canopy. Some types of trailing shoes are designed to cut a shallow slit in the soil to aid infiltration.

Rapid incorporation

57. The aim should be to incorporate slurry into the soil as rapidly as possible after spreading on the surface. The most effective abatement is achieved by incorporation immediately after spreading (i.e., within a few minutes) achieving a 70%–90% reduction. Incorporation within 4 hours is estimated to achieve 45%–65% reduction, while incorporation within 24 hours is estimated to achieve 30% reduction. Completely burying the slurry by ploughing is a slow operation and, in many cases, the use of a tine or disc cultivator may be as effective because the slurry will remain exposed on the surface for a

shorter time before being well mixed with the soil by cultivation. The use of contractors or equipment sharing can be useful to help achieve rapid incorporation. Incorporation of solid manures is discussed below.

Dilution of slurry

58. NH_3 emissions from dilute slurry with low DM content are generally less than for undiluted slurry because of faster infiltration into the soil. Two options are available:

(a) Slurry can be added to irrigation water to be applied onto grassland or growing crops on arable land. This is best done by injecting slurry into the irrigation water pipeline and pumping under low pressure to the sprinkler or travelling irrigator (not under high pressure to a big gun which sprays the mix onto land). Dilution rates may be up to 50:1 water:slurry, but at least 1:1, resulting in an estimated emission reduction of 30% (ECE/EB.AIR/120, para. 146 and figure 1).

(b) Water can be added to viscous slurries before application, either in the slurry store or in the tank wagon. For viscous cattle slurries even dilution rates of 0.5:1 water:slurry can contribute to loss reduction. However, the extra costs for the transportation of water are considerable and it is important that the slurry application rate is increased proportionally to the reduction of the total ammonia nitrogen (TAN) content.

Application timing management systems

59. The following techniques that take into account external conditions, or the timing of application, can also help to reduce NH_3 emissions from slurry application, although they may not be as effective or reliable as those outlined above:

(a) Spreading under cool, windless and humid conditions will help to reduce NH_3 emissions;

(b) Application shortly before rainfall (only effective if at least 10 millimetres (mm) of rainfall occurs immediately after spreading). This measure is only applicable on flat land and away from surface waterways, otherwise there will be a risk of run-off;

(c) Spreading in the evening, when wind speed and air temperature are decreasing;

(d) Spreading on freshly cultivated soils, provided that there is more rapid manure infiltration.

Acidification of slurry

60. Low pH reduces loss of NH_3 from manure. Lowering the pH of slurries to a stable level of 6 or less is commonly sufficient to reduce NH_3 emission by 50% or more. This can be achieved by adding sulphuric acid to slurry. A technique which automatically doses sulphuric acid during the application of slurry is now being successfully marketed. When adding sulphuric acid to manure at any stage of the farm operation, it is necessary to do this safely to avoid any risk to workers, animals and the environment.

Other additives

61. The use of other additives to slurry, apart from acids, has either not proven to be effective in reducing NH_3 emissions or presents practical problems limiting their use.

C. Reduced-emission techniques for solid manures

62. Rapid incorporation into the soil is the only practical technique for reducing NH_3 emissions from solid manure, although recently there has been some success in the United States of America with slot injectors for poultry litter. Most of the NH_3 is released from solid manure within a few hours of spreading. It is recommended, therefore, that incorporation should take place within a few hours after spreading. The manure should be completely mixed with soil or buried for maximum abatement and it is often more difficult to achieve this with some solid manures (e.g., those containing large amounts of straw) than with slurries.

63. Reductions of 60%–90% of NH_3 emissions can be achieved when solid manures are incorporated into arable land by plough within 4 hours of application. By comparison, incorporating within 24 hours is estimated to achieve about 30% emission reduction. In contrast to slurry, studies have shown that incorporation of solid manures by plough is always more effective than incorporation by disc or tine, despite the slower work rate of ploughing.

D. Practical considerations

64. Effectiveness in reducing emissions, applicability and costs should be taken into account in selecting the most suitable techniques for reducing NH_3 emissions. Guidance on the effectiveness and applicability of the different methods is given in table 3. The reduction of NH_3 emissions is expressed as a percentage of the reference method. The reference for a manure application method is defined as the NH_3 emission from untreated slurry or solid manure spread over the whole soil surface (“broadcast”). For slurry, this would be with a tanker equipped with a discharge nozzle and splash plate. For solid manure, the method would be to leave the manure on the soil surface for a week or more.

65. The following considerations are relevant in working to reduce NH_3 emissions from manure spreading:

(a) The amount of abatement achieved with band spreaders and injectors will vary with the DM content of the slurry, soil properties, neatness of work and crop characteristics;

(b) The effectiveness of incorporation varies with the type of manure and the time since spreading; immediate incorporation is most effective;

(c) Band spreaders (trailing hoses) are, in general, more effective on arable than on grassland and when used with dilute pig slurries than with more viscous cattle slurries;

(d) Band spreaders and open slot injectors are not always suitable for use on steeply sloping land due to run-off potential. Slurry application to such land should be avoided to minimize the risk of run-off. Sub-surface injection techniques do not work well on very stony or compacted soils;

(e) Open-slot injectors are more applicable to a wider range of soil types and conditions than closed-slot machines;

(f) Small, irregularly shaped fields present difficulties for large machines; low-emission equipment should be chosen that is most suitable to local terrain;

(g) Incorporation is restricted to land that is cultivated; on grassland, band spreading and injection methods are most appropriate;

(h) Systems that improve the logistics of spreading manure may have a bearing on emissions by allowing more timely application. For example, umbilical systems, where the applicator is mounted directly on the tractor and fed from a tank or pipe via a long flexible hose, offer an alternative to mounting the applicator on a tractor-drawn tanker or tanker truck. They have the advantage of allowing greater work rates and lessening the risk of soil damage by compaction on wet soils. However, it is time consuming to roll out hoses and roll them back in again;

(i) Dilution in irrigation systems is limited to situations where irrigation is practiced, in which case this can be a very effective measure for abating NH_3 emissions;

(j) Diluting slurry in mobile systems is only practical on small farms, since additional water to be spread reduces the spreading performance and increases spreading costs;

(k) Capital and operating costs for reduced emission systems are likely to be more than for broadcast spreading techniques, but savings of mineral nitrogen fertilizer can more than compensate these extra costs when the most effective options are used;

(l) Solid-liquid separation may be helpful in managing manure nutrients. Applying the liquid fraction from an efficient separating machine can give a significant reduction in NH_3 emissions of 20%–30%, due to more rapid infiltration associated with lower DM content. To achieve the benefit of this approach, the liquid fraction should as far as possible be applied under soil conditions that support infiltration (e.g., not saturated or very compacted). If no action is taken, emissions from the solid fraction will be larger (due to higher DM content, which limits infiltration into the soil). Emissions from the solid fraction should therefore be reduced during storage and during spreading (i.e., by rapid incorporation into the soil), or the solid fraction should be applied for other uses (e.g., anaerobic digestion);

(m) Overall there is little difference in emissions after application of raw manure and the liquid digestate remaining after anaerobic digestion. While digestate has a low DM content allowing it to infiltrate quickly on application to well-draining soils, it also has a high pH, making it liable to high NH_3 emissions. As with raw manure, low-emission techniques should be used (e.g., injection, band spreading or acidification);

(n) The working width is limited for injectors, while band-spreading methods offer a much wider working width. Because of the narrower working width, an increased amount of damage from the wheels should be considered when using manure injector systems;

(o) If manure is acidified, this is normally done by mixing concentrated sulphuric acid into the slurry prior to or during application. However, sulphuric acid is a dangerous chemical, and it is therefore necessary to handle it with care in order to avoid risk to workers, animals and the environment.

Table 3
Practical considerations in the selection of ammonia abatement techniques for land spreading of manures

Abatement technique	*Manure type*	*Land use*	*Typical reduction in ammonia emission (%)*[a]	*Restriction on applicability*
Trailing hoses	Slurry and other liquid manure	Grassland and arable land	30–35	Field slope, size and shape. Not highly viscous slurry. Width of tramlines for growing cereal crops. On arable land, emission reduction increases with crop height.
Trailing shoe	Slurry and liquid manure	Grassland and arable land (pre-seeding) and row crops	30–60	As above. Not usually suitable for use in arable crops but may be suitable for rosette stage of row crops.
Shallow injection	Slurry and liquid manure	Grassland and arable land. Also on growing cereals	Open slot, 70; closed slot, 80 at 10-cm depth	As above. Not for very dry, stony or very compacted soils
Deep injection (including arable injectors)	Slurry and liquid manure	Arable land	90	As above. Needs high powered tractor. Not suitable on shallow soils, high clay soils (> 35%) in very dry conditions, on peat soils (> 25% organic matter content) and perforated-tile drained soils that are susceptible to leaching.
Active dilution of slurry for use in water irrigation systems	Slurry	Arable land and grassland	50% dilution (i.e., 1 slurry:1 water) = 30% reduction	Only where irrigation is practised. Only for low-pressure irrigation systems.
Dilution before spreading with mobile spreading systems	Particularly viscous cattle slurry	Arable land and grassland	Up to 50 for viscous cattle slurries (50% dilution = 30% reduction)	Extra volume needed to be spread. Only for small farms and for irrigation. Dose should be increased proportionally to the reduction of the TAN content.
Application timing management systems	All manure types	Arable land and grassland	Variable	This technique requires local validation

Abatement technique	*Manure type*	*Land use*	*Typical reduction in ammonia emission (%)[a]*	*Restriction on applicability*
Incorporation into soil	Slurry	Arable land, including new grass leys, seedings. Only effective, if incorporation occurs right after application.	Immediate ploughing = 90; immediate non-inversion cultivation = 70; incorporation within 4 hours = 45–65; incorporation within 24 hours = 30	Land that is cultivated.
Incorporation into soil	Solid manure	Arable land, including grass leys. Only effective if incorporation occurs right after application	Immediate ploughing = 90; immediate non-inversion cultivation = 60; incorporation within 4 hours = 45–65; incorporation within 12 hours = 50; incorporation within 24 hours = 30	Land that is cultivated.

[a] Relative to reference system, see para. 64.

VI. Limiting ammonia emissions from the use of mineral fertilizers

A. Introduction

66. Most NH_3 comes from livestock manures and slurries, but in many temperate countries around 10% or more is emitted following nitrogen fertilizer application, when large areas are used for crops. Losses from ammonium nitrate (NH_4NO_3) are usually small, typically in the range 0.5%–5% of the total nitrogen applied. Losses from other N fertilizers, e.g., ammonium phosphate, ammonium sulphate, urea and urea ammonium-N may be much greater, in the range 5%–40%, depending on conditions.

67. Favourable conditions for the efficient absorption of ammonium ions in the soil include: (a) when fertilizer is incorporated into the soil; (b) when the soil has a high absorption capacity; (c) when the soil is sufficiently moist; (d) when the soil has a low pH; and (v) when the temperature is low.

B. Urea

68. To be useful as a fertilizer, urea needs to be broken down by the naturally occurring enzyme urease. NH_3 and carbon dioxide are released during this process. If this happens on the soil surface, then NH_3 (and carbon dioxide) will be lost to the atmosphere. If the breakdown does not take place until the urea has been mixed into the soil then the NH_3 can be captured by clay and organic matter in the soil, or form more stable compounds. Urea application thus needs to be well managed to maximize its effectiveness as a fertilizer and to reduce the likelihood of NH_3 emission. It is, therefore, important that urea is mixed or washed into the soil before it begins to break down.

69. NH_3 losses from urea application are often greatest on light, sandy soils due to their low clay content and limited capacity to absorb ammonium-N. Despite their high pH, losses on chalk soils may be less than on some other soil types because of their greater clay and calcium content and their capacity to retain ammonium-N. Hydrolysis of urea placed in bands tends to cause a local increase in pH and can lead to high emissions unless the urea bands are injected or well incorporated into the soil, which will trap the volatilized ammonia.

70. In dry periods, NH_3 losses may be greater from urea applied to grassland than to arable crops.

71. NH_3 emissions from aqueous solutions containing urea are similar to those from solid formulations. The amount of water applied in solution fertilizers is very small and not usually enough to wash the urea into the soil. However, absolute losses may be less if the application rates are significantly smaller.

72. Foliar sprays of urea can increase the grain-protein concentration of milling wheat and other cereals, but can result in high emissions of ammonia.

C. Reducing ammonia emissions from urea

73. To minimize NH_3 emissions from urea fertilizers, the following guidelines should be adhered to:

(a) *Incorporate the urea into the soil*. Quickly mix urea into the soil wherever possible. This option reduces emissions for urea by around 50%–80%. This option is not available where urea is top-dressed onto cereals or grassland, but can be used where urea is applied to seedbeds or between seed rows;

(b) *Inject urea into the soil*. The closed-slot injection of the solid and liquid urea is more effective than shallow incorporation, with emission reduction of up to 90%. Improperly closed or incorporated bands of urea are prone to very high emissions due to a rise in pH within the band when the urea hydrolyses. The rise in pH is mitigated by slow-release urea products and urease inhibitors. As for all nitrogen fertilizers, if seedbed applications are made, care should be taken to avoid large amounts of urea close to the seed because this may inhibit germination/sprouting. Risk of crop injury is reduced by products that slow urea hydrolysis;

(c) *Urease inhibitors* can be used to delay the breakdown of urea until it has been washed deep enough into the soil, and to prevent sharp increases in pH, especially in bands, giving emission reductions of 40% for liquid urea ammonium-N and 70 % for solid urea;

(d) *Irrigate the field after urea application*. Irrigation of at least 5 mm immediately after application of urea leads to an emission reduction of 40%–70%. This technique is only considered to be practical where there is a water need for irrigation;

(e) *Polymer-coated urea granules* provide a slow-release fertilizer that may reduce emissions by about 30% by delaying hydrolysis. However, not much practical experience is available to date;

(f) *Switching from urea to NH_4NO_3 fertilizer* can substantially reduce NH_3 emissions (by up to 90%). A possible negative side effect is the potential increase in direct N_2O emissions, but this occurs mainly under wet conditions and on fine-textured soils (and should be offset against the reduction in indirect N_2O emissions resulting from NH_3 emissions). NH_4NO_3 fertilizers can be more expensive (10%–30% higher costs) than urea, but the net cost may be negligible because of the lower N losses. In some countries NH_4NO_3 is not readily available.

D. Ammonium sulphate and ammonium phosphate

74. The potential for NH_3 losses from ammonium sulphate and ammonium phosphate largely depend upon soil pH. Losses will be smaller from soils with pH < 7.0.

75. On calcareous soils (pH > 7.5), do not use ammonium phosphate or ammonium sulphate fertilizers if rapid incorporation, injection into the soil, immediate irrigation or the use of polymer-coated fertilizer is not possible, but seek alternative sources of N, phosphorous and sulphur.

E. Reducing ammonia emissions from ammonium-based mineral fertilizers

76. Several of the techniques described above for urea, including incorporation, injection, immediate irrigation and the use of slow-release fertilizers, can also be used to reduce NH_3 emissions from ammonium sulphate-, ammonium phosphate- and NH_4NO_3-based fertilizers.

F. Ammonium bicarbonate

77. Ammonium bicarbonate may be available in some areas of the ECE region. Gaseous N losses of up to 50% have been measured following its application. Although emissions may be reduced during field application of ammonium bicarbonate by appropriate placement (see para. 76), substantial losses also occur during storage of ammonium bicarbonate. Given the very high rates of NH_3 emission, ammonium bicarbonate should therefore not be used as N fertilizer. According to annex IX to the Gothenburg Protocol, Parties are to prohibit the use of this fertilizer.