Ammonia Emission from Aviary Housing Systems for Laying Hens

Inventory, Characteristics and Solutions

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Abstract

The development and practical application of welfare friendly aviary housing systems for laying hens, that generally emit more ammonia per hen than battery cage housing systems, would conflict with the Dutch policy to substantially reduce the total emission of ammonia from animal husbandry.

This thesis describes the knowledge assessed by research on the ammonia emission levels of various types of aviary houses for laying hens (the inventory), the processes and factors involved in the kinetics of this ammonia emission (the characteristics) and the development of technical solutions which will lower the emission (the solutions).

Housing systems for laying hens are described as and classified into *battery cages* and *alternative systems.* The waste resulting from the fresh droppings in these two types of housing systems for laying hens are classified as *slurry*, *dry manure* or *litter*. The degradation of nitrogenous components and the volatilisation of ammonia to the air are influenced by the manure composition, the process conditions and the local climate above the manure. Levels of emission from housing systems for laying hens vary strongly due to influencing factors that are related to *the housing type, the animal, the climatisation* or *the management.*

The distribution of droppings over the two sources of emission in aviary houses, being the manure on the belts and the litter on the floor, was investigated under experimental circumstances. The effects of manure and litter handling and litter composition, and the effect of the physical parameters of the air on the emission of ammonia were quantified. The physical and chemical relationships of the volatilisation of ammonia from litter of various commercial aviary houses and the degradation of organic material in litter to ammonia were verified and demonstrated the great impact of the dry matter content of litter on the emission.

A litter drying system in a Tiered Wire Floor aviary housing system was developed and the effect it had on the composition of litter and the emission of ammonia was investigated. With the knowledge acquired about the physical relationships of water evaporation from litter and the water input load to the litter through fresh droppings, it is possible to control the ammonia emission from the litter by influencing its dry matter content.

Voorwoord

'Winnen is niet alleen een kwestie van snelheid en kracht, maar bovenal een kwestie van volhouden'. De totstandkoming van dit proefschrift heeft langer geduurd dan doorgaans gebruikelijk is en dan oorspronkelijk was gepland. Vele zijpaden op het gebied van huisvesting van dieren, emissies en stalklimaat zijn bewandeld. Dit heeft zeker een verrijking van kennis en vaardigheden betekend. De realisatie van dit proefschrift heb ik echter nooit uit het oog verloren.

Het doel was duidelijk en ik heb nooit hoeven twijfelen of ik het zou halen. Dat kwam vooral door het vertrouwen in mij van promotor Bert Speelman. Hooggeleerde professor, hartelijk dank voor de hulp die ik op vele wijzen heb mogen ontvangen. Verder was de geïnspireerde begeleiding van co-promotor Jos Metz onontbeerlijk. Vele manuscripten heeft hij voorzien van degelijk en scherp commentaar dat bijdroeg aan de vereiste kwaliteit voor de gepubliceerde artikelen. Jos, hartelijk dank daarvoor. De promotor en co-promotor vormden samen met Gert-Jan Monteny, Bert Elzing en Bertus Keen mijn begeleidingscommissie. Mede door de goede sfeer op de afdeling Mestbehandeling en Emissies en door de geboden kansen van het Instituut voor Milieu- en Agritechniek, ben ik in de gelegenheid geweest om dit proefschrift zoals dat nu voor u ligt te realiseren. Allen hartelijk dank daarvoor.

Eén lid van de begeleidingscommissie kan het resultaat van zijn bijdrage niet aanschouwen. Bertus Keen was in de eerste jaren de drijvende kracht achter de statistische analyses van de verkregen data. Zijn kundigheid was van een bijzonder hoog niveau, zijn gevoel voor humor opmerkelijk en we spraken vaak over onze passie voor sport. Bertus, ik zal nog vaak aan je denken.

Vele collega's hebben uiteraard direct of indirect een steentje bijgedragen aan de realisatie van de proeven, publicaties en de afzonderlijke artikelen. Enkelen van hen wil ik met name noemen. Zo hebben Berber Reitsma, Herre Montsma en Robert Bleijenberg enkele proeven uitgevoerd, waarbij vaak gedurende vele maanden de ammoniakemissie werd gemeten. Verder was de incidentele hulp van kamergenoot en uitvoerder van de metingen in het EU-project 'Aerial Pollutants', Gerard Uenk, onmisbaar. De 'finishing touch' van de artikelen werd doorgaans gerealiseerd op een vrijdagmiddag. Ik wil mijn collega's Nico Ogink, Karin Groenestein en René Braam en KCW-collega René Kwakkel van de LUW vakgroep Veevoeding bedanken voor de kritische opmerkingen en soms heftige discussies die de basis vormden voor verbeteringen van de artikelen.

Daarnaast heeft een aantal studenten en stagiaires bijgedragen aan de uitvoering van proeven, de verwerking van resultaten en aan het modelleerwerk: Erlinde Vermulst, Edwin Bos, Ronald Jacobs, Sijo Smit, Arjen Menkman en Pim Raaben. Dank voor jullie bijdragen en inzet.

Ook de medewerkers en pluimveehouders op de verschillende locaties waar ik dit onderzoek heb uitgevoerd, ben ik dankbaar. Wouter Hiskemuller en Jaap Bloem van proeflocatie 'Het Spelderholt' en pluimveehouders Siemons te Roosendaal en Jansen en van der Linden van EKOZ te Schore wil ik hier met name noemen.

Tenslotte een woord van dank aan mijn ouders. Ik realiseer me dat zij ogenschijnlijk onzichtbaar en onopgemerkt een belangrijke rol spelen in mijn leven en zo hebben bijgedragen aan dit proefschrift. Ook jij Ellen bent natuurlijk een belangrijke schakel geweest de afgelopen jaren, ook al begreep je doorgaans weinig van mijn technische verhalen en statistische problemen. De weekeinden en avonden zullen weer wat rustiger worden, zodat er meer tijd is voor elkaar, onze zonen Ragnar en Quirijn en de verbouwing van onze 'boerderij'.

Peter W.G. Groot Koerkamp
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Stellingen

1. De hoogte van de ammoniakemissie uit alternatieve, welzijnsvriendelijke huisvestingssystemen voor pluimvee, in het bijzonder leghennen, hoeft geen belemmering te zijn bij de invoering van deze systemen *(dit proefschrift).*

2. Toen bleek dat de 20 procent van de uitwerpselen die door de hennen werd uitgescheiden in het strooisel verantwoordelijk was voor 80 procent van de totale ammoniakemissie uit een volièresysteem, was daarmee zowel het probleem als de oplossingsrichting ter vermindering van de ammoniakemissie feitelijk bepaald *(dit proefschrift).*

3. De hogere luchtsnelheden benodigd voor het drogen van het strooisel-mestmengsel in volièrestallen zijn niet nadelig voor het welzijn van de leghennen *(Report of CIGR working group 13, 1994. Climatization and environmental control in animal housing).*

4. Omdat huisvestingssystemen in de veehouderij en de veedichtheid tussen landen en regio's binnen West Europa sterk verschillen, zijn oplossingen voor de ammoniakemissie en de stikstofverliezen in deze landen en regio's niet uniform toepasbaar *(Commission of the European Communities / Silsoe Research Institute, contract PL 900703, 1992-1996. 'Reduction of aerial pollutant emissions in and from livestock buildings' - final report).*

5. De methode om de ammoniakemissie uit stalsystemen te relateren aan het gewicht van dieren (emissie uitgedrukt per Live weight Unit = 500 kg) gaat voorbij aan de relevante fysische en chemische processen in de mest en kan derhalve gemakkelijk tot verkeerde conclusies leiden *(J. Hartung and V.R. Phillips, Journal of Agricultural Engineering Research 57 (1994): 173-189).*

6. Anno 1990 was men in de producentenkringen niet overtuigd van de deugdelijkheid van volièrehuisvesting voor leghennen in verband met het nooit uit te sluiten risico van veel grondeieren en meer kans op parasitaire aandoeningen met bovendien nog een grotere emissie van ammoniak *(Prof. Dr Ir E.H. Ketelaars, De historie van de Nederlandse Pluimveehouderij, van kippenboer tot specialist, 1992, p. 245).*
   Ondanks het feit dat onderzoek inmiddels de argumenten grotendeels ontkracht heeft, is voor het veranderen van deze mening *niet alleen* meer onderzoek nodig *(Pluimveehouderij 28 (1998) 15: 8-9; Agrarisch Dagblad 12 (1998): 143 (3 april).*

7. Aangezien het maar zeer de vraag is of de plaats, de samenstelling en de structuur van het strooisel in volièrestallen voldoet aan de eisen die de hen daar vanuit gedragsoogpunt aan stelt voor het scharrel- en stofbadgedrag, kunnen vraagtekens worden gezet bij de voorgestelde ontwerpeisen aan huisvestingssystemen voor leghennen die voorschrijven dat een aanzienlijk deel van het leefoppervlak uit strooisel moet bestaan *(D.W. van Liere, 1991. Function and organisation of dust bathing in laying hens. Thesis LUW; Studiedag WPSA afdeling Nederland, 2 april 1998: Welzijn en diergezondheid in de pluimveehouderij).*

8 Om de Nederlandse landbouw in staat te stellen haar leidende positie in de wereld te handhaven, is een intensievere samenwerking tussen het onderzoek en het landbouwbedrijfsleven noodzakelijk.

9. Een empirisch model voor de ammoniakemissie uit stallen met het ventilatiedebiet als verklarende variabele bevat veel lucht.

10. Om positieve verwachtingen te bevestigen worden statistische methoden veelvuldig verkeerd gebruikt.

11. Het feit dat het eigenlijke effect of de werking van een product of methode niet aangetoond kan worden, betekent niet noodzakelijkerwijs dat de gebruiker hiervan geen nuttig voordeel kan hebben.

12. Tegenwoordig kun je *je gelijk* kopen door 'onderzoek' uit te laten voeren door commissies, adviesbureaus of wetenschappelijke instellingen *(M.P.C.M. van Schendelen, Intermediair 34 (1998): 7 (12 februari); Icke, NRC Handelsblad, 28 (1998): 7 maart).*

13. De retorische vraag 'Wie was er eerder, de kip of het ei?' is uit oogpunt van de milieubelasting minder relevant.

Stellingen behorende bij het proefschrift
Ammonia Emission from Aviary Housing Systems for Laying Hens -
Inventory, Characteristics and Solutions

Wageningen, 5 juni 1998

Peter W.G. Groot Koerkamp

Voor mijn ouders

Contents

CHAPTER 1

General Introduction and Outline

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1 Introduction to the problem

Imagine a world without hens: there would be no droppings, no poultry related ammonia emissions and no poultry related environmental problems. We would, however, also have to cope without cooked eggs for Sunday breakfast, without drumsticks for the barbecue, and last but certainly not least without this thesis. Fortunately, there are hens. So, let us begin.

The hen as we know it today stems from the Bankiva hen which was originally found in Southeast Asia. The Bankiva hen originated twenty-five million years ago from races present at that time. The Chinese, Egyptians and Romans played a major role in the distribution of hens across the world. The races and species that are currently used for commercial meat and egg production comprise only a fraction of the total number of different races and species, and is certainly not representative of the wide variety of species that have been identified today and in the past (Schippers, 1996).

The registered number of chickens in the Netherlands increased from approximately three million in 1900 (layers and broilers together) to approximately 20 million layers in 1940. Since then, the number of layers for egg production and the number of pullets has further increased to about 30 and 7 million respectively in 1996. Parallel with this development, the number of layers per farm increased drastically which resulted in approximately 1500 farms with laying hens in 1996. The developments since the Second World War can be characterised by an increase in scale of the farms, increased productivity of the hens and an increased number of layers per unit of labour. This was possible due to the development of battery cages, the mechanisation of feed and water distribution, egg collection and manure handling, and improved hygiene, nutrition, breeding and health care of the hens (Ketelaars, 1992).

These developments also triggered criticism, however. Both in the Netherlands as well as in other north-western Europe social criticism on the developments in animal husbandry grew stronger and scientific evidence proved that these developments harmed the welfare of the hens (Harrison, 1964; Brambell, 1965; Webster, 1984). This resulted in fierce debates on the implications of intensive farming for animal welfare. In 1973 the Commission for Welfare of Farm Animals was founded in the Netherlands by the National Council for Agricultural Research (NRLO). Among the issues described were the welfare of laying hens in battery cages and traditional deep litter systems (NRLO, 1975). One of the conclusions of this report was that the small space for the hens and the absence of litter and laying nests in battery cages have a negative effect on the behaviour of the hens. Feather pecking was mentioned as a frequently occurring problem in the deep litter systems. As a result research into the development of adapted cage housing for laying hens was begun in 1975 at the Centre for Poultry Research and Information Services 'Het Spelderholt'.

After some years research on welfare friendly housing systems for laying hens focused on aviary systems, because earlier research showed that there is little future in the further development of an enriched cage or *Get-Away-Cage* (Brantas, 1981; Blokhuis and Haye, 1986). An aviary housing system is basically a traditional floor housing system with extra wire floor tiers which increase the use of vertical space (Appleby *et al.*, 1992). In aviary systems each hen disposes over an area of approximately 1000 cm^2, they can move around freely, they can scratch and dust bath in the litter on the floor and they can rest on perches and lay their eggs in nests. Prototypes and commercial aviary systems were described by Ehlhardt *et al.* (1988), Appelby *et al.* (1992) and Blokhuis and Metz (1995).

In 1990 the collaborative research programme 'Aviary Housing for Laying Hens' was initiated in the Netherlands as a co-operation between the Institute of Agricultural and Environmental Engineering (IMAG-DLO), the Centre for Poultry Research and Information Services 'Het Spelderholt' (which has merged with ID-DLO, the DLO-Institute for Animal Science and Health) and other expert groups. The main objective of this programme was to provide well-founded information on the feasibility of aviary housing under commercial circumstances which was important to the political decision-makers (Blokhuis and Metz, 1995). The other objectives of this research programme included both further technical development as well as practical testing of aviary housing systems for laying hens. An integrated approach followed, involving experts from such fields of expertise as animal welfare, technical management, labour management and labour conditions, economics and environmental pollution. The higher ammonia emission from aviary housing systems in comparison with battery cages was considered as a major bottle-neck for the successful continuation of development and the practical application of welfare friendly aviary housing systems for laying hens.

National as well as regional and local authorities are involved in the policy concerning the reduction of the ammonia emission resulting from animal husbandry. The level of the emission per hen from animal houses is an important piece of information for the granting of a licence on environmental pollution that farmers receive from the local authorities in the Netherlands (Uitvoeringsrichtlijn, 1996). Besides the emission of odour and the amount of manure produced by the animals, restrictions on the total emission of ammonia are one of the most limiting factors for changing from one to another housing system, or increasing the total number of animals.

Most of the work in the area of ammonia emissions that was carried out within the scope of the research programme 'Aviary Housing for Laying Hens' is included in this thesis. The project was continued with the financial support of the Finance Board for Manure and Ammonia Research (FOMA).

2 Objectives and outline of the thesis

The objectives of this thesis are to acquire knowledge on the levels of ammonia emission from various types of aviary houses for laying hens (inventory), to describe the kinetics of the ammonia emission as well as the processes and factors involved (characteristics) and finally to use this knowledge for the development of technical solutions for lowering the emission. The level of ammonia emission from battery cages equipped with belts and regular removal of the manure, is the lowest of all the types of housing systems for hens, and in the Netherlands it has been certified with a Green Label certificate (Stichting Groen Label, 1993a and 1993b; Uitvoeringregeling Ammoniak en Veehouderij, 1996). This emission level was therefore the goal that was set for the development of sustainable, welfare friendly housing systems for laying hens.

This thesis begins in chapter two with a review of the state-of-the-art at the start of this study. In this chapter the housing systems for laying hens are described and classified as *battery cages* or *alternative systems*. The latter offer a litter area and more space for the hens. Based mainly on the dry matter content, the waste resulting from the fresh droppings of the hens are classified as *slurry*, *dry manure* or *litter*. Nitrogen components present in these wastes are liable to degradation to ammonia. The ventilation process which takes the air out of the house and leads to ammonia emission in the environment is one of the processes influencing the degradation and volatilisation processes. These processes, as well as factors affecting these processes, are qualitatively described in chapter two. Furthermore, levels of ammonia emission from the various housing systems are given and the main factors which account for the differences in the levels of emission are classified as *housing system*, *animal*, *climatisation* or *management*.

The following two chapters (three and four) describe two experimental studies. The first one is a comparative study between the Tiered Wire Floor aviary system and a battery cage system (chapter three) and the second compares three types of commercial aviary systems (chapter four). In the first one the manner in which the droppings are distributed over the two sources of ammonia emission in the TWF aviary system, the manure on the belts and the litter on the floor, is investigated and compared with the amount of manure on the belts in the battery cage system. The effects of the physical parameters of the air above the sources of emission, the effects of manure and litter handling and the effect of litter composition on the emission from the two sources are quantified. The effects of these influencing factor are compared in a sensitivity study to assess their relative effect. In chapter four differences are investigated in the ammonia emission of three aviary systems with hens aged 16 to 36 weeks. Furthermore, the effect of manure and litter handling and the effect of the physical parameters of the air in the aviary systems (co-variables) were determined. Special attention has been paid to the changes in time and the differences between the three systems in the manure and litter composition during this first part of the laying period.

To achieve a substantial reduction of the ammonia emission from aviary houses, it is essential to have a better understanding of the physical and chemical relationships of the volatilisation of ammonia from litter and the degradation of organic material in litter to ammonia. These relationships are described and verified by means of experimental data in chapter five. Litter samples from various types and sizes of aviary systems and various types and ages of hens were subject to a number of laboratory analyses. Special attention was given to the variation of properties between litter samples within aviary houses.

A technical solution to lower of the ammonia emission from litter following from the results in chapter five is worked out in chapter six. In this chapter a litter drying system in a Tiered Wire Floor aviary housing system is described and its effect on the composition of litter and the ammonia emission is investigated.

Knowledge of the flows of water to and from the litter is essential in order to control the dry matter content of litter in aviaries. The physical relationships of the evaporation of water from litter are described and verified by means of experimental data in chapter seven. The effects of air velocities above the litter, the indoor climatic conditions and the water activity of the litter on the evaporation of water are determined. The emission of ammonia is expressed as a function of the physical qualities of the air and the litter and as a parameter for the manure handling. In chapter eight the flow of droppings, the belt manure and the litter in a Tiered Wire Floor aviary system are described by a physical model and verified by means of experimental data. The dynamics of these flows for hens in the age of 16 to 32 weeks are determined and the water input load of the litter through fresh droppings is derived from this.

In chapter nine knowledge from previous chapters is summarised, structured and discussed in a broader context. This chapter focuses on practical solutions to reduce and minimise the ammonia emissions from aviary housing systems for laying hens (solutions for reduction).

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CHAPTER 2

Review on Emissions of Ammonia from Housing Systems for Laying Hens in Relation to Sources, Processes, Building Design and Manure Handling

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Review on Emissions of Ammonia from Housing Systems for Laying Hens in Relation to Sources, Processes, Building Design and Manure Handling

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Abstract

The ammonia emissions from housing systems for laying hens must be reduced to abate environmental damage. In traditional cage systems and alternative, welfare oriented, housing systems for laying hens two types of waste can be distinguished, namely manure and litter. Manure is encountered as slurry or as dry manure. Litter on the floor is a dry and granular mixture of droppings and e.g. sand. It is used by the hens for dust bathing and scratching. In the processes involved in the emission of ammonia, the most important process parameters are temperature, pH and water activity, i.e. the availability of water for micro-organisms in the substrate. Air temperature, relative humidity and air velocity best define the influencing climatic conditions. Despite the effectiveness of pH control, application of this measure has too many negative side-effects. Forced drying of manure seems the only effective and acceptable way for temporary control of ammonia emissions inside housing systems. Regular removal of manure out of the house is always necessary.

Reduction of ammonia emissions can be achieved by changing over from housing systems with composting to battery systems with manure belts underneath the cages, which enable drying of manure and regular removal. The emission from these two housing systems are 386 and 34 g NH_3/yr per hen respectively. The drying rate of the manure and the frequency of removal are crucial in relation to the emission. A minimal emission from the manure is achieved if a dry matter content of 60% is reached within 50 h after excretion of the droppings. The emission from battery systems with belts can be reduced to 10 g NH_3/yr per hen if the manure is removed from the house two times a day instead of two times a week. The emissions of ammonia from alternative housing systems with litter are several times higher compared with battery cages with belts. This is due to the long stay of litter inside the house. A higher dry matter content of litter slows down the volatilisation of ammonia, but a practical way to actually reduce the emission from litter in this way are not yet available. Besides this, a good understanding of water activity is still not available.

1 Introduction

The effects of acidification on the environment can be severe [1,2]. Ammonia and chemical combinations of it (NH_x) are important components responsible for acidification in addition to sulphur compounds (SO_x), nitrogen oxides (NO_y) and volatile organic components (VOC). The deposition of NH_x is high over large areas of Western Europe. In 1989 ammonia accounted for about 45% of the total acid deposition in the Netherlands. About 80% of the ammonia deposited in the Netherlands originated from Dutch sources. About 85% (over 220,000 t/yr) of the total emission of ammonia in the Netherlands originates from livestock farming. The ammonia is emitted from buildings, stores (e.g. tanks), pastures (grazing) and manure applications, e.g. slurry spreading. In 1986 livestock housing and storage tanks contributed 36% (82,000 t/yr) of the emission from Dutch livestock farming [3,4]. The emission from poultry houses, mainly for laying hens and broilers, was responsible for about 22%

(about 19,000 t/yr) of this amount. Ammonia emissions from livestock housing must be reduced to abate environmental damage [5,6]. In the Netherlands, legislation to support this is already in force [7]. The objective of the Dutch government is to reduce emissions of ammonia by least 50 % of in the year 2000 as compared with 1980.

The objective of this paper is to discuss the present state of knowledge about ammonia emissions from various types of housing systems for laying hens. First, this will contribute to an understanding of how and why differences in emissions occur between different types of buildings. Secondly, it will show how the emissions may be reduced effectively. Thirdly, it will give (technical) specifications for building design and the management required to achieve reduction and it will highlight impediments to this reduction.

2 Housing systems and manure handling

The most common housing systems for laying hens are battery cages. These cages were introduced in the fifties and are renowned for their production efficiency and high stocking densities. The cages generally have wire floors. This enables the poultry manure to fall into a storage system underneath the cages or onto conveyer belts (figures 1 and 2). Battery systems can be classified according to differences in cage design or according to the way the waste is managed, i.e. the type of waste and the removal and storage method (table 1) [8,9,10]. The storage time in this table represents the maximum possible period. The droppings can be treated to become slurry or dry manure. For the former, the droppings are eventually mixed with water and stored in a manure pit. The droppings fall directly into a manure pit underneath the cages (figure 1) or belts or scrapers can be used to transport the manure from the house regularly to a storage system, e.g. once or twice a week. This storage system can be situated in the basement or outside the animal house. The storage period can vary from several months to a year. In the last case the droppings are dried, either in special channels underneath the cages (channel house) or in the whole basement of the house (deep-pit), either on the manure belts in the poultry house or in a special

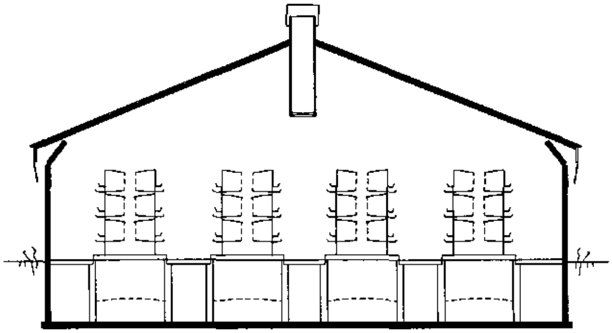

Figure 1 Battery cages with slurry storage under the cages.

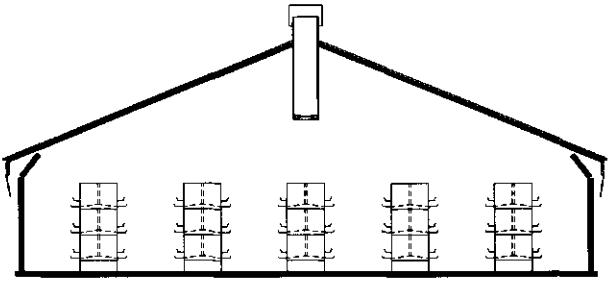

Figure 2 Battery cages with belts equipped with a manure drying system.

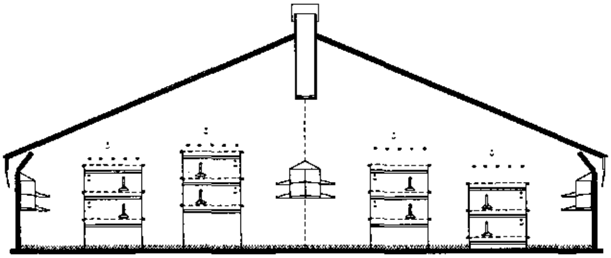

Figure 3 Example of an alternative housing system for laying hens: the Tiered Wire Floor aviary system.

drying system separated from the chickens' living space. The evaporation of water is enhanced by air flowing over the manure. Especially in the first two ways (channel and deep-pit houses), the drying process is stimulated by means of composting of the manure. This takes place naturally until a stabilised product with a dry matter content in the range of 50 to 70% has been produced. However, manure composting encourages vermin and produces high concentrations of ammonia [11]. The stay of manure on belts or in a special drying system takes at most one week. After this drying process the manure is stored in sheds or is covered.

Public concern for animal welfare has stimulated research into alternative systems for keeping laying hens. Various approaches have been initiated by workers in several countries. Research has been and still is being done to test existing types of alternative systems or to develop new and improved systems. With the introduction and testing of alternative systems a lot of problems have appeared which prevent an autonomous transition from battery cages to alternative systems. Depending on the country, emphasis is laid on one or more of the following problems: bird health and welfare, product quality, working conditions and the economic and environmental consequences (all in comparison with battery cages) [12, 13]. However, in a few countries the keeping of laying hens in battery cages is already forbidden because of welfare reasons (Switzerland), may be forbidden in the near future (Sweden) or is under discussion (the Netherlands, European Community).

Table 1 Overview of housing systems and manure handling (DM = dry matter content).

Housing system	Waste (type)	DM (% wt/wt)	Storage system (treatment and location *)	Storage time (year)
Battery Cages	Slurry	10-20	Open manure pit under cages	1
			Manure pit under house, outside	1
			Manure pit (covered over), outside	1
	Dry manure	40-70	Composting in channels	0.3
			Composting in basement	1
			Drying on belts	0.02
			Drying in special system, outside	0.01
			Storage in sheds or covered, outside	1
Alternative systems	Slurry	10-20	As battery cages	
	Dry manure	40-70	As battery cages	
	Litter	60-80	Drying in scratching area	1
			Storage in shed or covered, outside	1

* If outside: the emission from the storage system does not contribute to the emission from the animal house

Several alternative systems have been developed. They include modified cages (get-away cage), percheries, aviaries, terraces, deep litter systems, covered straw yards and free range systems [13,14]. These systems are all equipped with nest boxes, a feeding and watering system, slatted or wire floors or perches over a manure pit or belts, and a litter area (figure 3). The configuration (siting, areas, dimensions) of these elements vary according to the system. In these alternative housing systems the total living area consists of the litter area, the wire floors and perches. The alternative systems vary in terms of the stocking density, freedom of movement (e.g. pen size), indoor/outdoor system, perches, tiers (gridded floor) or terraces as living area (platforms) or a combination of these. In these various types of alternative systems two types of waste can be distinguished, manure and litter (table 1). As in battery cages, manure can be defined as droppings that are inaccessible to the hens, because of a manure storage or belt system underneath tiers and perches. This manure can be handled in the same way as the manure in battery cages (table 1). The litter consists of droppings deposited in the scratching and dust bathing area mixed with the litter material initially present (e.g. straw, sand or wood chips). After a certain period it consists predominantly of droppings, but it is still called litter. The litter generally has a relatively high dry matter content (60-80%) and a granular structure. If the litter is not removed during the laying period, the scratching and dust bathing area also retains a manure storage function. Spilt water, feed, feathers, dust and cracked eggs augment the manure and litter. Droppings that do not fall into either category of waste, manure or litter, are responsible for pollution of housing system elements, mainly perches and wire floors.

Various aspects of use and recycling of chicken manure have been discussed by Voorburg [15]. Despite some disadvantages (variable composition, unknown availability of nitrogen, risk of spreading weeds and pathogenic organisms) poultry manure is the most valuable livestock manure and is appreciated by arable farmers. During storage and use of manure, especially for dry poultry manure and litter, high emissions of ammonia can occur. Therefore, the emissions of a housing system must be considered as a part of the sum of emissions from the housing and storage system and from manure application.

3 Sources and processes

3.1 Production and composition of droppings

Ammonia originates from poultry droppings. Both the quantity and the composition of the droppings are of interest when studying ammonia emission. Droppings are defined here as the fresh excreta from chickens. Table 2 gives ranges for droppings production and composition, representing a summary of published results [9,16,17,18]. The droppings production varies between 160 and 180 g/(hen d), depending on factors such as the dry matter content (which is typically between 20 and 25%). The nitrogen components uric acid, urea, ammonia/ammonium and undigested proteins are the potential sources for ammonia volatilisation. Uric acid and undigested proteins are the two main nitrogen components in droppings, representing about 70% and 30% of the total nitrogen respectively. The dry matter content, acidity (pH), temperature and physical properties of the droppings are important process factors.

Table 2 Droppings production and contents of dry matter and nitrogen components.

Droppings production g/(hen d)	Dry matter content g/kg	Total N g/kg	Uric acid N % of total N	Urea N % of total N	Ammonium N % of total N	Undigested proteins/ residual N % of total N
160-180	200-250	13-17	60-75	0-3	0-3	25-34

3.2 Release and fixation of ammonia

Ammonia is mainly a product of the degradation of uric acid and undigested proteins. The relevant biochemical processes are complex, but they can be simplified as follows:

$$C_5H_4O_3N_4 + 1.5\ O_2 + 4\ H_2O \rightarrow 5\ CO_2 + 4\ NH_3 \qquad (1)$$

$$\textit{undigested proteins} \rightarrow NH_3 \qquad (2)$$

Both processes are microbially mediated. Various authors have described the aerobic decomposition of uric acid to ammonia [19,20]. In figure 4 the decomposition of uric acid (simplified) is given as described in the extensive work of Vogels and Drift [21]. According to this and other descriptions, water and oxygen must be available, and ammonia and carbon dioxide arise as products of this degradation process (figure 4). The enzyme uricase, commonly present in micro-organisms, is specific to this reaction. However, degradation of uric acid by anaerobic micro-organisms along other pathways is also possible. But anaerobic processes generally are much slower than aerobic processes.

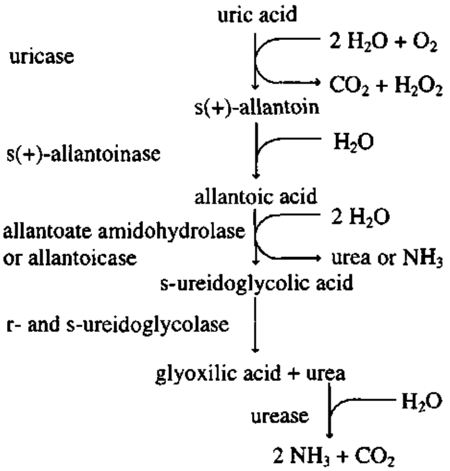

Figure 4 Aerobic decompostion of uric acid.

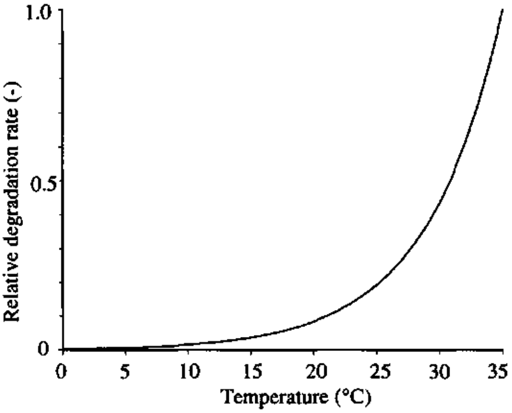

Figure 5 Effect of temperature on degradation of uric acid.

The degradation of uric acid and proteins is influenced by temperature, pH and moisture content. Elliot and Collins [22] described the degradation of uric acid in reused broiler litter quantitatively in relation to temperature and pH. The relative effect of these factors on the degradation rate of uric acid is given in figures 5 and 6. The degradation rate is given relative to the maximum value. Rising temperatures cause faster breakdown rates, with a sharp increase between 20 and 30 °C. Levels of pH of 5.5 and higher increase breakdown rates, with an optimum pH of about 9 for uricase [21].

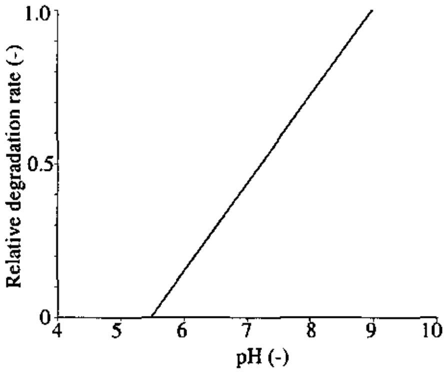

Figure 6 Schematic effect of pH on degradation of uric acid.

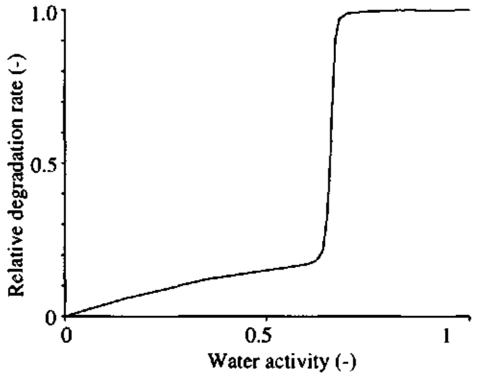

Figure 7 Schematic effect of water activity on degradation of uric acid.

Figure 8 shows schematically the dependence of the ammonia release rate on the litter moisture content [23]. Despite the lack of numerical information on the release rate, it shows that microbial growth in chicken manure is optimal between 40 and 60% moisture content (wet basis). At values above and below this range the ammonia release decreases. At low moisture contents ammonia release stops. This moisture content is not exactly known. In practice, dry matter contents of litter vary between 60 and 80%. Thus, an increase of the moisture content enhances ammonia release. The water is necessary for the growth of microbes. The water activity of a material, indicated as A_w, is a measure of the availability of water for micro-organisms [24]. Water activity is therefore a better explanatory variable for microbial growth than moisture content. Higher dry matter contents generally reduce A_w values, but the relation may vary for different solid materials. The relation between dry matter content and water activity is represented by sorption/desorption isotherms. The relative effect of A_w on the degradation of uric acid is given schematically in figure 7 [25, 26]. This graph varies for different groups of micro-organisms, but an A_w of 0.7 is generally considered to be the absolute minimum for microbial growth [24]. Useful research has been done on the relation between water activity and microbial growth or enzyme activity [27, 28]. However, water activity is inadequate for describing water-related phenomena in matric systems, because it fails to distinguish between different types of water interactions and is quite insensitive in moist systems [24,29]. The concept of 'water potential' offers a means to characterise water better as a basic ecological factor. Water potential is the sum of matric, osmotic, gravimetric and other potentials, each describing different attraction forces on water. For reasons of simplification and clarity, only A_w will be used in the following.

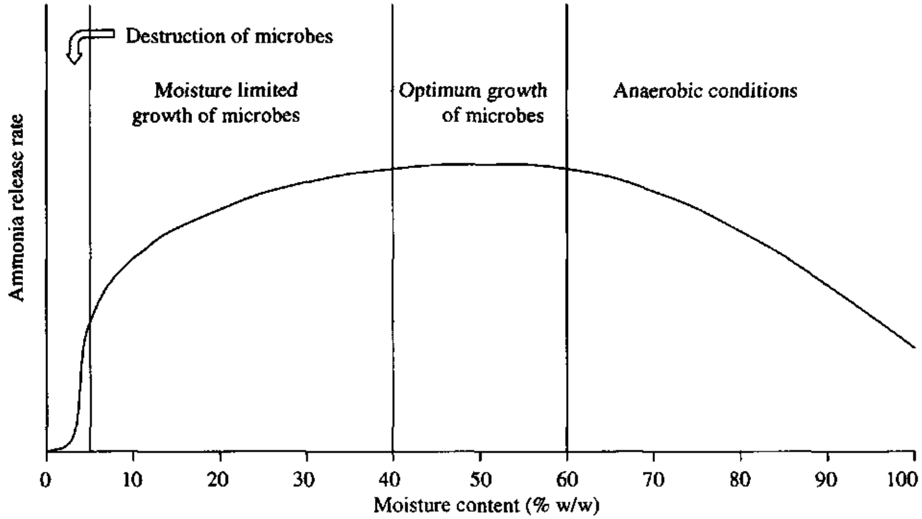

Figure 8 Schematic representation of dependence of rate of ammonia release on litter moisture content.

The degradation process of uric acid and proteins can be minimised by lowering the temperature, by lowering the pH, or by lowering the moisture content until a critical A_w value is reached. The effect of the single parameters has been multiplied to calculate the actual breakdown rate under given conditions as a percentage of the maximum breakdown rate [22,26]. But these models have not been verified adequately. Burnett and Dondero [30] showed degradation rates of uric acid of 8 and 40% per day (of the amount of uric acid present) for dry and liquid poultry manure respectively; for litter, 20% per day has been reported under optimal conditions [22] (35 °C, pH 9). Also empirical models for litter were developed for predicting ammonia concentrations in broiler houses with pH as dependent and temperature and moisture content as independent variables [31]. Results from these models also show a strong increase of ammonia concentrations with increasing temperature and moisture content.

The decomposition of the intermediate product 'urea' is included in the diagram of figure 4. This last step in the degradation process of uric acid depends on the urease activity, pH and temperature. The enzyme urease is secreted by micro-organisms and is commonly present in manure. The effect of pH and temperature is included in the total breakdown of uric acid to ammonia. Elzing *et al.* [32] described the breakdown of urea in cattle urine on a dirty slatted floor. They measured a total breakdown of urea within several hours under normal house conditions. This is relatively fast compared with the degradation of uric acid to ammonia which lies between 8 and 40% of the amount of uric acid per day. The degradation rate of uric acid is therefore mainly restricted by the first steps in the degradation process.

The non-biological decomposition of organic nitrogenous materials is kinetically very slow. Thus, micro-organisms are required to mediate this reaction, which is normally defined as degradation. Above temperatures of about 30 °C this mineralisation process is known as composting, and requires aerobic conditions [29,33]. Composting will take place as long as sufficient water and oxygen are available in dry poultry manure and litter containing organic matter. If heat transport to the environment is restricted, the heat produced by the micro-organisms causes high temperatures in the manure, up to 70 °C. Due to the degradation process and the volatilisation of water vapour and carbon dioxide, relatively large amounts of organic material can be lost. The nitrogen in the organic material will be released as ammonia [34,35]. If oxygen is absent the degradation is called rottening or fermentation [36]. Under anaerobic circumstances, e.g. in wet slurry, many gaseous components can be released, e.g. ammonia (NH_3), methane (CH_4), carbon dioxide (CO_2), hydrogen sulphide (H_2S) and fatty acids. Taiganides [37] gives a scheme for the anaerobic degradation of organic material into N, C and S compounds.

A review of microbial transformation of inorganic nitrogen is given by Painter [38]. Three main processes can be distinguished:

(a) The fixation of dinitrogen leading to ammonia production (aerobic or anaerobic).

(b) Due to nitrification (autotrophic or heterotrophic) ammonium can be converted to nitrite and hence nitrate. Autotrophic nitrification is considered to be most important, in which case sufficient oxygen must be available. The ammonia concentration will then be lowered.

(3) Nitrate can be utilised by micro-organisms either for its nitrogen (assimilation - synthesis of N), or for its oxygen (dissimilation). For assimilation, ammonia is generally preferred to nitrate, since nitrate first has to be reduced to ammonia. The end product of the dissimilation can be nitrite, nitric oxide, nitrous oxide or dinitrogen. If any of the last three are formed, the process is called denitrification. For dissimilation the conditions must be anaerobic or nearly so.

The importance of nitrification in manure and litter is dubious. Oxygen is mainly used by heterotrophic micro-organisms for degradation processes and therefore is hardly available for autotrophic micro-organisms. Despite sufficient aeration of manure and litter, shortage of oxygen in small particles (micro scale) is supposed to occur [39]. Further, neither manure nor litter contains much nitrate or nitrite. Finally, the ammonia concentrations found in manure and litter may even be toxic for microbial activity. Denitrification is also of minor importance if nitrate is hardly present.

The incorporation of ammonia into new N-containing organic compounds (e.g. proteins) by bacterial activity (assimilation or immobilisation) diminishes the amount of ammonia available for volatilisation. In addition to sufficient water, C/N ratios of at least 30 are necessary for this process. These ratios are not common in poultry manure and litter, so large quantities of e.g. straw, are required during composting to achieve a significant reduction in nitrogen loss [40]. The preparation of substrate for mushroom growing is a well-known application of this principle [41]. Moreover, the newly formed proteins are still liable to degradation into ammonia. In other words, only a temporary withdrawal of ammonia from possible volatilisation is achieved.

The processes related to organic and inorganic nitrogen are mainly studied in aqueous conditions. The availability of water for these microbial processes varies, especially in litter and dried manure. The numerous and complex reactions involving nitrogen make it difficult to predict and decide what happens in manure with mixed communities of micro-organisms on poultry farms. Deviations from the processes mentioned are not uncommon. The reported denitrification by specific micro-organisms under aerobic conditions is one example of this [42].

3.3 Volatilisation of ammonia

The ammonia in the manure or litter is liable to volatilisation. Before being liberated into the air the ammonia is involved in two equilibrium equations, (3) and (4). The ammonium - ammonia equilibrium,

$$NH_4^+(l) \Leftrightarrow NH_3(l) + H^+ \qquad (3)$$

is influenced by temperature (denoted as T) and pH [43]. Figure 9 shows the relation between pH and the part of ammonia of the total amount of ammonia and ammonium (total ammoniacal nitrogen) for two temperatures for aqueous solutions. Below a pH of 7 nearly all the ammonia is bound as ammonium and not available for volatilisation. Higher temperatures favour ammonia concentrations, because of the positive influence of temperature on the dissociation constant K_a, which is defined as:

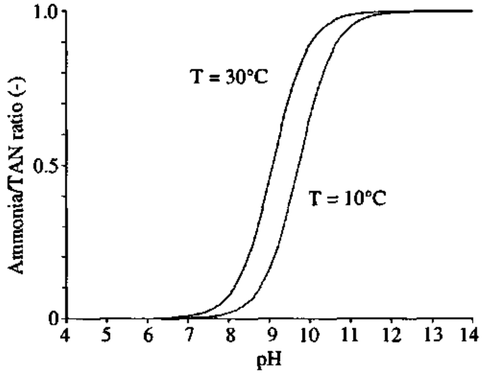

Figure 9 The dependence of ammonia/total ammoniacal nitrogen (TAN) ratio on pH and temperature

$$K_a = \frac{[NH_3][H_3O^+]}{[NH_4^+]} \qquad (4)$$

The volatilisation equilibrium of ammonia to the gas phase,

$$NH_3(l) \Leftrightarrow NH_3(g) \qquad (5)$$

follows Henry's Law for dilute systems. The partial pressure of gaseous ammonia, $NH_3(g)$, is proportional to the $NH_3(l)$ concentration. Higher ammonia concentrations in the liquid raise the partial pressure. Higher temperatures also raise the partial pressure: a temperature rise from 20 to 30 °C decreases the Henry constant by about 50 %. The volatilisation of ammonia from manure to air,

$$NH_3(g, manure) \Leftrightarrow NH_3(g, air) \qquad (6)$$

is defined as the mass flux. This flux is generally defined as the product of difference in partial pressure between the two media and a mass transfer coefficient. A higher partial pressure difference increases the flux. Mass transfer coefficients rise with increasing air velocity [44].

The volatilisation process can thus be restrained either by lowering the pH and the temperature of the manure or litter or by minimising the air velocity over the surface. Although the equilibrium equations and mass flux given are for dilute systems, they may be qualitatively valid for non-dilute systems such as manure and litter.

3.4 Volatilisation of water

Because of the relatively high percentage of dry matter in the droppings of laying hens and the implicit need to raise this percentage in systems with dry manure and litter, the water diffusion in the droppings and the water volatilisation from the droppings are of interest. Equations (5) and (6) also hold validity for the evaporation of water. Higher temperatures and velocities of the air favour the volatilisation of water, while an increase of the relative humidity (r.h.) or water vapour pressure diminishes the volatilisation [45]. Eventually, ventilation brings fresh air into the poultry house while ammonia, water vapour, other gases and air contaminants are removed with the exhaust air. The ventilation affects not only the global internal climate, but also the local climate above the manure and litter.

4 Reduction of emissions

In table 3 the influencing factors involved in the ammonia emissions from housing systems are summarised. After nitrogen has been excreted by the animal the process conditions in the manure and litter and the micro climate (or local climate) above the manure and litter determine the volatilisation of ammonia. In principle, reduction of ammonia emissions is possible in all five phases distinguished in table 3. Techniques which interfere with the first four processes can be classified as preventive measures. Air cleaning by means of bioscrubbers or biofilters is available as an 'end of pipe technique' [46]. Possible ways of influencing the factors related to ammonia emissions and appropriate technical solutions are discussed and evaluated below [8].

Table 3 Schematic overview of processes and factors involved in ammonia release from poultry houses. The arrows indicate the interaction between process conditions in the manure and the local climate above the manure.

Processes	Nitrogen components and appearance	Affecting factors
1. Droppings production ↓	Uric acid + undigested proteins	Animal
2. Degradation ↓	Ammonia / ammonium in manure	Process conditions (manure): T, pH, A_w
3. Volatilisation ↓	Ammonia in air	Process conditions & ↑ local climate ↓
4. Ventilation ↓	Ammonia in poultry house	Local climate (air): T, r.h., velocity
5. Emission	Ammonia in environment	Air cleaning

(1) The *content of nitrogen in droppings* is influenced by the composition of the feed and the feed conversion ability. The total nitrogen (N) excreted by laying hens can be reduced in the long term by up to about 25% [47]. This is a substantial contribution. However, for various reasons (e.g. costs, time for research and development) implementation is limited or impossible in the short term. Moreover, N-excretion cannot be totally prevented by these measures.

(2) Control of moisture content. Dilution of manure, i.e. slurry, by adding water lowers the N concentrations. The increase in the amount of slurry is a big disadvantage.

Drying, by stimulation of water volatilisation from manure and litter, raises the dry matter content. Control of the local climate is used here to change process conditions in the manure. Sorption isotherms might yield practical values for dry matter contents to reach minimum A_w values in order to minimise the degradation rate [24]. Until now, not much is known about the features of these curves for manure and litter. After all, drying reduces the amount of manure and improves its quality. Drying of manure and litter can also be achieved by composting. But the drawbacks of composting are that it generally causes high emissions of ammonia. Spontaneous composting must therefore be minimised. Intensive composting can be prevented by reducing the water content [48]; this minimises the rate of degradation.

(3) *Control of pH.* The micro flora and enzyme activity can be reduced by lowering the pH. Besides affecting degradation, this also strongly affects the ammonia-ammonium equilibrium. Decreasing the pH by adding liquid acids like ferrous sulphate or superphosphate to slurry or litter can reduce ammonia emissions, but practical problems have arisen (homogeneous mixing, increased moisture content). Furthermore, large amounts of acid are generally required (this raises the costs) and precautions must be taken to safeguard people and birds [23]. Finally, adding of liquid acids leads to an undesirable increase of the mineral content of the litter and corrosion problems concerning equipment may occur.

(4) *Control of temperature.* Lowering the temperature slows down the degradation processes and has a favourable effect on the process equilibrium for ammonia. Temperatures down to 10 °C are necessary to have a substantial effect on the degradation and volatilisation. Using temperatures below a range of 20 to 25 °C as a control parameter inside the poultry house may interfere with the climatisation of the birds' environment; higher temperatures should, of course, also be prevented [49]. So, temperature can hardly be used as a control parameter.

(5) *Control of bacterial processes.* Only in the case of nitrification followed by full denitrification is nitrogen permanently removed from the manure or litter. N-fixation is only a temporary solution (immobilisation). Certain conditions (C/N ratio, aerobic/anaerobic, water content) must be met if these processes are to reduce the ammonia concentrations substantially. The optimal values for the process parameters may differ or may even conflict. Control of these processes inside a housing system in practice will be difficult. Therefore, these processes are generally not considered to contribute to a solution of the problem of emissions [50].

(6) Once ammonia has been formed, its *volatilisation can be reduced* [36] by: (a) reducing the surface area of manure exposed to air, (b) reducing the time manure is in contact with air (regular removal of manure out of house) or (c) reducing the air velocity (e.g. closed storage systems). Contact time and contact area can be affected by the design of the housing system and waste management. Air velocity in the house is mainly determined by the ventilation process.

(7) *Physical* (adsorption) or *chemical fixation* of ammonia and other N-components to certain materials (e.g. carbon, clay minerals, formaldehyde, salts). Small or temporary effects have been reported, but the large amounts of additives required together with negative side-effects reduce the feasibility of applying this technique in practice [50,51]. Although significant reductions have been achieved by adding calcium and magnesium salts during manure decomposition [52] or peat as litter material [53], practical application could mean an undesirable input of minerals to (calcium, magnesium) or increase of the amount of manure.

(8) *Air cleaning.* The practical application of bioscrubbers, biofilters or chemical scrubbers remains limited due to relatively high costs and the technical problems due to dust in poultry houses. Moreover, only mechanically ventilated buildings can be equipped with air cleaning devices and an 'end of pipe' technique does not reduce ammonia concentrations inside the poultry house [54].

From the preceding chapters it can be concluded that the following processes and circumstances may cause high emissions of ammonia in practice: (a) composting of manure and litter, during drying or storage (b) volatilisation of ammonia from open storage of slurry and (c) high degradation rates in wet

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From the preceding chapters it can be concluded that the following processes and circumstances may cause high emissions of ammonia in practice: (a) composting of manure and litter, during drying or storage (b) volatilisation of ammonia from open storage of slurry and (c) high degradation rates in wet litter, in the house or during storage. To reduce ammonia emissions the principles mentioned under (2) and (6) are considered to have the best chances of being implemented on commercial farms, that is, control of moisture content by means of drying and reduction of ammonia volatilisation by lowering contact time, contact area and air velocity. Both principles are based on the control of the local climate above the manure and litter. However, the control (increase) of air temperature and velocity, and also contact time and area, in order to enhance the drying process conflicts with the goal of reducing ammonia volatilisation. But, due to the relatively slow degradation rates of nitrogen components in droppings, the amount of liberated ammonia will be small if the degradation process is minimised by the higher dry matter content (lower A_w value) within a sufficiently short period.

5 Ammonia emissions from housing systems

The effect of various ways of manure handling by means of different techniques and of other influencing factors on the emissions from houses for laying hens on commercial farms are discussed in this section. The different techniques and factors are classified as follows: the housing system, the animal, the climatisation of the environment and the farmer's management strategy. Differences and similarities between battery cages and alternative systems are discussed.

5.1 Housing systems

Kroodsma *et al.* [48] showed that manure drying on belts reduced the increase of ammonia emission during a period of one week (31 g NH_3/yr per hen) compared with the system without drying and removal of the manure twice a week (34 g NH_3/yr per hen). Similar results are reported by Chiumenti *et al.* [55]. Emissions from manure on belts after one week of drying with dry matter contents above 50% were less than half of those with dry matter contents lower than 40% (Ref. 56). These results are confirmed by Frenken and Petersen [57] who investigated the changes in concentrations of nitrogen components of droppings. The ammonia emission from deep-pit and channel houses, i.e. systems with manure composting, was estimated to be 386 g NH_3/yr per hen (Ref. 7). Kroodsma *et al.* [48] simulated the composting of dried poultry manure from hens during the storage period. They found an inverse relationship between the amount of ammonia lost from manure and the dry matter content; the ammonia emission varied between about 100 and 200 g NH_3/yr per hen. This is up to seven times higher than that from a housing system with drying of manure on belts. The results of this simulation confirmed the high emission from systems with composting. Demmers *et al.* [58] investigated the drying of droppings in a tunnel next to a poultry house. The manure was transported from the house to the tunnel twice a day. Low emissions from the animal house and the drying system, 10 g NH_3/yr per hen, could be achieved if a minimum dry matter content of 60% was reached within 50 h after the droppings had been excreted. These data are confirmed by measurements on another drying tunnel [59]. The rate by which the dry matter content increases during composting apparently leaves enough time for high degradation rates due to (near) optimal conditions. By means of forced drying a sufficiently high drying rate can be reached to avoid these harmful effects of composting.

The ammonia emission from housing systems for laying hens with litter were about four times higher than with battery cages (Oldenburg [60]). The reported levels were about 200 and 50 g NH_3/yr per hen respectively. Ehlhardt *et al.* [61] found that ammonia concentrations in the TWF aviary system were higher than in the battery system. This led to higher emissions from the TWF system, being 90 g NH_3/yr per hen, compared with battery system with belts (figure 2) [62]. Appleby and Hughes [14] also reported high ammonia concentrations in deep litter houses for laying hens, particularly compared with battery houses. In the Netherlands the ammonia emission from deep litter systems for laying hens was estimated to be 178 g NH_3/yr per hen. Despite the differences in droppings and behaviour between laying hens and broilers, the litter in broiler houses is also a cause of high ammonia concentrations. Elliot and Collins [23] and Carr and Nicholson [63] achieved reduction of ammonia volatilisation by adding acid liquids to broiler litter. They emphasised the practical problems with application rates, e.g. because the higher moisture content promotes degradation. Despite its effectiveness, pH control of litter seems not feasible in the Netherlands.

The efficacy of an insulated concrete floor in combination with floor heating on the litter composition and hence on the emission from a broiler house, was demonstrated by Ouwerkerk and Voermans [64] and Hedström and Nilsson [65]. The higher dry matter contents of the litter were attributed to the prevention of the condensation of water vapour on the floor. But the effect of floor heating on the emission depends on various factors, e.g. the ground water level and the outside climate [48]. Improving the litter quality in a broiler house by blowing air through the litter reduced the ammonia emission up to 90 % compared with the traditional system [66].

The stocking density of battery cages, the number of hens per square meter of ground floor, hardly affects the ammonia emission per hen [60]. In alternative systems, however, the ammonia emission from litter will depend on several factors. Many factors influence the amount of droppings that is dropped upon the litter. They include the proportion of the litter area as part of the total living space, the system design and the stocking density. However, little is known yet about the quantitative effect of these factors on the emission.

5.2 The animal

In this section the droppings, the heat production and the behaviour of the hens are discussed. Droppings production and composition depend on the food and water intake, food composition, age of the hens and egg production [9]. Age and breed have been reported to influence the total amount of droppings and percentage of dry matter of the droppings [18]. Besides the normal variation in heat production, an interaction with the local climate and the hens' behaviour can be expected in hens kept in loose housing systems. The feed consumption of hens kept in loose houses, e.g. alternative systems, will be higher than of hens kept in battery cages. This is probably due to more activity, a higher feed intake and consequently a higher heat production.

Hens in alternative systems have freedom of movement. Their behaviour determines where they deposit their droppings, in the litter or on the manure belts. The siting and type of equipment in the house and the areas of litter and tiers may influence the distribution of the hens through the system [67]. In some alternative systems the hens have controlled access to the litter area. In others the scratching and dust bathing in litter is stimulated by means of the supply of e.g. oats. The use of the litter will affect its dry matter content, in combination with the physical circumstances. The effects of high ammonia concentrations in the hens' house, often partly as a result of the presence of litter, have been discussed in relation to health, diseases and welfare of the hens [68,69] and working conditions for men [70,71,72]. From this point of view it is preferable to apply techniques that prevent ammonia being produced instead of using air cleaners as an ‘end of pipe’ method for reducing ammonia emissions.

5.3 Climatisation

Although the animal climate is very complex, climatisation is generally based on control of temperature only [73]. Ventilation is used to equalise the heat balance of the house. Heat transport through the building (roofs, walls, floors), the temperature of the indoor and outdoor air and the ventilation process determine the storage, supply and discharge of energy. The ventilation rate is thereby influenced by the stocking density, insulation of the animal house, outside climate and control strategy. The air velocity pattern depends on the ventilation rate, the siting and size of the inlets and outlets, the siting of elements inside the house and the distribution of the hens within the house.

As well as affecting the animal environment, climatisation also affects the temperature, the relative humidity and the air velocity above the manure and litter in the housing system. An increase of temperature above the set point temperature [74], generally about 22 °C, should be prevented because degradation and volatilisation processes are highly favoured. Oldenburg [60] found a positive linear relationship between outside temperature and ammonia emission from battery houses. He also showed higher emission rates during the day period. These effects were contributed to by a combination of variations in the ventilation rate, the inside temperature and the diurnal animal activity. In the case of forced drying of manure e.g. on belts under cages, the local climate is deliberately influenced in order to stimulate water evaporation [45]. Ehlhardt *et al.* [61] reported the use of faster ventilation rates in a TWF aviary system to eliminate excess ammonia. This resulted in lower inside temperatures, despite the greater heat production of the freely moving hens [49]. Higher stocking densities allow faster ventilation rates which result in lower ammonia concentrations [14]. Despite the clear relation between ventilation (e.g. system and air exchange rate) and the local climate, hardly any examples are known of the quantitative effect of singular factors on the emission.

5.4 Management

Although management is the collective name for the farmer's activities, in this context especially those elements related to the handling of manure and litter and the climatisation of the animal environment are discussed. The frequency of manure removal from the belts underneath the wire floors or in the manure pit determines how long the manure remains in the building. The effect of frequent manure removal (twice a week) on the ammonia emissions from battery houses with belts compared to slurry storage under the cages has been shown by Kroodsma *et al.* [48]. The emissions from these two systems were 34 g NH_3/yr per hen and 83 g NH_3/yr per hen respectively, a difference of about 60%. From the results of Demmers *et al.* [58] it can also be concluded that a further, substantial emission reduction from battery systems with manure belts can be achieved by raising the frequency of manure removal from twice a week to twice a day. A minimal emission is predicted [58] of 10 g NH_3/yr per hen. Full mechanisation and automation seem necessary for daily manure removal.

The quality of the litter in loose housing systems can be classified as good if it is dry and granular. Management of the litter may consist of removing accumulated litter and loosening it manually or mechanically. Both measures may improve the drying of the litter, but loosening of wet litter in a turkey house raised the emission considerably over several hours [75]. Loosening will also be achieved by stimulating the scratching behaviour of hens by supplying oats or grain. Removal of the litter may be necessary if the layer becomes too thick [76]. In the case of automatically controlled ventilation, temperature set point, bandwidth and sensitiveness of the climatisation can be adjusted to the farmers' wishes. There is a resemblance between laying hens and broilers concerning the use of the equipment and the housing system and their effect on the litter [77].

6 Measurement of ammonia emissions

The amount of ammonia emitted from a building is the sum of the mass flows through all outlets. Each mass flow is the product of the ventilation rate times the ammonia concentration [78]. Both parameters must be registered continuously to determine the ammonia emission. Techniques are available to measure both ammonia concentrations and ventilation rates [79, 80, 81]. With these techniques high requirements on the accuracy of the emission rates can be met. However, efforts are made to calculate ammonia losses from poultry houses on the basis of nitrogen input-output balances [9]. A special note should be made about the accuracy of this method. In the case of laying hens the ammonia losses measured represent only a small part, about 3 to 20% depending on the housing system, of the total amount of nitrogen in the manure [36]. In addition, errors due to sampling of inhomogeneous chicken manure or litter, and errors when determining the N content in manure cause errors in the estimation of the ammonia losses that are often as large as the losses themselves.

7 Conclusions

The degradation and volatilisation of ammonia can be reduced by control of temperature, pH and water activity (A_w) in the manure and litter. Temperatures in the animal house must therefore be kept close to 20 °C. Despite its effectiveness, the application of pH control has too many negative side-effects. Forced drying of manure and litter lowers the water activity and gives a real possibility for reduction of emissions inside the housing system. Air temperature, relative humidity and velocity are controlled to enhance the volatilisation of water during drying.

Reduction of ammonia emissions can be achieved by changing over from deep-pit and channel houses to battery houses with manure belts. In this way composting is prevented and regular removal of manure to a storage system is possible. Reduction can be reached by drying of manure on the belts or by increasing the removal frequency of wet manure to a closed storage system from weekly to twice a day. In the case of manure drying on belts or in a drying tunnel, the drying rate is crucial. A minimum dry matter content of approximately 60% must be reached within about 50 h after the droppings are produced in order to minimise degradation rates and prevent high emissions of ammonia.

The emission of ammonia from alternative housing systems with litter on the floor surface is several times higher than from battery houses with belts due to the long stay of the litter inside the house. A higher dry matter content of litter will reduce degradation rates of the nitrogen compounds and therefore the liberation of ammonia. However, no techniques have been applied yet in the case of laying hens to reduce the high emissions from litter. Moreover, the critical boundary for the amount of water or 'water activity' in the litter, is not known yet. Also during storage of dry manure and litter, lower moisture contents are needed as they will reduce composting and hence emissions of ammonia. Accurate measurement of both ventilation rates and ammonia concentrations are necessary for a comparison of emissions of ammonia from housing systems for laying hens.

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CHAPTER 3

The Effect of Manure and Litter Handling and Indoor Climatic Conditions on Ammonia Emissions from a Battery Cage and an Aviary Housing System for Laying Hens

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Abstract

Ammonia emissions from both traditional and new welfare-based housing systems for laying hens must be reduced to prevent detrimental effects on the environment. In a comparative study the effect of only manure handling (variation in drying and removal frequency) in a battery cage and the effect of manure handling (as in battery cage system) and litter treatment (removal of litter) in a Tiered Wire Floor (TWF) aviary system on the emission of ammonia were investigated. Each system housed 6480 hens, manure and litter treatments were varied in time, and effects were analysed by means of time-series analysis.

The hens in the TWF system deposited 22.5% of their droppings in the litter and the remaining part, like all manure in the battery cage system, was dropped on the manure belts. The estimated emission from the manure on the belts in both systems was 18.8 g/h (daily mean, manure removal twice a day), whereas the emission from the litter in the TWF system amounted to 62.5 g/h. Emission from the belt manure on a typical day increased with 14, 39, 109 and 177% from the 1st until the 4th day after manure removal. The effect of temperature and water vapour pressure difference on the emission was +17 and -22% per degree and per kPa, respectively. Drying the manure on the belts increased the dry matter content of the manure and showed a tendency to lower emissions.

The dry matter content of the litter varied between 780 and 840 g/kg, the mean total nitrogen content was 3.3% of the dry matter, and the layer thickness varied between 2 and 9 cm. Both the unionised ammonia content, which ranged between 20 and 190 mg/kg, and the layer thickness of the litter had a positive influence on its emission.

1 Introduction

Ammonia emissions from both traditional and new welfare-based housing systems for laying hens have to be reduced to prevent detrimental effects on the environment (Heij and Schneider, 1991). This implies that the level of ammonia emission will be an important factor for the acceptance of these systems and their sustainability in the future. Blokhuis and Metz (1992) concluded that aviary housing systems for laying hens meet most of the behavioural needs of the hens and seem promising in terms of egg production. However, one of the drawbacks of these housing systems is a high ammonia emission. Preliminary research into the emission of ammonia from the Tiered Wire Floor (TWF) aviary system showed emission rates that were about three times higher than the rates from battery houses (Groot Koerkamp and Metz, 1992). Further research into the factors that are involved in the emission of ammonia is necessary to develop solutions so that ammonia emissions from these housing systems can be reduced.

Manure handling and litter conditions strongly affect the emission of ammonia from housing systems for laying hens. The degradation process of uric acid and undigested proteins in the manure and litter to ammonia is mainly influenced by dry matter content, temperature and pH. The drying of manure and litter is influenced by the temperature, water vapour pressure difference and velocity of the air. The total nitrogen and ammonia concentrations in the manure and litter are influenced by the degradation process and the volatilisation of ammonia (Groot Koerkamp, 1994).

This paper summarises a comparative study of the effects of manure handling in a battery cage and a TWF system and the effects of litter treatment in the TWF system on ammonia emissions. Its purpose is to present insight about the quantitative effects of the various factors influencing the ammonia emission and explain differences between the two housing systems.

2 Materials and methods

2.1 Housing systems

The hen house in this experiment consisted of two completely separate rooms of 14 by 23 m. The rooms were identical except for exterior insulation of the floor of the room with the aviary system. Each room had its own light regulation and a mechanical ventilation system. Outside air entered the rooms through inlets in the side-walls, mixed with the indoor air and was blown outside by means of ventilators in the ceiling. The room temperatures were set at 22 °C. One room was equipped with a conventional battery cage system with manure belts. The cages were 0.50 m wide and 0.45 m deep, could house up to five hens and were placed in six rows of three tiers. The other room was equipped with the Tiered Wire Floor (TWF) aviary system. It consisted of four rows of stacked wire floors and four rows of laying nests. The concrete floor was completely covered with approximately 5 cm of sand at the beginning of the laying period. The characteristics of both systems are given in table 1. A cross-section of the TWF system is given in figure 1. The TWF system is extensively described by Ehlhardt *et al.* (1988, 1989) and Blokhuis and Metz (1992).

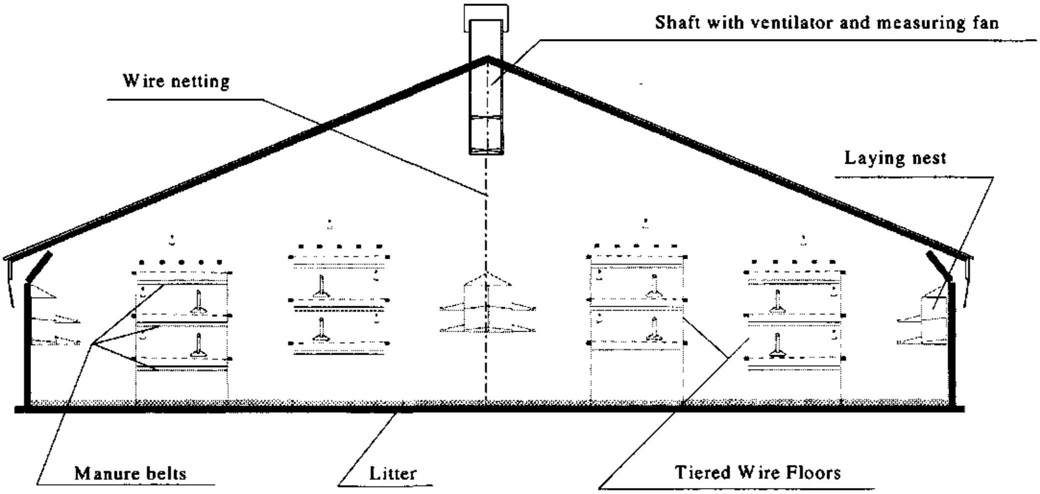

Figure 1 Cross-section of the Tiered Wire Floor (TWF) system.

The droppings produced by the hens fell onto the conveyer belts underneath the cages in the battery cage system and underneath the wire floors of the tiers in the TWF system. All belts were equipped with a manure drying system (Kroodsma *et al.*, 1985). Air from outside was warmed up in a heat exchanger, one for each room, and blown through tubes with holes above the manure belts (holes with a diameter of 3 mm and a distance between them of 10 cm). The conveyer belts transported the belt manure outside the house where it was taken away by means of containers. The hens in the TWF system deposited their fresh droppings partly in the litter.

Table 1 Characteristics of the battery cage system and the Tiered Wire Floor (TWF) system.

	Battery cage	TWF
Number of hens (20 weeks of age)	6480	6480
Stocking density (hens/m ground floor)	20.1	20.1
Stocking density (m^2/hen)	0.045	0.100
Ventilation capacity (m^3/h per room)	30,000	30,000
Number of rows of tiers	6	4
Number of levels (cages or wire floors)	3	3
Litter area (m^2)	0	303

Both the cage and the TWF system were, in length, divided into two sections. In the TWF system sections were separated by means of wire netting. In each system one section was used for 3240 light-weight White Leghorn hens (LSL) and the other for 3240 middle-weight Brown Leghorn hens (ISA Brown). Hens were fed a commercial diet at a restricted level. Water was supplied during the lighting period by means of nipple drinkers. At night the water supply was cut off. Light schemes based on optimal management were used: 16 hours light (L): 8 hours dark (D) in the TWF system, and an intermitting scheme of 1L:3D per hour during 16 hours in the cage system. Both cage and TWF hens were debeaked to prevent problems with cannibalism.

2.2 Treatments

The experiments were carried out with hens that were 41 weeks old at the start of the experiment. The experiment lasted a total of 173 days (March until September 1992). The treatment schedule is given in figure 2. The age of the hens (weeks) was used as the time basis. The handling of manure on the belts in both systems was varied and repeated in four blocks, beginning in weeks 45, 50, 59 and 63. Three drying treatments were applied: A (no drying), B and C (both drying). Drying treatment C was only applied in the TWF system and differed from treatment B. In treatment C

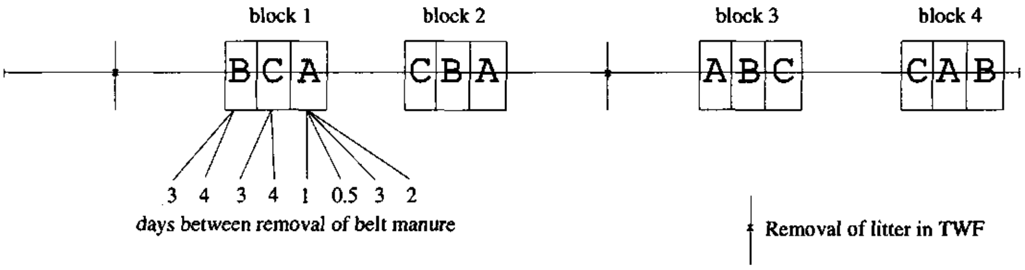

Figure 2 Treatment scheme with the treatments of manure on the belts for the Tiered Wire Floor (TWF) system and battery system; without manure drying (A) or with manure drying on the belts with equal (B) or adjusted (C) distribution of drying air and manure removal interval in days. The litter treatments in the TWF system are also indicated.

most of the drying air was passed over the manure on the belt of the upper floors. Each drying treatment lasted 7 days and was randomly carried out within a block. Within a drying treatment the removal frequency was varied. For drying treatments B and C, manure was removed after 3 or 4 days; for drying treatment A manure was removed after 0.5, 1, 2 and 3 days. These removal frequencies were assigned randomly within a drying treatment. All days in the experiment were given a letter-number combination. The letter indicated the drying treatment, whereas the number indicated the number of days since the belt manure had been removed. For example, code B3 was used for the 3rd day after manure removal when manure drying treatment B was applied. This day was preceded by days with code B2 and B1. Manure was removed between 11 00 and 12 00 hours, and for treatment A0.5 also between 20 00 and 21 00 hours. To reduce the thickness of the layer, most of the litter in the TWF system was removed at week 43 and again at week 55. Manure drying treatment B was applied during the periods of the litter treatment and between the blocks.

2.3 Measurements

Measurements of ammonia concentrations and ventilation rates were continuously carried out in all ventilation shafts according to the method described by Scholtens (1993). Temperature and relative humidity were measured by means of combined sensors (Rotronic I-100) that were placed in the centre of each room: one above the manure belt of each tier, one at a height of approximately 2.5 m and in the TWF room also one above the litter. The temperature in the litter was measured at four spots, two in each section (AD-592 sensors). A combined sensor was placed outside close to the inlet openings, so that the temperature and humidity outside could be measured as well. Hourly averages of ammonia concentration, ventilation rate, temperature and humidity were automatically recorded (Bleijenberg and Ploegaert, 1994). The ammonia emission was calculated to be the difference between the concentration of ammonia in the exhaust air and in the inlet air multiplied with the volume of exhaust air. The following data were calculated: total ventilation rate, mean ammonia concentration of the exhaust air, total ammonia emission, mean temperature and humidity above the manure belts and mean temperature in the litter. Air temperature and humidity above the manure belts and the litter were used to calculate the saturated and the actual water vapour pressure of the air (Anon., 1993a). The water activity of manure and litter with a dry matter content above 20% (wet base) and temperatures between 20 and 30 °C is 0.9 (Beeking *et al.*, 1994). The water vapour pressure in the manure and litter was therefore calculated to be 0.9 times the saturated water vapour pressure. Daily means were calculated from noon until noon. Egg production and feed and water intake by the hens were daily registered per section.

Manure and litter samples were taken separately in the sections. Samples of belt manure were taken during the drying and removal treatments in all blocks. During the removal of the belt manure approximately 10 samples of manure were taken from the conveyer belt at a fixed time interval and mixed. This sample was taken for analysis of dry matter content (NEN 6620). Manure samples of days with treatment A0.5 were also analysed on the content of total nitrogen (NEN 6481), total ammoniacal nitrogen (TAN) (NEN 3235 4.1), inorganic matter (NEN 6620) and pH. The pH was determined in a mixture of two parts demineralised water and one part manure. The amount of belt manure per section was weighed after each treatment A2 (a total of four times). Litter samples were taken during each treatment block, before and after litter removal (total nine times) from 10 designated spots that were evenly distributed per section. The samples were mixed and analysed on total nitrogen, TAN, dry and inorganic matter content and pH. Along with the litter samples, the quality of the litter and the thickness of the layer were measured (total eight times). The quality was subjectively estimated on a linear scale from 1 (wet and soppy) to 9 (dry and friable).

Notation

η_t	Natural logarithm of the daily mean ammonia emission (g NH_3/h)
ε_t	Deviation between the measured and predicted daily mean ammonia emission
$C_{BC,bm}$	Mean ammonia emission from the belt manure in the battery cage system
$E_{TWF,bm}$	Effect of the TWF system on the mean ammonia emission from the belt manure
$E_{A,B,C}$	Effect of drying of belt manure, treatment A, B and C
E_{DAR}	Effect of removal frequency of belt manure, i.e. number of Days After Removal
$T_{bm/litter}$	Mean temperature of the air above the belt manure in both systems or in the litter in the TWF system (°C)
$P_{difbm/litter}$	Difference between the saturated water vapour pressure times 0.9 and the actual water vapour pressure of the air above the belt manure in both systems or of the air above the litter in the TWF system (kPa)
$C_{TWF,litter}$	Mean ammonia emission from the litter in the TWF system
$c_{NH_3,litter}$	Unionised ammonia content in the litter in the TWF system (mg/kg)
D_{litter}	Layer thickness of the litter in the TWF system
α_i	Regression coefficient for co - variable i

2.4 Statistical analysis

All singular manure and litter data were statistically analysed (ANOVA) on an arithmetic scale whereas the measurements in time were used as pseudo-repetitions. The trends in TAN content (NH_3 plus NH_4^+) and pH in the litter were modelled with spline-functions of order 6 with time as the independent variable. The unionised ammonia content of the litter (NH_3) was calculated with the empirical relation for poultry manure of Hashimoto (1972). The pK_a of this empirical relation is 10.1 instead of 9.4 that is used for aqueous solutions. The rate of increase of the thickness of the layer of litter was estimated with a linear model with time as the independent variable.

The differences between the battery cage and the TWF system in the ventilation rate, the ammonia concentration in the outgoing air and the ammonia emission were quantified by using the natural logarithm of these variables. The use of the logarithmic scale implies that proportional effects were studied instead of absolute effects. The logistic curve was used to describe the fixed effects of the outside temperature on the ventilation rate in both housing systems. The deviation was assumed to follow an auto-regressive process of order 1. The calculation method was essentially the same as the one used for the ammonia emission.

2.5 Model for the emission of ammonia

The ammonia emission process is influenced by time-dependent processes such as air temperature and ventilation rate. Thus statistical techniques involving time-series analysis were used. The natural logarithm of the daily mean ammonia emission (called log emission), instead of the absolute level of emission was modelled. In this way the emission is kept positive. The variance is assumed constant on the log scale and corresponds to a constant coefficient of variation of the emission. It is our experience that this is more realistic than the assumption of constant variance for the emission itself. A linear model for log emission means a multiplicative model for emission. Let z_t be the log emission at time t, η_t be its mean and ε_t be the deviation, then

$$z_t = \eta_t + \varepsilon_t \tag{1}$$

Hence, η_t will depend on time-dependent explanatory variables and ε_t will represent the deviation of observation z_t from its mean. The mean and the deviation are functions of time. For ease and clarity of notation the index t is omitted in the equations below. The emission was considered to be the result of two separate and independent processes. The first was the emission from the belt manure and the other was the emission from the litter. Belt manure existed in both systems, but litter existed only in the TWF system. Define η_{bm} and η_{litter} as the mean log emission from the belt manure and from the litter respectively. The mean log emission from both processes together then becomes:

$$\eta = \log(e^{\eta_{bm}} + \delta_{TWF} \cdot e^{\eta_{litter}}) \tag{2a}$$

in which δ_{TWF} indicates which observation belongs to the TWF system ($\delta_{TWF}=1$) and which to the battery cage system ($\delta_{TWF}=0$). In this way it was possible to model the measurements of both systems in one analysis. The separate processes were represented by the following equations:

$$\eta_{bm} = C_{BC,bm} + E_{TWF,bm} + E_{A,B,C} + E_{DAR} + \alpha_1 \cdot T_{bm} + \alpha_2 \cdot P_{diff,bm} \tag{2b}$$

and

$$\eta_{litter} = C_{TWF,litter} + \alpha_3 \cdot T_{litter} + \alpha_4 \cdot P_{diff,litter} + \alpha_5 \cdot c_{NH_3,litter} + \alpha_6 \cdot D_{litter} \tag{2c}$$

In this way the daily mean emission from both systems for each day in the experiment was estimated. The letter-number combination of each day was used for the estimation of the effect of the drying treatment and removal frequency. The deviation ε_t was assumed to follow an auto-regressive process of order 1:

$$\varepsilon_t = \varphi \cdot \varepsilon_{t-1} + a_t \tag{3}$$

with a_t being independently distributed errors called innovations, with zero mean and variance σ^2_a, the innovation variance. The ϕ is the correlation between successive observations. The ε_t is a weighed sum of past innovations. The relationship between σ^2_ε, the variance of ε_t, and σ^2_a is:

$$\sigma_\varepsilon^2 = \frac{\sigma_a^2}{1 - \phi^2} \tag{4}$$

2.6 Estimation and inference

The relationship between η_t and the explanatory variables, expressed in equations (2a) to (2c) is partly non-linear. To keep as much of the linearity as possible the model was considered a generalised linear model (GLM) that links η to the contribution of the belt manure η_{bm}, whereas η_{litter} is the contribution of the litter, which was considered to be the non-linear part, containing the parameters of the link function. The advantage of this is that the general solution of GLM can be used, being an iterative reweighed regression, with adjusted response and explanatory litter variates and weights depending on the relative contribution of the belt manure. Appendix 2 derives and describes the algorithm in detail.

The solution for the fixed part of the model has been formulated as a linear regression, therefore the complete model is linear with auto-regressive errors. For this model a maximum likelihood solution can be obtained with existing software, such as the time-series facilities of Genstat 5, Release 3 (Anon., 1993b). The analysis results in estimates of regression coefficients with standard errors.

The assumption of constant innovation variance after fitting of the model was checked by inspecting residual plots and found to be adequate for the purpose of this research. The assumption of an auto-regressive process of order 1 was checked by inspecting the partial correlogram and the spectrum and was also found to be adequate.

The σ^2_ε was used as measure for the goodness of fit, which resulted from the innovation variance σ^2_a and auto-regressive parameter ϕ. The amount of variance explained by the regression parameters in equations (2a) to (2c) was indicated by the percentage of σ^2_ε. Estimated standard errors (s.e.) of parameter estimates of time-series analyses were multiplied by 1.96 to calculate 95%-confidence intervals. A sensitivity analysis of the model was carried out where explanatory variables were varied between the minimum and maximum value of the measurements.

3 Results

3.1 Production results

The production results of the hens in the two housing systems are shown in table 2. Statistical analysis of the production results was not found to be useful due to the lack of repetitions. Hens in the TWF system produced almost the same number of eggs as the hens in the battery cage system. The egg weight of the hens in the TWF system was 1.6% lower and their feed intake was 2.6% higher. This resulted in a 4.6% higher feed conversion ratio. The water:feed ratio was almost equal for the hens in both system, as was mortality, which was low.

Table 2 Mean production results of the laying hens in the battery cage system and the Tiered Wire Floor (TWF) system from 20 to 84 weeks of age.

	Battery Cages			TWF		
	LSL	Isabrown	Total	LSL	Isabrown	Total
Number of hens housed	3240	3240	6480	3240	3240	6480
Egg production (number of eggs / housed hen)	366.3	352.5	359.4	364.1	350.7	357.4
Egg production (kg egg / housed-hen)	23.65	23.09	23.37	23.45	22.52	22.99
Feed consumption (g / day per hen)	118.3	116.8	117.6	120.5	120.6	120.6
Feed conversion ratio (kg feed / kg egg)	2.18	2.21	2.19	2.25	2.32	2.29
Water:feed ratio (g / g)	2.04	2.00	2.02	2.02	1.97	2.00
Mortality (%)	7.19	6.02	6.61	7.27	9.67	8.47

3.2 Manure and litter

Table 3 shows the production and composition of belt manure. The amount of dry matter of manure on the belts in the TWF system was about 80% of the manure production in the battery cage system. The dry matter content of the belt manure sampled after 12 hours, which from now on will be called fresh droppings, was 48 g/kg higher in the TWF system and the total nitrogen content was 5.4 g/kg lower. These differences were significant. About 20% of the nitrogen was present as ammoniacal nitrogen, and the pH was less than 7. Table 4 shows that for all drying treatments and removal frequencies, higher dry matter contents were found in the TWF system. In both systems, dry matter contents of the manure on the belts increased as it remained in the house longer. Through drying of manure, treatment B, the dry matter contents in both systems were raised significantly as compared to not drying. The adjusted air flow in treatment C in the TWF system did not result in higher dry matter contents than in treatment B.

Table 3 Mean production (during treatment A2) and composition (during treatment A0.5) of belt manure for the battery cage system and the Tiered Wire Floor (TWF) system.

Manure		Battery cages mean	TWF mean	s.e.d.
Production	g/day per hen	137.5	89.4^{***}	4.52
	g dry matter/day per hen	38.3	30.5^{***}	1.80
Composition				
Dry matter content	g/kg manure	244	292^{***}	8.0
Total N	g/kg dry matter	50.5	45.1^{**}	1.92
Total Ammoniacal Nitrogen	% of total N	21.3	18.9	2.56
pH	-	6.7	6.8	0.09
Ash content	% of dry matter	24.3	22.9^{*}	0.52

* $P<0.05$, ** $P<0.01$, *** $P<0.001$

Table 4 Mean dry matter content (g/kg) of belt manure of four blocks after 8 drying and removal treatments (see figure 2) for the battery cage system and the Tiered Wire Floor (TWF) system.

Treatment	Battery cages	TWF
A0.5	245.9^{c}	290.3^{c}
A1	278.9^{b}	323.4^{b}
A2	288.7^{b}	333.2^{b}
A3	286.7^{b}	331.2^{b}
A4	300.2^{b}	344.6^{b}
B3	351.2^{a}	395.6^{a}
B4	364.6^{a}	409.1^{a}
C3	-	400.1^{a}
C4	-	413.6^{a}

$^{a-c}$ Column means without a common superscript differ significantly ($P<0.05$).

The litter in the TWF was dry (805 g/kg) and friable (quality 8.9 units), see table 5. The total nitrogen content was 33.3 g/kg dry matter, which was considerably lower than the concentration in the fresh droppings. The mean ash content and pH were higher in the litter than in the fresh droppings, and the relative TAN concentration was lower. The mean thickness of the litter was 5.4 cm, but varied in the course of time. Removal of the litter reduced the thickness 6.5 and 2.5 cm for the first and second time respectively, next it increased 5.65 mm/day. Figure 3 shows the variation of the dry matter, the total nitrogen and unionised ammonia content in the litter during the experiment. The highest dry matter content coincided with the highest total nitrogen content and the lowest unionised ammonia content and vice versa. The highest dry matter contents also coincided with the highest ventilation rates (not shown).

Table 5 Mean and standard error of the quality, thickness of the layer and composition of the litter in the Tiered Wire Floor system (DM = Dry Matter, TAN = Total Ammoniacal Nitrogen).

Quality (-) (n=16)	Layer thickness (cm) (n=16)	DM content (g/kg) (n=18)	Total N (g/kg dry matter) (n=18)	TAN (% of total N) (n=18)	pH (-) (n=18)	Ash content (% of DM) (n=18)
8.9 (0.06)	5.4 (0.50)	805 (6.3)	33.3 (0.36)	7.1 (0.60)	8.5 (0.10)	27.6 (0.31)

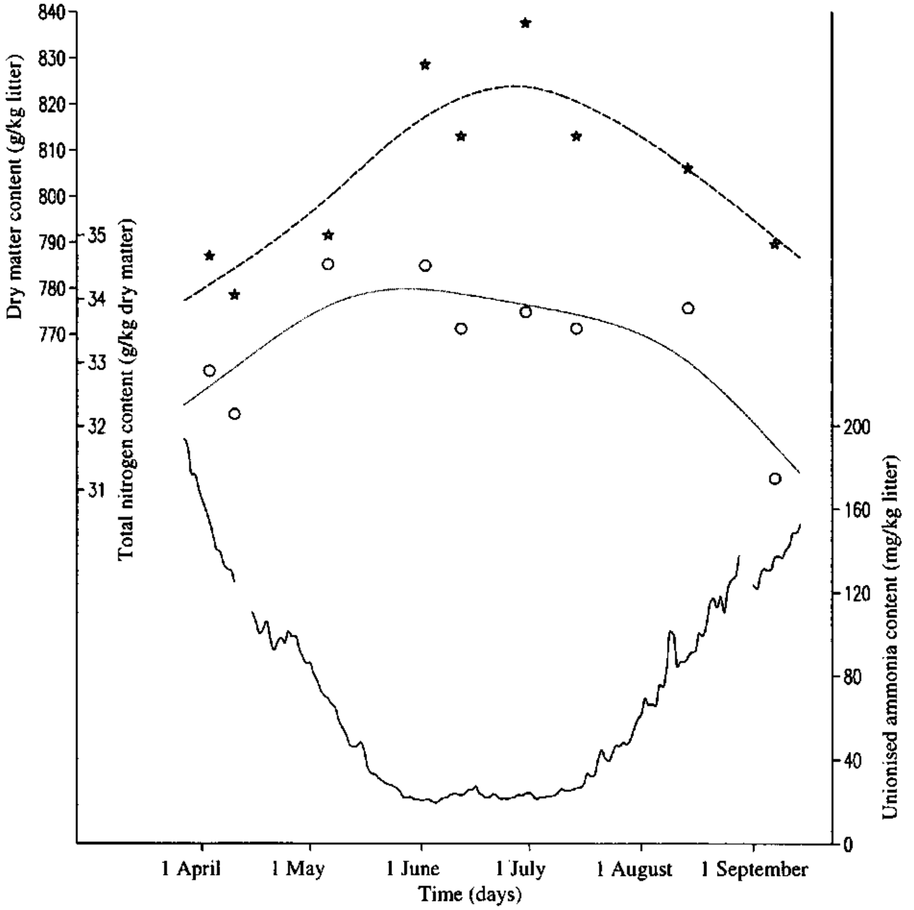

Figure 3 The dry matter (points: *, trend: ---), the total nitrogen (points: o, trend: ····) and the unionised ammonia content (——) of the litter in the Tiered Wire Floor (TWF) system during the experiment. The points are the mean values of the samples in the two sections.

Table 6 Results (means and s.e.) from the time-series regression analysis of the natural logarithm of the ammonia emission rate from two housing systems for laying hens. The means are also given on the linear scale (g/h or %).

	Symbol	Level or measured range	Battery Cages			Tiered Wire Floor		
			log scale		linear scale	log scale		linear scale
Parameter			mean	s.e.	mean	mean	s.e.	mean
Mean ammonia emission belt manure battery cage system	$C_{BC,bm}$	-	2.93	0.13	18.8 g/h	-	-	-
Effect of TWF system on ammonia emission belt manure	$E_{TWF,bm}$	-	-	-		-0.12	0.37	-11%
Drying treatment belt manure	$E_{A,B,C}$	A	-	-	-	-	-	-
		B	-0.06	-0.06	-6%	-0.06	-0.06	-6%
		C	-0.32	0.32	-27%	-0.32	0.32	-27%
Day After Removal belt manure	E_{DAR}	day 0.5	-	-	-	-	-	-
		day 1	0.13	0.06	14%	0.13	0.06	14%
		day 2	0.33	0.07	39%	0.33	0.07	39%
		day 3	0.74	0.07	109%	0.74	0.07	109%
		day 4	1.02	0.07	177%	1.02	0.07	177%
Temperature belt manure	α_1	21-29 °C	0.15	0.02	17%	0.15	0.02	17%
Water vapour pressure difference belt manure	α_2	0.4-1.7 kPa	-0.25	0.10	-22%	-0.25	0.10	-22%
Mean ammonia emission litter	$C_{TWF,litter}$	-	-	-	-	4.14	0.07	62.5 g/h
Temperature litter	α_3	19-29 °C	-	-	-	0.031	0.024	3%
Water vapour pressure difference litter	α_4	0.9-1.6 kPa	-	-	-	-0.19	0.18	-17%
Volatile NH_3 concentration litter	α_5	20-190 mg/kg	-	-	-	5.4 E-3	1.4 E-3	0.5%
Layer thickness litter	α_6	2-9 Cm	-	-	-	0.053	0.038	5%
ϕ	-	-	0.89	0.03	-	0.89	0.03	-

3.3 Emission of ammonia

The coefficients of the logistic curves of the ventilation rate versus the outside temperature were not significantly different for the two housing systems, except for the steepness of the curves. They were 1269 and 836 m^3/h per degree Celsius for the battery cage and TWF system, respectively. This resulted in lower ventilation rates in the TWF system when the daily mean outside temperature was above 12 °C and vice versa.

Ammonia concentrations in the exhaust air of the battery system varied between 0.50 and 5.51 mg/m^3 with the mean being 1.91 mg/m^3. These concentrations were significantly lower than the concentrations in the TWF system, which varied between 1.68 and 12.82 mg/m^3 and a mean of 4.59 mg m^3.

Table 6 shows the time-series coefficients of the model for ammonia emissions from the two housing systems. The effects per system are given in relationship to the mean emission from the belt manure and the litter. The mean for the belt manure represents the emission for the first level of the factors $E_{A,B,C}$ and E_{DAR} and the mean value of the co-variables temperature, water vapour pressure difference, unionised ammonia content and layer thickness. The mean emission from the belt

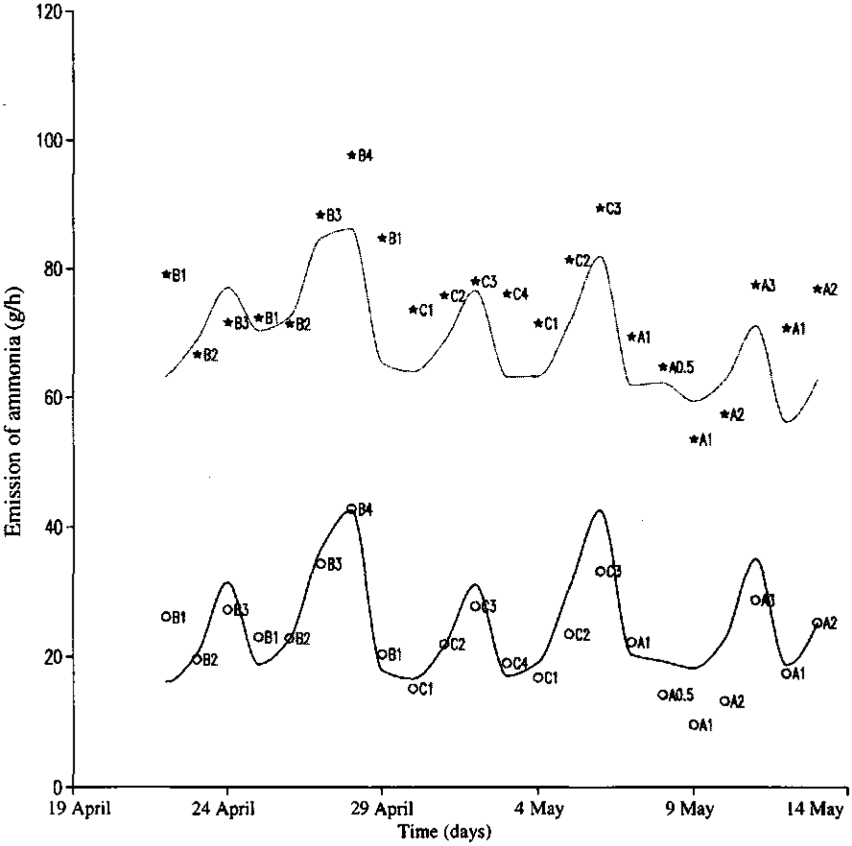

Figure 4 The predicted (lines) and measured (points) mean ammonia emission per day (g/hour) for the battery cage (— and o) and the Tiered Wire Floor (TWF) system (··· and *) during the first block with drying treatments and removal frequencies. The measurements are indicated with the treatment code.

manure in the TWF system ($e^{(2.93-0.12)}$ = 16.6 g/h) was not significantly lower than from that in the battery cage system ($e^{2.93}$ = 18.8 g/h). Drying treatment B and C decreased the emission from the belt manure by 6 and 27% respectively, but neither of these effects were significant. The emission from the belt manure increased by 14, 39, 109 and 177% from the first until the fourth day after manure removal. The effects of temperature and water vapour pressure difference of the air above the manure were significant and amounted to 17%/°C and -22%/kPa respectively.

The litter in the TWF system increased the mean emission from the aviary system with 62.5 g/h ($e^{4.14}$). The effect of the temperature in the litter on the emission, 3%/°C, was smaller than the effect of temperature above the manure belt. The effect of the water vapour pressure difference above the litter was -17%/kPa, similar to the effect it had above the manure belt. Neither the effect of temperature nor the effect of water vapour pressure was significant. The unionised ammonia content in the litter (mg/kg), which is shown in figure 3, increased the emission from the TWF system by

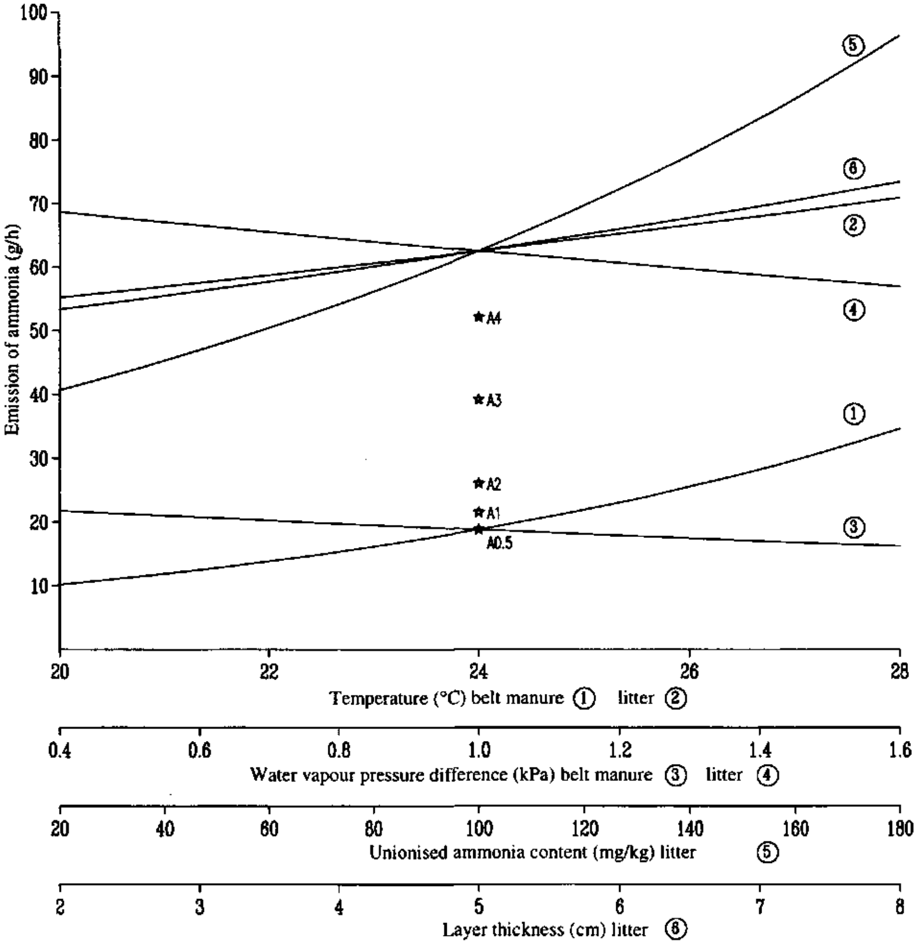

Figure 5 Sensitivity analysis of the ammonia emission model. The points (*) represent the predicted emission from the belt manure for drying treatment A from the first until the fourth day for the mean value of the co-variables shown on the x-axes. The effect of the co-variables on the emission from the belt manure is given relative to the treatment A0.5 (18.8 g/h). The effect of the co-variables on the emission from the litter is given relative to the mean (62.5 g/h).

0.5% per unit of concentration. The emission from the litter increased significantly with the layer thickness of the litter (5%/cm). A numerical example of the model is given in Appendix 2.

Figure 4 illustrates the predicted emission of the model along with the measurements for the battery cage and TWF system for the first block of drying and removal treatments. The model predictions follow the pattern of the measurements in both systems fairly well, but the deviations in the TWF system are greater.

A sensitivity analysis of the model for ammonia emission is given in figure 5. All effects on the emission from the belt manure are relative to the predicted ammonia emission for a typical day with treatment A0.5. The daily mean ammonia emission from the belt manure increased greatly for the treatment without drying (A) from the level of a typical day when belt manure was removed twice (A0.5) to the level of the 4th day after manure removal (A4). Drying treatment B and C showed a tendency towards lower emissions from the first until the fourth day after manure removal compared to not drying (not shown in figure 5). Air temperature had a strong positive effect on the emission from the belt manure, whereas the content of unionised ammonia in the litter influenced the emission from the litter much stronger than temperature and layer thickness. The water vapour pressure difference decreased the emission from both the belt manure and the litter. This effect was, however, relatively small.

4 Discussion

4.1 Production

The production results of both caged hens and TWF hens were in accordance with production standards in practice. The higher feed intake and the lower egg mass production agrees with earlier results of Ehlhardt *et al.* (1989) who found a 4.75% higher feed conversion ratio for the TWF hens. The higher feed conversion ratio can be explained by the higher energy requirements for activity. The mortality rate of this experiment was slightly higher than in a previously reported experiment (Blokhuis and Metz, 1992), but because this one lasted 8 weeks longer it was to be expected.

4.2 Manure and litter

The 2.5% higher feed intake of the TWF hens will have resulted in a higher manure production. About 22.5% of the droppings of the hens in the TWF system was dropped in the litter when it was assumed that the hens in the TWF systems also excreted 2.5% more dry matter. The amount of droppings deposited in the litter in two commercial hen houses was roughly estimated to be 36 and 32% of the total manure production (Evers *et al.*, 1992a and 1992b). The distribution of droppings will depend on the distribution of the hens in space, for example the sojourns of the hens on the different functional locations, and in time, for example the variation of the droppings production during a day. The amount of litter transported from the litter area to the manure belts in the TWF system by the hens (between their feathers) was estimated to be negligible. At least 20% of the nitrogen in the belt manure was degraded to ammonia within 12 hours, whereas it is assumed that fresh droppings hardly contain any ammonia. This means that degradation processes in the manure start immediately after excretion by the hens. Complete volatilisation of this amount of ammoniacal nitrogen would cause an emission of 126 g NH_3/h. Only a relatively small amount of this ammonia is actually emitted from the manure, because the predicted emission on a day with treatment A0.5 was 18.8 g/h.

The water:feed ratio was not significantly different in the battery cage system and the TWF system. It could therefore be expected that the droppings of both groups contained about the same percentage of dry matter at the time of excretion. It can therefore be concluded that the differences found in the composition of the manure on the belts were a result of the type of housing system and manure drying system. The higher dry matter content of fresh droppings on the belts in the TWF system compared to the battery cage system (table 3) could be explained by a higher water evaporation rate as a result of higher air velocities above the manure due to the open structure of the tiers and the free movement of the hens. Also, because part of the droppings fell into the litter area and because of the larger manure belt area in the TWF system, the mean density of manure on the belts (kg dry matter/m^2) in the TWF system was 71% of that in the battery cage system. The difference in the dry matter content of the fresh droppings (treatment A0.5) caused the differences between the dry matter contents of belt manure in the TWF and the battery cages for the other drying and removal treatments (table 4). The dry matter content of the belt manure after three and four days drying was higher than without drying, but was lower than that measured by Kroodsma *et al.* (1988) (40 to 60% after 7 days drying). The shorter drying time was partly responsible for the difference. Besides this, the static pressure in the drying systems was lower than recommended by Kroodsma *et al.* (1985). This will have had a negative influence on the drying process. Drying treatment C was applied because most of the manure on the belts in the TWF system was found on the belt of the upper floors underneath the perches where the hens rest. The mean dry matter content after three and four days drying according to treatment C was not higher than with treatment B despite the adjustment of the air flow above the belt manure.

The sand, which was for more than 90% ash, in the litter area at the start of the laying period could hardly be distinguished in the litter during the experiment. The ash content at the start of the experiment had already dropped to a constant level a few percent higher than the ash content of the fresh droppings. This higher ash content of the litter was the result of the degradation of organic material. This process decreased the amount of dry matter, whereas the amount of inorganic matter remained constant. The lower total nitrogen content of the belt manure in the TWF system could not be explained by differences in ammonia volatilisation or addition of feed as a result of spilling from the feeding pans. It was calculated that the nitrogen excretion of the hens in the TWF system amounted to 55% of the nitrogen uptake by the feed, resulting in a nitrogen retention of about 45%. This was far above normal values, so that is was concluded that the measured concentrations in the manure in the TWF system must have been low. The mean total nitrogen content in the litter showed that a substantial part of the nitrogen, 17.2 (50.5 minus 33.3) g/kg dry matter of the fresh droppings, was volatilised. This is equivalent to an ammonia emission of about 50 g NH_3/h. This was close to the predicted mean level of the model, being 62.5 g NH_3/h. The mean relative TAN content of 7.1% in the litter resulted from the discharge of ammonia by means of volatilisation and supply by means of degradation of uric acid and proteins. The opposite trend of the unionised ammonia content in the litter during the experiment as compared with the trend of total nitrogen and dry matter contents could be explained as follows: higher dry matter contents diminished the degradation rate of uric acid and proteins considerably, resulting in a lower unionised ammonia content in the litter. The lower volatile ammonia content reduced the ammonia emission from the litter and led to a small increase of the total nitrogen content (figure 5). The dry matter content of the litter might have been influenced by the ventilation rate and the water vapour pressure difference between the litter and the air.

4.3 Emission of ammonia

The higher maximum rate of increase of the ventilation rate in the battery cage system meant that higher ventilation rates were necessary to maintain the set temperature in this room (22 °C). This data as well as the observations and calculations of Ouwerkerk *et al.* (1994) in these rooms, showed that the air velocity patterns in the two housing systems differed greatly. The difference in the ventilation rate and the air velocity pattern could have had an effect on the ammonia emission rate. Any possible effect however is included in the difference between the emission from the belt manure in the two housing systems. Room temperatures below 20 °C were not measured due to the temperature controlled ventilation system, but the increase in room temperatures up to 28 °C on days with high outside temperatures, could not be prevented. The difference in the ammonia concentrations in the exhausted air between the battery cage and TWF system corresponded to the difference in the ammonia emission. The difference in the ammonia emission, which is the product of concentration and ventilation rate, was therefore mainly caused by the concentration difference and for a minor part by the difference in the ventilation rate.

The daily increase of ammonia emissions after removal of the belt manure, and with increasing amount of manure on the belts, was also reported by Kroodsma *et al.* (1988). They also found that drying reduced the emission compared to not drying and that the ammonia emission from manure belts strongly decreased if dry matter contents rose above 40%. In this experiment manure drying had a positive effect on the dry matter content of the belt manure. The emission however was not significantly decreased, probably caused by the fact that the dry matter content of the belt manure did not raise above 41%. Inadequate functioning of the drying installation could very well have been the reason for the lower dry matter contents. However, the lower manure density on the belts and the higher dry matter contents of the belt manure in the TWF system than the battery cage system, did not decrease the mean ammonia emission from the belt manure in the TWF system (16.6 g/h) significantly as compared to the battery cage system (18.8 g/h). The daily mean ammonia emission of 18.8 g NH_3/h was equivalent to a nitrogen volatilisation of about 1.8% of the nitrogen intake by the hens.

The effect of the local climate in the houses on the ammonia emission was reflected by the temperatures above the belt manure and the litter and the water vapour pressure differences (Groot Koerkamp, 1994). The effect of the temperature on the emission from the belt manure represents the combined effect of temperature on the degradation and the volatilisation process, which was also found by Oldenburg (1989). The evaporation of water from manure and litter particles was enhanced by a higher water vapour pressure difference. A higher volatilisation rate of water resulted in dryer manure, which in turn diminished the degradation rate of nitrogen compounds and hence the volatilisation of ammonia. The variation between the measured minimum and maximum ammonia emission from the belt manure in the battery cage system, 9 and 74 g NH_3/h respectively, was well explained by the model. The reported mean ammonia emission over longer periods from belt batteries with different drying treatments and removal frequencies in other experiments were all within this range (Groot Koerkamp, 1994; Groot Koerkamp *et al.*, 1994). It could be concluded that by means of control of the indoor temperature and regular removal of the manure, ammonia emission from manure on belts can be reduced.

The daily mean ammonia emission from the litter in the TWF raised the total emission to 79.1 g NH_3/h (16.6 + 62.5) and confirmed results of earlier measurements (Groot Koerkamp and Metz, 1992). It was remarkable that the 22.5% of the droppings of the hens that were deposited in the litter in the TWF system caused 79% of the ammonia emission of this system. However, the effect of temperature and water vapour pressure difference on the emission from the litter was not significant.

But temperature and water vapour pressure difference might have had a long term effect on the emission rate of ammonia. The unionised ammonia content in the litter on a typical day resulted from degradation and volatilisation rates in the past. Both processes were then influenced by local climatic conditions. Unionised ammonia contents below 20 mg/kg litter were necessary to substantially reduce the emission from the litter in the TWF system. The positive relationship between emission and layer thickness (a 5% increase in emission for every cm layer thickness) could be explained by the larger amount of manure and thus larger amount of unionised ammonia in the litter in the TWF system. This meant that the volatilisation of ammonia from the litter not only depends on the surface area, but also on the volume of the litter. This was logical because as a result of the scratching and dust bathing of the hens, the litter was friable and mixed many times per day. Therefore, unionised ammonia may have diffused through the litter. Another, and possibly more important, adverse effect of thicker litter layers is the development of inadequate conditions for water evaporation from small particles of droppings in the sub-layers of the litter. The drying of these particles will be hampered if the water has to pass a thicker layer. It was concluded that the degradation process in the litter must be minimised to reduce emission from the litter. Control of the layer thickness and the dry matter content of the litter are possibilities to achieve this. Technical measures that increase the water volatilisation from the litter have thus to be developed.

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APPENDIX 1 Estimation of regression coefficients for emission of ammonia

For ease and clarity of notation index t is omitted. Log stands for natural logarithm. Equations (2a) to (2c) represent the formulation of a generalised linear model (GLM) in η_{bm}, with link function $g(\eta_{bm}) = \mathrm{Log}\left(e^{\eta_{bm}} + \delta_{TWF} \cdot e^{\eta_{litter}}\right)$, containing as unknown parameters the regression coefficients of η_{litter}.

Estimation when η_{litter} is known

For a given η_{litter} the standard algorithm is Iterative Reweighed Least Squares (IRLS) with link-adjusted response variate:

$$\zeta = \eta_{bm} + (z - \eta)\frac{\partial \eta_{bm}}{\partial \eta} \tag{1.1}$$

and weights:

$$w = \left(\frac{\partial \eta_{bm}}{\partial \eta}\right)^{-2} \tag{1.2}$$

With $\mu = e^{\eta}$:

$$\frac{\partial \eta_{bm}}{\partial \eta} = \frac{e^{\eta}}{e^{\eta} - \delta_{TWF} \cdot e^{\eta_{litter}}} = \frac{\mu}{\mu - \mu_{litter}} = \frac{\mu}{\mu_{bm}} \tag{1.3}$$

the link-adjusted response variate and weights are:

$$\zeta = \eta_{bm} + (z - \eta)\frac{\mu}{\mu_{bm}} \quad \text{and} \quad w = \left(\frac{\mu_{bm}}{\mu}\right)^{2} \tag{1.4}$$

z can be taken as the starting value for η. Weighed regression with explanatory variates for belt manure emission yields an estimate of η_{bm}. Then, ζ and w are updated and the regression can be repeated. Convergence is obtained if the change in η_{bm} between iterations is negligible.

Estimation of the litter contribution

Note that η_{bm} depends on η_{litter} and therefore on the regression coefficients β_{litter} of the explanatory variates for litter emission. This is emphasised in the notation $\eta_{bm}(\beta_{litter})$. Parameters of β_{litter}, β_j, j=1...J in which J represents the number of explanatory variates for litter emission, are estimated according to a linear approximation, using only the first term of the Taylor series expansion (Pregibon, 1980):

$$\eta_{bm}(\beta_{litter}) \approx \eta_{bm}(\beta^{*}_{litter}) + \sum_{j}(\beta_j - \beta^{*}_j)\left(\frac{\partial \eta_{bm}(\beta_{litter})}{\partial \beta_j}\right)^{*} \tag{1.5}$$

The partial derivative $\frac{\partial \eta_{bm} \cdot (\beta_{litter})}{\partial \beta_j}$ 1 can be found by applying the chain rule:

$$\frac{\partial \eta_{bm}}{\partial \beta_{litter}} = \frac{\partial \eta_{bm}}{\partial \eta} \cdot \frac{\partial \eta}{\partial \eta_{litter}} \cdot \frac{\partial \eta_{litter}}{\partial \beta_{litter}} \tag{1.6}$$

Because: $\frac{\partial \eta_{\mathrm{bm}}}{\partial \eta} = \frac{\mu}{\mu_{\mathrm{bm}}}$ (see above), (1.7)

$$\frac{\partial \eta}{\partial \eta_{\mathrm{litter}}} = \frac{\delta_{\mathrm{TWF}} \cdot e^{\eta_{\mathrm{litter}}}}{e^{\eta_{\mathrm{bm}}} + \delta_{\mathrm{TWF}} \cdot e^{\eta_{\mathrm{litter}}}} = \frac{\mu_{\mathrm{litter}}}{\mu} \tag{1.8}$$

$$\frac{\partial \eta_{\mathrm{litter}}}{\partial \beta_{\mathrm{j}}} = x_{\mathrm{j}} \tag{1.9}$$

in which x_j is the explanatory variate with regression coefficient β_j. An estimate of the parameter of β_{litter} can be calculated by multiplying each explanatory variate for litter emission with $\frac{\mu_{\mathrm{litter}}}{\mu_{\mathrm{bm}}}$ (for the observations of the TWF system) and then carry out regression with all explanatory variates, for the belt manure emission as well as for the litter emission. For the regression coefficients of the litter emission, the difference with the previous value is estimated. The new estimate is the sum of the previous value and the estimate of the difference. Iteration is continued until the estimated difference is negligible.

APPENDIX 2 Numerical example of the use of the model for the emission of ammonia

The model predicts the daily mean ammonia emission in g/h depending on the housing type (TWF or battery cage system), the handling of belt manure (drying and removal frequency), climatic conditions (temperature and humidity), the litter condition (unionised ammonia content) and the litter management (layer thickness).

Circumstances:

- * drying treatment B, the third day after removal
- * belt manure: temperature 22.0 °C (mean 24.0), water vapour pressure difference 1.4 kPa (mean 1.0)
- * litter: temperature 21.0 °C (mean 24.0), water vapour pressure difference 1.6 kPa (mean 1.0)
- * litter: 20 mg unionised ammonia per kg litter (mean 100)
- * litter: layer thickness 2.0 cm (mean 5.0)

Battery Cage system:

$$e^{(2.93 - .06 + .74 + (22.0\text{-}24.0)*.15 + (1.4\text{-}1.0)*\text{-}.25)} = 24.8 \text{ g/h}$$

Tiered Wire Floor system:

$$e^{(2.93 - .06 + .74 + (22.0\text{-}24.0)*.15 + (1.4\text{-}1.0)*\text{-}.25)} +$$
$$e^{(4.14 + (21.0\text{-}24.0)*.031 + (1.6\text{-}1.0)*\text{-}.19 + (20\text{-}100)*5.4\text{E-}3 + (2.0\text{-}5.0)*.053)} = 24.8 \text{ g} + 28.3 = 53.1\text{g/h}$$

CHAPTER 4

Effects of Type of Aviary Housing System and Manure and Litter Handling on the Kinetics of Ammonia Emission from Layer Houses

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Effects of Type of Aviary Housing System and Manure and Litter Handling on the Kinetics of Ammonia Emission from Layer Houses

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Abstract

An experiment with laying hens of 16 to 36 weeks of age was carried out to investigate the differences in ammonia emissions between three commercially available aviary housing systems and what the additional effect the manure and litter handling had on these emissions. The ammonia emission from the Tiered Wire Floor (TWF), the Natura and the Boleg aviary system increased rapidly after placement of the hens in theses systems and reached its peak at 20 weeks of age. Equilibrium levels were found at 11.55, 11.24 (not significant compared to TWF) and 14.55 ($P<0.001$ compared to TWF) mg ammonia per h per hen. After removal of the manure on the belts the emission increased 5.6% on the first day and 11% on subsequent days. The litter layer was allowed to increase up to approximately 7 cm in all three aviary systems, after which 6.5 cm were removed. This resulted in a 20% reduction of the emission level ($P<0.001$). Ammonia concentrations varied between 1 and 16 ppm, while ventilation rates varied between 1 and 4 m^3/h per hen in order to maintain the inside temperature at approximately 22 °C. Some 82% of the droppings produced by the hens was found on the belts: either because it was excreted there directly by the hens or because it was dropped there by the hens as litter material. The composition of both the belt manure and the litter, which was a sand-droppings mixture, changed significantly in time during the first 20 weeks after placement of the hens in the three aviary systems. Differences in the composition of the belt manure and litter between the three aviary systems were found with respect to the DM, pH, ash, N_{kj} and the total ammoniacal nitrogen concentration. The different levels of ammonia emission and the differences that were found in the composition of the belt manure and the litter between the three aviary systems were related to the design of the aviary systems, the behaviour of the hens and the degradation and the volatilisation processes.

1 Introduction

In the last decade, progress has been made in the development of welfare-based aviary housing systems for laying hens (Blokhuis and Metz, 1992; Blokhuis, 1996). Essential characteristics of these systems are the freedom of movement for the hens, a large living area compared to battery cages and the presence of nest boxes and a dust bathing area with litter. The most important drawbacks of aviary houses compared to traditional battery cages are the higher concentrations of dust, ammonia and micro-organisms in the air, injurious working postures, higher labour requirements and higher level of ammonia emission (Blokhuis and Metz, 1995). As a result of the detrimental effects of ammonia deposition on the environment (Heij and Schneider, 1991; Lekkerkerk *et al.*, 1995), ammonia emissions from livestock husbandry have to be reduced substantially (Voorburg, 1991). Ammonia from agricultural sources is emitted from animal houses, stores, pastures and after manure application. Besides other aspects, in the future housing systems will be judged on their ammonia emission.

Since 1980, aviary houses for laying hens have been tested under experimental circumstances and they are currently being commercially operated on poultry farms in the Netherlands, Sweden and Switzerland as a welfare-friendly alternative to battery cages. Two main sources of emission of ammonia can be distinguished in aviary houses, being the manure on the belts and the litter-droppings mixture on the floor. Recent investigations on the emission patterns of ammonia from aviary housing systems revealed that, in general, the emissions from aviary housing systems were about three times higher than from battery cage systems with daily manure removal. This difference was caused by the emission from the litter (Groot Koerkamp, 1995; Groot Koerkamp *et al.*, 1995). The degradation of nitrogenous components and volatilisation of ammonia and water as well as influencing factors on these processes were described by Groot Koerkamp (1994). Experimental work showed that the volatilisation of ammonia from manure on the belts increased with the amount of manure and the temporary storage time on the belts in the house, and decreased with higher dry matter contents of the dropping as a result of manure drying (Groot Koerkamp *et al.*, 1995). The formation of ammonia from uric acid and undigested proteins in litter was positively influenced by higher pH, temperature and water content. Volatilisation of ammonia from litter to the air was shown to be linearly related with the unionised ammonia concentration in the water of the litter (Groot Koerkamp and Elzing, 1996). Concluding, the emission depends primarily on the area, the amount and the composition of both the litter and the belt manure. Climatic conditions influence not only the emission of ammonia directly, but also indirectly by the evaporation of water. Water plays a key role in the degradation of nitrogenous components. An aviary house can be regarded as a complex system because hens can freely move around. The design of an aviary system may influence their behaviour, which in turn will influence climatic conditions and where fresh droppings are put in these systems. Research showed that the emissions of ammonia from different types of aviary under varying conditions varied in a wide range (Groot Koerkamp, 1995) and confirmed the complexity of the many factor that are involved in the emission of ammonia.

Explanations for differences in the emissions of ammonia might be found in the systematic effect of differences between the characteristics of certain aviary systems on climatic variables, e.g. temperature distribution and air flow patterns, and in manure and litter properties. The objective of this research was to investigate differences in ammonia emission between three commercially available aviary housing systems and the additional effect of manure and litter handling.

2 Materials and methods

2.1 Housing systems

The three aviary housing systems in this experiment were placed in three adjacent dark rooms located at the Spelderholt Research Centre in Beekbergen. The aviary systems were split from the work areas with wire nettings which were covered with black impermeable plastic. Doors connected the work areas at the front and the back of the rooms with each other. Each room had its own temperature controlled mechanical ventilation system (capacity about 4,500 m^3/h), a temperature sensor about 50 cm above the perches of the upper tier, a water and feeding system and light regulation.

The first room was equipped with the Tiered Wire Floor aviary system (TWF), the second room with the Natura aviary system (Natura) and the third room with the Boleg II aviary system (Boleg). A cross-section of the three systems is given in figure 1. The TWF system consisted of two rows of three stacked wire floors and two rows of laying nests. The whole floor area was covered with litter material. The Natura and Boleg system had two rows of respectively 3 and 2 stacked wire floors

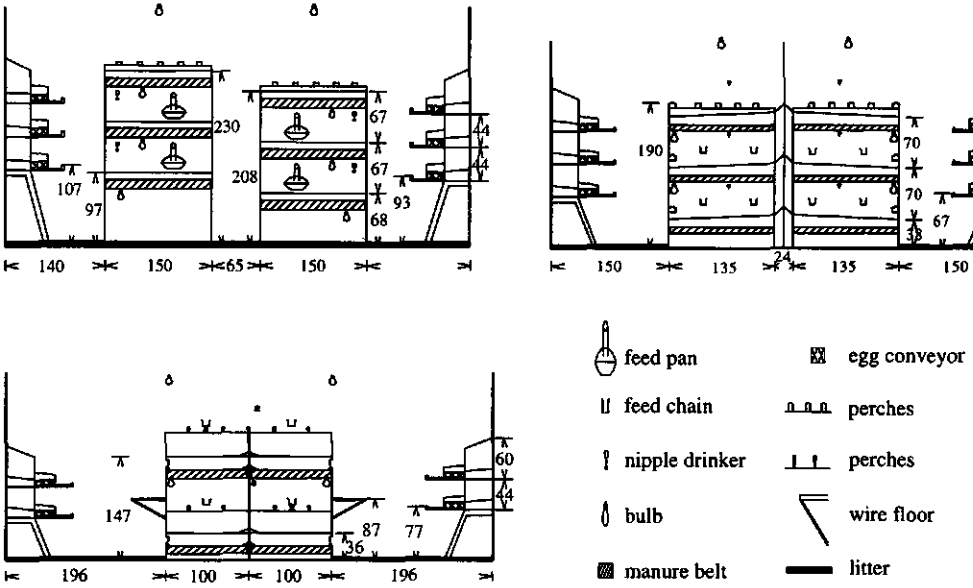

Figure 1 Cross sections of the Tiered Wire Floor (upper left), the Natura (upper right) and the Boleg system (lower left). Measures in cm.

standing against each other with a wire netting between them. The bottom floor was placed on the concrete floor. In the Boleg system perches were placed about 30 cm above all wire floors. In all three systems the complete litter area was covered with approximately 0.5 cm of sand when the hens were placed in the systems. All three systems offered about 1,000 cm^2 living area per hen, of which 39, 26 and 35% consisted of litter area in the TWF, Natura and Boleg system respectively (table 1). Thus, the litter area per hen varied strongly between the systems (424, 260 and 355 cm^2/hen), while the remaining part of the living area was available as wire floors. In the Boleg system part of the wire floors were placed above the litter, whereas in the TWF and Natura system all wire floors were situated above the manure belts. The hens put part of their droppings on the conveyer belts beneath the wire floors of the tiers in all three aviary systems. This part was removed from the house by the belts into a container outside the house. The volatilisation of water from manure on the belts was not enhanced by means of a drying system. The hens deposited the other part of their droppings in the litter.

2.2 Management and hens

Room temperatures were set at 22 °C. In the three systems, respectively 996, 806 and 995 hens of a commercial strain (Isabrown) were housed. Hens were fed a commercial layer diet (16.8 g/kg crude protein; 11.93 MJ ME/kg). Water was supplied *ad libitum* only during the lighting period by means of nipple drinkers with cups. The lighting scheme started with 11 h of light per day at 16 weeks of age and increased 1 h weekly until 15 h per day for all systems. All hens were debeaked.

Table 1 Characteristics of the Tiered Wire Floor (TWF), Natura and Boleg system.

	TWF	Natura	Boleg
Number of hens at 20 weeks of age	996	806	995
System area (m * m = m^2)	6.6 * 6.4 = 42.2	7.0 * 6.0 = 42.0	9.0 * 6.0 = 54.0
Litter area (m^2)	42.2	21.0	35.3
Wire floor area (m^2)	65.3	59.6	64.2
Stocking density (hens/m^2 groundfloor)	23.6	19.2	18.4
Stocking density (cm^2/hen) (litter+floors)	1079	1000	1000
Laying nests (van Gent) (hens / nest)	8.3	8.2	8.3
Length of perches (m)	184.8	140.0	153.0
Number of hens per feeding unit	35.6 / pan	14.7 / m chain	28.0 / m chain
Number of hens per nipple (with cup)	10.0	6.4	7.0

2.3 Treatments

At the start of the experiment the hens were 16 weeks of age. They were housed until 36 weeks of age (August 5th until December 24th). Apart from the differences between the three aviary systems, additional treatments were assigned to the three aviary systems. These treatments involved manipulation of the amount of both the manure on the belts and the litter. The removal frequency of the manure on the belts in all systems was varied within 5 measuring periods (blocks) of approximately 2 weeks, beginning in week 16, 19, 26, 32 and 34 (age of hens). In each period manure was removed after 0.5 (two times a day), 1, 2, 4 and 5 days. Manure was removed between 11 00 and 12 00 h, and for treatment 0.5 also between 17 00 and 18 00 h. The removal frequencies were assigned randomly within a measuring period. The treatment scheme is given in table 2. Small deviations from this scheme occurred during periods 4 and 5. Each measuring period included one or two days before and after the treatments. The litter treatment consisted of a reduction of the thickness of the layer by removal of most of the litter in the three systems at week 34.

Table 2 Treatment scheme for manure and litter handling.

Block	Age of hens (weeks)	Number of days between removal of belt manure	Litter treatment
1	16-18	4, 2, 5 ,1 , ½, ½	-
2	19-21	½, ½, 5, 2, 1, 4	-
3	26-28	4, 2, ½, ½, 1, 5	-
4	32-34	4, 3, 1 ,1, 2	-
5	34-36	4, ½, ½, 2, 3, 1	90% removed

2.4 Measurements

Ammonia concentrations and ventilation rates were continuously recorded during the 5 measuring periods in the ventilation shaft of each room according to the method described by Scholtens (1993). The outdoor concentration of ammonia was measured as well. Ammonia in the air was transported from the ventilation shafts through heated and insulated tubes via a thermal NH_3 converter to a NO_x chemiluminescence analyser. Ventilation rates were measured by means of a measuring fan with the same diameter as the ventilation shaft. Temperature and relative humidity (r.h.) were measured by means of combined sensors (Rotronic I-100) which were placed in the centre of each room 50 cm above the perches of the upper tier. A combined sensor was placed outside close to the air inlets (2 m high) to measure the outdoor temperature and humidity as well. Hourly averages of ammonia concentration, ventilation rate, temperature and r.h. were automatically recorded (Bleijenberg and Ploegaert, 1994). The ammonia emission was calculated as the difference between the concentration of ammonia in the exhaust air and in the inlet air multiplied by the ventilation rate. Air temperature and r.h. were used to calculate the saturated and the actual water vapour pressure of the air (ASHRAE, 1993). The water vapour pressures in the manure and litter were calculated as product of the water activity and the saturated water vapour pressure of the air. The water activity of manure and litter with a dry matter content above 20% (wet base) and temperatures between 20 and 30 °C is 0.9 (Beeking *et al.*, 1994). Egg production and feed and water intake of the hens were daily recorded per room.

Manure and litter samples were taken in each room separately. Samples of belt manure were taken in all measuring periods at the end of treatments of 0.5 and 5 days (4 days in period 4, 3 days in period 5). During the removal of the belt manure approximately 5 samples of manure were taken from the conveyer belt at a fixed time interval and mixed. This sample was taken for analysis for the content of dry matter (DM), N-Kjeldahl (N_{kj}), total ammoniacal nitrogen (TAN), ash and pH. The amount of belt manure per room was weighed after the removal treatment of 5 days. Litter samples were taken each week (total 20 times) from approximately 8 spots which were evenly distributed per room. The samples were mixed and analysed on DM content. Once per measuring period the samples were also analysed on N_{kj}, TAN, ash content and pH. The thickness of the litter layer was measured weekly at 20 spots per aviary system and averaged.

2.5 Statistical analysis

2.5.1 Composition and amount of belt manure and litter

Linear regression models with measuring period and aviary systems as independent variables were used to describe the composition of the manure on the belts. The pattern of the amount of DM on the belts in the three systems was described with an exponential model ($y = \alpha + \beta * \tau^{\text{age hens}}$). The change of the composition of the litter was also described with exponential curves. The measurements at week 35 and 36 were omitted from the regression analyses of the litter composition because of the removal of the litter in week 34. The litter was supposed to consist of 100% ash and contain no N_{kj} and ammonia at the housing of the hens at 16 weeks. The increase of the thickness of the layer of litter was modelled with time as independent variable.

2.5.2 Temperature, r.h., ventilation rate, ammonia concentrations and total emission

Hourly values of temperature, r.h., ventilation rate and ammonia concentration and total ammonia emission were checked. Pair wise differences between the hourly values of two systems were analysed per measuring period and a Student t-test was carried out to test significancy.

Notation

z^i_t = natural logarithm of the measured emission of ammonia at day t from system i

η^i_t = mean emission of ammonia at day t from system i

ε^i_t = deviation at day t in system i

C^i_j = constant for period j and aviary system i

age^i_t = age of the hens at day t in aviary system i (days)

$Esystem^{2,3}_j$ = effect of aviary system 2 and 3 compared to system 1 during period j

$Elitter^i_5$ = effect of removal of the litter during period 5 in system i

$time\_bm^i_t$ = mean time since removal of the belt manure at day t in system i (hours)

$Temp^i_t$ = temperature in aviary system i at day t (°C)

$P\Delta H_2O^i_t$ = water vapour pressure difference between litter/manure and air at day t (kPa)

$\alpha^i_j, \beta^i_j, \gamma^i_j, \delta^i_j$ = regression coefficient for period j and aviary system i

t = time (days)

ϕ = correlation parameter of the AR - 1 process

a_t = independently distributed error, called innovations $(0, \sigma^2_a)$

2.5.3 Emission of ammonia

Daily means of all variables were calculated from noon until noon. A database was created of these emission rates together with identifying and influencing variables per system. The series per system were put under each other and analysed as follows:

$$z_t = \eta_t + \varepsilon_t \tag{1}$$

The expected mean emission of ammonia on day t in period j of system i was supposed to consist of a mean emission per period for all three systems (C^i_j) and a decreasing or increasing course in time (α^i_j) (1st line equation 2). The systematic effect of the Natura and Boleg system on the emission compared to the TWF system was estimated in period 3 to 5, while the effect of the stay of the belt manure in the systems was basically estimated in all five periods with an additional effect in period 1 (2nd line equation 2). The effect of the reduction of the amount of litter (layer thickness) is also given in the second line. The whole model, together with the co-variables temperature and water vapour pressure difference (3rd line equation 2), was:

$$\begin{aligned} \eta_t &= C^i_j + \alpha^i_j \cdot age^i_t \\ &+ Esystem^{2,3}_{3-5} + (\beta^{1-3}_{1-5} + \beta^{1-3}_1) \cdot time\_bm^i_t + Elitter^{1-3}_5 \\ &+ \gamma^{1-3}_{1-5} \cdot Temp^i_t + \delta^{1-3}_{1-5} \cdot P\Delta H_2O^i_t \end{aligned} \tag{2}$$

The deviation ε_t was assumed to follow an autoregressive process of order 1 and is a weighed sum of past innovations:

$$\varepsilon_t = \phi \cdot \varepsilon_{t-1} + a_t \tag{3}$$

This linear model on the log scale meant a multiplicative model for the emission itself. The variance was assumed to be constant on the log scale and time-series analysis was used for the time-dependent processes (Box and Jenkins, 1990). The relationship between σ^2_ε the variance of ε_t, and σ^2_a is: $\sigma^2_\varepsilon = \sigma^2_a / (1-\phi^2)$. The directive 'BJIDENTIFY' of Genstat was used to check the innovations a_t. Significancy of estimates of regression coefficients were tested under the assumption of a Standard Normal distribution. Best exponential models were selected by means of F-tests. Significancy of differences are indicated as follows: ˜: $P<0.10$; *: $P<0.05$; **: $P<0.01$; ***: $P<0.001$ (one sided). All statistical analyses were carried out with the Genstat 5 statistical package (Genstat 5 Committee, 1993).

3 Results

3.1 Technical performance

The mean production results per system from 20 to 36 weeks are summarised in table 3. Mortality, egg production and feed consumption were more or less equal for the three aviary systems. Water usage (intake and spoilage) and consequently the water to feed ratio showed small differences between the three systems. Both parameters were highest for the TWF system and lowest for the Boleg system.

Table 3 Number of hens, mortality, egg production, and feed and water consumption

	Tiered Wire Floor	Natura	Boleg
Number of hens housed (20 weeks)	996	806	995
Rate of lay (eggs / housed hen day)	0.88	0.90	0.87
Egg mass (g egg / housed hen day)	49.8	49.2	49.7
Feed consumption (g / hen day)	114.5	115.6	114.0
Feed efficiency (kg egg / kg feed)	0.439	0.443	0.439
Mortality (%)	1.00	0.87	0.70
Water usage (ml / hen day)	227	221	213
water/feed ratio (g / g)	1.98	1.91	1.87

3.2 Climatic conditions and ammonia concentrations

Table 4 shows that the mean outdoor temperature decreased from 19 °C in period 1 to about 6 °C in period 5. The r.h. showed an opposite trend. Temperatures in the three aviary systems were close to the set-point temperature of 22 °C. The mean relative humidity varied between 55 and 67%. Temperatures were highest in the Boleg system and lowest in the Natura system. For the relative humidity this was the opposite. The ventilation rates per hen decreased from 3 to 4 m^3/h per hen in period 1 to 1.3 to 1.4 m^3/h in period 5. In all periods highest ventilation rates were found in the Boleg system, and lowest generally in the Natura system. Detailed analysis revealed that the difference between the ventilation rate per hen between the Boleg and the other two systems became smaller with decreasing outside temperatures (not shown). Ammonia concentrations in the three systems varied between approximately 1 ppm in period 1 and approximately 16 ppm in period 2 (table 4). The differences between systems were generally small and not systematically higher or lower in a particular system.

Table 4 Mean and standard deviation (in brackets) of the temperature (°C), relative humidity (%), ventilation rate (m^3/h per hen), ammonia concentration (ppm) and total emission of ammonia (g/h) per measuring period for the outside climate and the three aviary systems per measuring (n= number of hourly values). Significant differences between the three aviary systems per measuring period are indicated with different superscripts ($P<0.001$).

	Period				
Trait and system	1 (n = 364)	2 (n = 408)	3 (n = 337)	4 (n = 266)	5 (n = 255)
Outdoor					
Temperature	19.0 (5.1)	14.0 (3.6)	7.0 (2.4)	5.6 (2.7)	5.7 (2.2)
Relative Humidity	79 (20)	89 (14)	94 (9)	96 (5)	98 (4)
Temperature					
TWF	23.1 (3.6) ^{b}	22.8 (0.8) ^{b}	22.0 (0.3) ^{b}	22.0 (0.3) ^{b}	22.2 (0.4) ^{b}
Natura	22.4 (3.5) ^{c}	22.2 (0.6) ^{c}	21.5 (0.3) ^{c}	21.4 (0.3) ^{c}	21.6 (0.3) ^{c}
Boleg	24.3 (3.3) ^{a}	23.2 (1.0) ^{a}	22.3 (0.7) ^{a}	22.2 (0.8) ^{a}	22.5 (0.8) ^{a}
Relative humidity					
TWF	63 (10 ^{b}	62 (5) ^{b}	56 (3) ^{b}	57 (4) ^{b}	57 (4) ^{b}
Natura	66 (11) ^{a}	67 (4) ^{a}	61 (4) ^{a}	62 (4) ^{a}	61 (4) ^{a}
Boleg	60 (7) ^{c}	61 (4) ^{c}	56 (4) ^{c}	55 (5) ^{c}	56 (4) ^{c}
Ventilation rate					
TWF	3.53 (1.0) ^{c}	2.13 (0.8) ^{b}	1.42 (0.3) ^{b}	1.27 (0.3) ^{b}	1.28 (0.3) ^{b}
Natura	3.86 (1.5) ^{b}	2.01 (0.7) ^{c}	1.33 (0.3) ^{c}	1.22 (0.3) ^{c}	1.20 (0.3) ^{c}
Boleg	3.92 (0.9) ^{a}	2.56 (0.8) ^{a}	1.50 (0.3) ^{a}	1.45 (0.4) ^{a}	1.44 (0.3) ^{a}
Ammonia concentration					
TWF	1.0 (1.0) ^{b}	16.0 (4.7) ^{a}	12.0 (3.2) ^{b}	13.3 (3.4) ^{b}	11.3 (2.9) ^{b}
Natura	3.0 (2.8) ^{a}	15.6 (3.7) ^{a}	15.1 (3.5) ^{a}	15.1 (3.7) ^{a}	11.1 (2.3) ^{b}
Boleg	0.8 (0.7) ^{b}	15.0 (3.6) ^{b}	14.6 (2.6) ^{a}	15.1 (2.6) ^{a}	11.8 (2.4) ^{a}
Ammonia emission					
TWF	2.3 (2.3) ^{b}	22.9 (8.6) ^{b}	12.0 (4.8) ^{b}	12.1 (5.3) ^{b}	10.2 (3.7) ^{b}
Natura	5.6 (5.0) ^{a}	17.4 (6.4) ^{c}	11.6 (4.5) ^{b}	10.7 (4.7) ^{c}	7.7 (2.9) ^{c}
Boleg	2.2 (1.8) ^{b}	25.8 (8.4) ^{a}	15.3 (4.6) ^{a}	15.3 (5.2) ^{a}	11.8 (3.6) ^{a}

3.3 Belt manure composition and production

The course of the DM content and pH of the manure on the belts after 0.5 day and 3 to 5 days is shown in figure 2. The DM content and the pH increased significantly ($P<0.001$) during the storage on the belts (23 and 10%, respectively), and decreased during the laying period. No differences were found between systems for the DM content and pH. The ash content of the manure on the belts showed a peak at 20 weeks of age and was 6.2 and 8.0% lower in the Natura and Boleg system respectively, than in the TWF system (figure 2). The mean nitrogen concentration in the DM of the manure on the belts in all three systems after 3 to 5 days (48.0 g/kg dry matter) tended to be lower than after 0.5 day (44.6 g/kg). The mean TAN concentration increased significantly ($P<0.001$) during the stay on belts from 15 to 27% of the N_{kj} concentration. Figure 3 shows that the amount of dry matter on the belts in the three systems (g/day per hen) increased exponentially to an asymptotic level: $31.3\text{-}694{*}0.81^{\text{age hens}}$ (R^2 89%). The measurements seemed to indicate differences between the systems. The final level of 31.3 g dry matter per hen per day amounted 82% of the total droppings production if a production of 38.3 g DM/day per hen was assumed (Groot Koerkamp *et al.*, 1995).

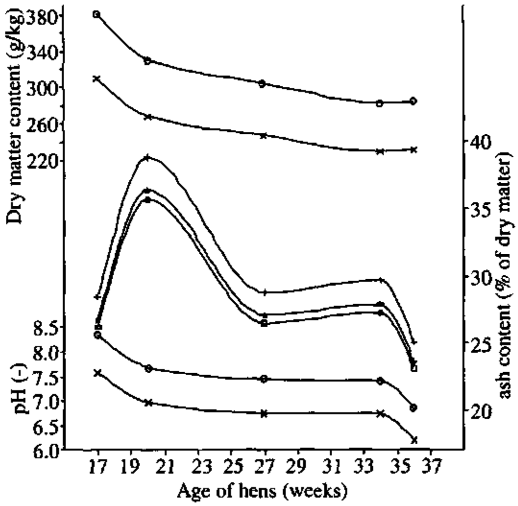

Figure 2 Trends and differences of the mean dry matter content and pH of the manure on the belts in the three systems after 0.5 days (x) and after 3 to 5 days (o). The trend of the ash content and the differences between the systems are also given: +: Tiered Wire Floor, *: Natura, ☐: Boleg.

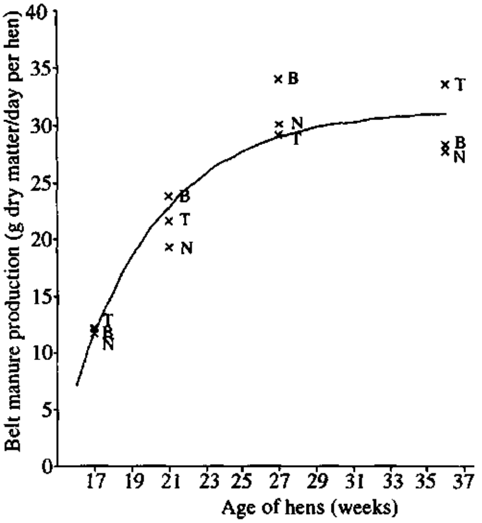

Figure 3 Amount of dry matter on the belts (manure and litter) in the three aviary systems: average exponential regression curve $(31.3 - 684^{*}\ 0.81^{\text{age hens}})$ and measurements: T = Tiered Wire Floor , N = Natura, B = Boleg.

3.4 Litter composition and layer thickness

The course of ash, TAN and N_{kj} concentration of the litter in the three systems is shown in figure 4. The exponential models for these three parameters showed significant ($P<0.05$) differences between the course of the concentrations of the litter in the three systems. The ash content in all three systems decreased from 100% at 16 weeks to asymptotic levels. Both TAN and N_{kj} concentrations increased gradually, but did not reach the maximum levels at 36 weeks (1.96, 2.97 and 3.2 for the TAN concentration and 63, 28 and 39 for the N_{kj} concentration). Especially the TAN concentration (week 36) showed a clear increase after removal of the litter in week 34. The mean pH of the litter was 8.52 (coefficient of variation 1.6%). No trend in time or differences between systems were found.

The trend of the DM content of the litter in the three systems is shown in figure 5. The DM content decreased in all systems, and had nearly reached the estimated asymptotic levels in the TWF and Natura system at 34 weeks. The DM content of the litter in the Boleg system was estimated to decrease to an asymptotic level of 638 g/kg litter. The DM content in the TWF system was consequently higher than in the Natura and Boleg system. The difference between the Natura and Boleg system altered at about 27 weeks. The DM content of the litter in week 35 en 36, after removal of the litter, clearly dropped in all three systems. The thickness of the litter layer in the three systems increased from about 0.5 cm to about 7 cm. The increase amounted 0.051, 0.061 and 0.045 cm/d (s.e. 0.007) for the TWF, Natura and Boleg system respectively. The litter thickness was reduced to less than 1 cm after the litter treatment.

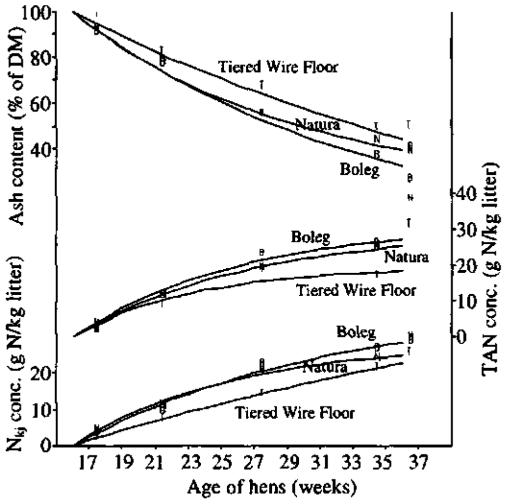

Figure 4 Course of the ash, total ammonical nitrogen (TAN) and N_{kj} concentration of the litter in the Tiered Wire Floor (T), Natura (N) and Boleg (B) aviary system: measurements (labels) and exponential regression lines. The measurement at week 36 were left out of the regression analysis.

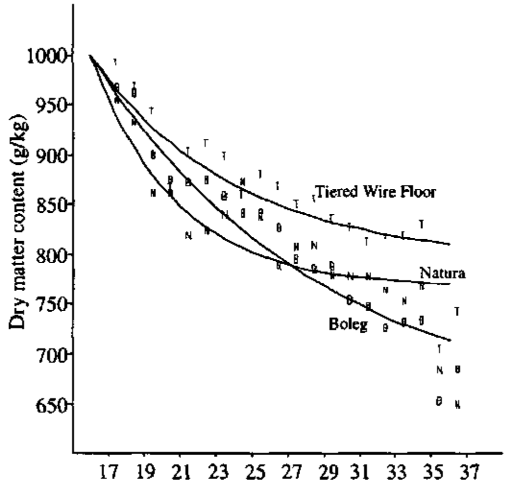

Figure 5 Course of the dry matter content of the litter in the Tiered Wire Floor (T), Natura (N) and Boleg (B) aviary system: measurements (labels) and exponential regression lines. The measurement at week 36 were left out of the regression analysis.

3.5 Emission of ammonia

The mean total emission of ammonia per measuring period is given in table 4, while the course of the emission of ammonia per hen is given in figure 6 for all three systems. The estimates of the constants and regression coefficients, standard errors and t-values are given in table 5. The emission increased from the start at 16 weeks (period 1) from about zero ($C_1^{1\text{-}3}$) with 20% per day in all systems ($\alpha_1^{1\text{-}3}$), whereas the emission from the Natura system was significantly higher during this period (C_1^2). The maximum emission was estimated at 32.7 mg/h per hen ($C_2^{1\text{-}3}$) around 20 weeks of age and decreased 2% per day ($\alpha_2^{1\text{-}3}$) during period 2. The basic level during periods 3 to 5 was estimated at 11.55 mg/h per hen for the TWF system ($C_{3\text{-}5}^{1\text{-}3}$). The emission from the Natura system was slightly lower (E*system*^{2}, -2.7%, not significant), and the emission from the Boleg system was 26% higher (E*system*^{3}). The emission increased in all systems with 0.44% per hour after removal of the belt manure ($\beta_{1\text{-}5}^{1\text{-}3}$), resulting in an increase of 5.6% on the first day after removal (mean of 12.5 h) and 11% on subsequent days (mean of 24 h). The relative effect of the stay of the manure on the belts on the emission nearly doubled during period 1 ($\beta_1^{1\text{-}3}$). Removal of the litter decreased the emission in all systems with 20% during period 5. The covariable temperature influenced the emission positively with 13% per °C, while the water vapour pressure difference had a negative, but not significant, influence on the emission.

The daily pattern of the emission of ammonia from the three systems is shown in figure 7. The coefficient of variation of the hourly means amounted 4.4%, 4.9% and 3.7% for the TWF, Natura and Boleg systems, respectively. The start of the lighting period at 6 00 h and the end at 22 00 h marked the increase and decrease of the emission of ammonia. The highest emissions were found at 16 00 h in the afternoon. The relative emission pattern in the Boleg system differed from the other two. The absolute pattern was probably close to the other two systems, because the emission level was higher.

Table 5 Estimates, standard errors and t-values (n=170) of the constants and regression coefficients of the linear model of the natural logarithm of the emission of ammonia.

Constant / coefficient	Estimate	S.E.	T-value	Linear scale
$C_1^{1\text{-}3}$	-1.46	0.12	-2.71	0.23 mg/h per hen
C_1^{2}	1.01	0.12	8.80	2.75 mg/h per hen
$\alpha_1^{1\text{-}3}$	0.18	0.01	17.29	20%/d
$C_2^{1\text{-}3}$	3.49	0.34	10.43	32.7 mg/h per hen
$\alpha_2^{1\text{-}3}$	-0.02	0.01	-1.93	-2.0%/d
$C_{3\text{-}5}^{1\text{-}3}$	2.45	0.06	43.25	11.55 mg/h per hen
$Esystem_{3\text{-}5}^{2}$	-0.03	0.07	-0.42	-2.7%
$Esystem_{3\text{-}5}^{3}$	0.23	0.06	4.00	26%
$\beta_{1\text{-}5}^{1\text{-}3}$	4.37 E-3	0.55 E-3	7.93	0.44%/h
$\beta_1^{1\text{-}3}$	4.31 E-3	0.98 E-3	4.41	0.43%/h
$Elitter_5^{1\text{-}3}$	-0.23	0.07	-3.43	-20%
$\gamma_{1\text{-}5}^{1\text{-}3}$ (mean temperature: 22 °C)	0.12	0.02	6.96	13%/°C
$\delta_{1\text{-}5}^{1\text{-}3}$ (mean ΔP: 0.8 kPa)	-0.07	0.14	-0.52	-6.9%/kPa

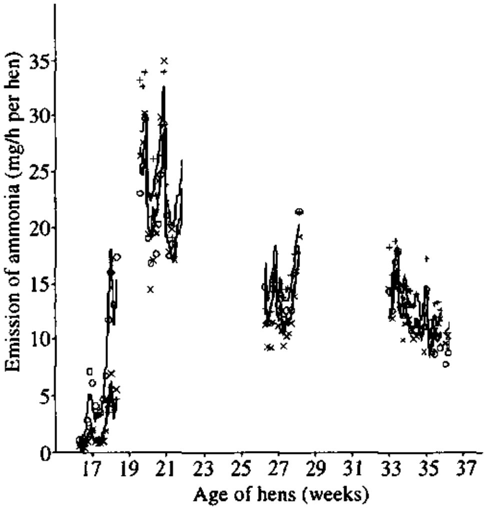

Figure 6 The course of the emission of ammonia from the Tiered Wire Floor (x), Natura (o) and Boleg (+) aviary system during 5 periods: measurements and linear regression lines. Removal of the litter in week 34 distinguished period 4 and 5.

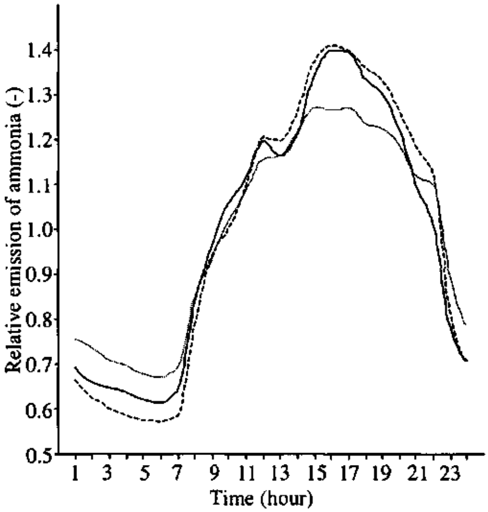

Figure 7 The circadian pattern of the emission of ammonia during the day from the Tiered Wire Floor (—), Natura (--) and Boleg (···) aviary system. Emission relative to the daily mean emission.

4 Discussion

4.1 Technical Performance

Egg production in the three aviary systems was close to what could be expected for hens kept in battery cages. Feed consumption was slightly higher due to energy demands for activity. The results were comparable with results obtained in other aviary systems in larger houses in the Netherlands (Blokhuis and Metz, 1995). The water usage in the Natura and Boleg system was 2.5 and 6.2% lower than in the TWF system. Causes for these differences due to water spoilage from the nipples or the water intake by the hens could not be traced.

4.2 Climate

The climate was controlled satisfactorily despite small differences in temperature and r.h. between the three systems. The dark plastic against the wire nettings contributed to this and also resulted in a more equal distribution of the hens through the aviaries as compared to an earlier experiment (Groot Koerkamp and Bleijenberg, 1994). The higher ventilation rates in the Boleg system compared to the other two systems could have been caused by a systematic difference of the air flow pattern, probably caused by the design of the Boleg system in combination with the behaviour of the hens. The ammonia concentrations were below the general threshold limit of 25 ppm for an 8 h working day for men and the living environment of animals, but mostly exceeded the stricter limit of 10 ppm that is applied in some countries.

4.3 Manure and litter

The amount of manure on the belts, being 82% of the total DM production of the hens, resulted from two sources: the droppings directly excreted above the belts and litter transported from the dust bathing area. This meant that 18% of the DM of the droppings remained in the litter, while the amount of DM transported from the litter to the belts in the three systems could not precisely be detected. The composition of the manure on the belts resulted from the degradation and volatilisation processes. Ash is not involved in the degradation and volatilisation processes and could therefore be used to trace differences. Besides the two input sources, the composition of the manure found after 0.5 day approximated freshly excreted droppings. A substantial variation in time was found for this composition: the DM and ash content and pH changed during the experiment as a result of physiological changes in the hen (growth and egg production) and changes in the behaviour of the hens. The peak in the ash content at 20 weeks in all three systems (35-40%) was probably caused by a greater amount of litter, still constituting of almost 100% ash, being transported to the belts by the hens. Droppings from hens have a lower ash content, about 25% of the DM. A peak in the dust bathing activity of the hens at 20 weeks of age and movement between litter and wire floors seemed to be the main cause and could be explained with the following two processes: (1) the hens explored the system and increased their dust bathing activity since the placement in the system at 16 weeks, (2) on the other hand, egg production increased from 19 weeks of age, and consequently hens spent less time dust bathing in the litter area. The belt manure in the TWF system had the highest ash content and the TWF system also offered the greatest litter area per hen. The larger litter area per hen seemed to be positively related to the amount of litter being transported to the belts. Despite the higher litter area per hen in the Boleg system compared to the Natura system, the ash content of the belt manure (figure 2) indicated that less litter was transported to the belts in the

Boleg system. This could be explained by the positioning of easy accessible wire floors above the litter in the Boleg system. Litter particles between the feathers of hens standing on these floors fell the back into the litter, instead of on the belts. The increase of the amount of manure on the belts was probably mainly caused by the increase of the manure production of the hens since 16 weeks of age, and this production stabilised at about 30 weeks of age. Already 15% of N_{kj} in the manure on the belts was degraded to ammonia within 0.5 day, while fresh droppings hardly contain any ammonia. The TAN concentration increased up to 27% after 5 days. The degradation process was enhanced by the increase of the pH during the stay on the belts and, probably to a small extent, decreased by the evaporation of water from the droppings. The difference in nitrogen concentration between 0.5 and 5 days (3.4 g N/kg DM) would have caused an ammonia emission of 5.4 mg/h per hen.

The composition and amount of litter resulted from the input of fresh droppings by the hens (DM, ash, water and nitrogen components), the degradation of uric acid and undigested proteins, and the transport of litter to the belts as well as evaporation of water and ammonia. The input of fresh droppings (about 25% ash and 25% dry matter) from 16 weeks onwards decreased the ash and DM content of the litter and increased the nitrogen concentrations during the laying period (figures 4 and 5). In course of time the initial amount of sand contributed less and less to the mean composition of the litter-droppings mixture. Eventually the composition hardly changed (asymptotic levels) and was the result of an equilibrium between the processes involved. Evaporation of water from the litter-droppings mixture had reached an equilibrium with the supply of water to the manure at 34 weeks in the TWF and Nature system (79.5% and 76.7% DM content). The equilibrium level for the Boleg system was lower (63.8%). Degradation of nitrogenous components in the litter led to an increase of TAN concentrations, which in their turn could volatilise from the litter and contribute to the emission of ammonia. The TAN concentrations in the three systems appeared to reach a constant level at 34 weeks, indicating that an equilibrium had established between the production of ammonia in the litter due to degradation and release of ammonia from the litter due to evaporation. Removal of the litter at 34 weeks hardly influenced the ash and total nitrogen content. But the TAN concentration increased substantially, probably caused by the higher degradation rates of nitrogen components due to the drop of the dry matter concentration up to about 10% in all three systems.

The differences in the composition of the litter in the three systems were related to the characteristics of the systems and could be explained as follows. The slower decrease of the ash content in the TWF system indicated that less manure per square meter was dropped in the dust bathing area compared to the other two systems. This system had the greatest litter area per hen (424 cm^2). The ash content of the litter in the Boleg system (355 cm^2/hen) was lower than in the Natura system (260 cm^2/hen) from 25 to 35 weeks of age. These differences in the ash content were also found in the course of the dry matter content in the three systems: the highest in the TWF, Natura higher than Boleg during the second half. This resemblance in the course of the ash and dry matter content confirms that the evaporation rate of water per square meter litter did not differ substantially between the three systems, because no differences were found in the dry matter contents of the freshly excreted droppings. It also meant that the hens in the Natura system with the smallest amount of litter (260 cm^2/hen) seemed to put less droppings per square meter in the dust bathing area than the hens in the Boleg system (355 cm^2/hen) from about 25 weeks on. However, this was not fully supported by the results of the increase of the layer thickness. But differences between the increase rates were not estimated accurately due to difficulties with these measurements. Again, the positioning of wire floors above the litter in the Boleg system were held responsible for the higher input of droppings in the litter. The difference in deposition of excreta in the litter by the hens also explained the difference in the nitrogen and dry matter content of the litter during the experiment.

The differences in TAN concentrations between the systems were probably mainly caused by the differences in dry matter content, as water content enhances the degradation rate of nitrogen components.

4.4 Emission of ammonia

The emission of ammonia is the sum of the emission from the litter in the dust bathing area and the manure on the belts and both sources had their own effect on the emission pattern. The rapid increase of the emission of ammonia to a peak at 20 weeks of age and subsequent stabilisation of the emission was also found in an earlier experiment (Groot Koerkamp and Bleijenberg, 1994). The results showed that differences between the emission of ammonia from different types of aviary systems existed. These differences were, however, small (-3% and +26%) compared to the variation in the emission between measuring periods and the variation of the emission within periods. The emission from the TWF system on the first day after manure removal (12.2 mg/h per hen) was close to the level measured in a semi-commercial TWF house (12.5 mg/h per hen; removal twice a day), but higher than the emission from the simultaneously measured battery cage house (2.9 mg/h per hen; Groot Koerkamp *et al.*, 1995). The mean emission from a commercial TWF house on the first day after removal of belt manure during a laying cycle of 14 months was 8.1 mg/h per hen (Groot Koerkamp en Reitsma, 1997).

The variation of the emission within periods was mainly caused by the manure on the belts and well described by the model. The emission from the manure on the belts under the wire floors increased exponentially with the amount and stay of the manure in the house, as was found by Kroodsma *et al.* (1988) for battery cages and Groot Koerkamp *et al.* (1996) and Groot Koerkamp and Reitsma (1997) in other TWF aviary systems. Due to degradation of nitrogen components, TAN concentrations in the manure increased and subsequent volatilisation of ammonia took place. The increase of the pH enhanced degradation and volatilisation processes, whereas the volatilisation of water only slightly increased the dry matter content of the manure on the belts (up to about 35%). The nitrogen loss from manure on the belts during 5 days due to emission of ammonia (5.4 mg/h per hen) was in agreement with the increase of the emission during these days (figure 6).

The variation of the emission between periods was mainly caused by the emission from the litter. The increase of the TAN concentrations in the litter during period 1 explained the increase of the emission from 16 weeks. Since 25 weeks of age the changes in the composition (especially dry matter content and TAN concentration) of the litter were small and in agreement with the stabilisation of the emission. The peak in the emission pattern at 20 weeks (period 2) could not be explained by a peak in the TAN concentration, nor by the volatile ammonia concentration in the water of the litter, as was found by Groot Koerkamp and Elzing (1995). The higher ventilation rates during period 2 compared to period 3 to 5 might have caused higher air velocities, which might have enhanced the volatilisation of ammonia from both the litter and the belt manure. A better explanation for the peak in the emission at 20 weeks and the dip at 35 weeks could be found when not only the composition of the litter was taken into account, but also the intensity of the dust bathing behaviour of the hens and the amount of the litter (layer thickness). The peak and dip could be explained if it was assumed that the litter under the top surface also contributed to the emission: ammonia volatilised to the air between the litter, but was not directly released to the air above the litter. In this way stirring of litter (a higher dust bathing activity at 20 weeks) increased the emission of ammonia and the removal of litter (at 34 weeks) decreased the emission of ammonia from the litter. The effect of the co-variable temperature could be explained by the positive effect of temperature on physical and biochemical processes. The numerical effect found in this study also covers the effect of correlated parameters that were not in the statistical model, e.g. the ventilation rate.

The daily pattern of the emission of ammonia suggests that the activity of the hens, as induced by the lighting scheme, had a strong positive influence on the emission. The higher emission during the afternoon could be explained by the fact that most hens lay their egg in the morning and scratch and dust bath in the litter during the afternoon (Lokhorst and Keen, 1996). The deposition of fresh droppings in the litter and the stirring of the litter enhanced emissions. It should be mentioned that together with the activity of the hens other influencing parameters of the emissions have a corresponding daily pattern, like outdoor and indoor temperature, ventilation rate and heat production of the hens.

It could be concluded that the design of aviary systems, i.e. the dust bathing area and the placement of wire floor, influenced the composition and amount of both the belts manure and the litter. Through manure and litter handling the amount and/or stay of the belts manure and the litter could be manipulated. This influenced the composition of these both sources of ammonia, which changed continuously due to degradation and volatilisation processes. The behaviour of the hens, especially the scratching and dust bathing activities in the litter, played an important role in the ammonia emission from the litter.

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CHAPTER 5

Degradation of Nitrogenous Components in and Volatilisation of Ammonia from Litter in Aviary Housing Systems for Laying Hens

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Degradation of Nitrogenous Components in and Volatilisation of Ammonia from Litter in Aviary Housing Systems for Laying Hens

P.W.G. Groot Koerkamp and A. Elzing

Abstract

Ammonia emissions from poultry houses for laying hens with litter are higher than the emissions from battery houses. The emission of ammonia must be reduced and the working environment should be improved to warrant the acceptance and sustainment of aviary houses in the future. Physical and chemical relationships of the volatilisation of ammonia and the degradation of organic material in litter from aviary houses for laying hens were analysed and verified by means of experimental data, which consisted of 66 litter samples taken from 12 commercial aviary houses. The volatilisation rate of ammonia from the litter was linear to the NH_3 concentration in the water of the litter, whereas the pK_a of the NH_3-NH_4^+ equilibrium was adjusted to 8.65. The concentration of the total ammoniacal nitrogen (NH_3+NH_4^+) in the litter found in the aviary houses, which is the result of the degradation of organic material, was approximately 4% higher per 1/10 unit of pH, 4% higher per unit of temperature (°C) and 4% higher per 10 units of water content (g/kg). The cold winter climate appeared to have had an adverse effect on the litter close to the outer walls of the aviary houses. Emissions of ammonia from litter can be reduced by maintaining a high dry matter content, a low pH or low a low temperature, thereby minimising the degradation rate of organic nitrogen and thus decreasing the volatilisation of ammonia. However, control of pH level and temperature of the litter may not always be possible or acceptable in aviary houses.

1 Introduction

As a result of the detrimental effects of ammonia deposition on the environment, ammonia emissions have become an important issue in the Netherlands (Heij and Schneider, 1991). The main source is livestock husbandry (94%). Research is being carried out to find ways of reducing the emission in order to meet the environmental requirements set out by legislation. The Dutch goal is a reduction of at least 50% in the year 2000 compared to the level in 1980 (Voorburg, 1991). Ammonia emissions from livestock husbandry must therefore be reduced substantially. Consequently, future housing systems will be even more severely judged on their ammonia emissions.

New, welfare-based housing systems, such as aviary houses for laying hens, will also be judged on their emission of ammonia. The litter in these aviary systems, which is a mixture of straw, wood chips, or sand, and excreta (droppings), is considered to be essential for the normal behaviour and welfare of the hens (Blokhuis and Metz, 1992). Groot Koerkamp and Metz (1992) found that the ammonia emission from a Tiered Wire Floor (TWF) aviary house for laying hens was about three times higher than the emission from a battery house. Groot Koerkamp *et al.* (1995) found a mean emission from the litter in the TWF system (6480 hens) of 62.5 g/h. This was high compared to the mean emission of 18.8 g/h from the manure on the belts. The emission from the litter varied greatly and increased with the unionised ammonia concentration (NH_3) in the litter. The trend of the unionised ammonia concentration was opposite to the trend of the dry matter content of the litter. The negative relationship between the dry matter content of the litter in houses for laying hens and also for broilers and the ammonia emission were more often reported (Elliot and Collins, 1983; Groot Koerkamp, 1994; Groot Koerkamp *et al.*, 1994).

Emission of ammonia is caused by the degradation of nitrogenous components in the manure and litter into ammonia and the volatilisation of ammonia from the manure and litter. Despite the knowledge of fundamental relationships of both processes and available research results obtained in animal houses, it was difficult to determine if and to what extent other factors besides the dry matter content influenced the emission of ammonia from the litter. Qualitative and quantitative knowledge of the factors involved in the separate degradation and volatilisation processes are necessary to find the influencing factors on the emission of ammonia from litter in aviary houses. As a result of the reduced emission of ammonia, the air quality in poultry houses will improve. Twenty-five ppm of ammonia is the MAC value for working conditions (Arbeidsinspectie, 1994), but higher concentrations have often been reported in hen houses with litter (Whyte, 1993; Wachenfelt *et al.*, 1993; Groot Koerkamp *et al.*, 1995).

Taking the circumstances in commercial animal houses into consideration, a variation in time and space of the physical and chemical properties of litter and ammonia volatilisation can be expected. Variation between animal houses can also occur. This paper describes research that was carried out to *i*) investigate the properties and the volatilisation rate of ammonia from litter in commercial aviary houses for laying hens and *ii*) explain the volatilisation rate of ammonia (volatilisation process) and the concentration of total ammoniacal nitrogen in the litter (degradation process) through analysis and modelling of physical and chemical relationships. The models for ammonia volatilisation and degradation of organic material are described first, next an experiment is described to verify the theory.

2 Physical and chemical relationships

Two processes are essential for the emission of ammonia from chicken manure: the degradation of organic material (uric acid and proteins) into, among others, ammonia, and the volatilisation of ammonia from litter. Litter in aviary houses is usually a mixture of wood chips or sand and excreta. The Total Ammoniacal Nitrogen (TAN) in the litter is found as unionised ammonia (NH_3) or as ions (NH_4^+) and the equilibrium in aqueous solutions between them is described by the following equation:

$$NH_4^+ + H_2O \Leftrightarrow NH_3 + H_3O^+ \tag{1}$$

This results in the following equation for the acid dissociation constant for aqueous solutions (see Notation for explanation of all symbols):

$$K_a = \frac{C_{NH_3} \cdot C_{H_3O^+}}{C_{NH_4^+}} \tag{2}$$

pH and temperature influence the fraction of unionised ammonia, F_{NH3}. The concentration of unionised ammonia, NH_3, can be calculated as follows:

$$C_{NH_3} = F_{NH_3} \cdot C_{\mathrm{TAN}} \tag{3}$$

Notation

Φ''_{NH_3} = volatilisation rate of ammonia (mmol/m^2.h)

$\Omega_{organic\ N}$ = degradation rate of organic nitrogen (mmol N/h.kg litter)

C_j = concentration of component j in litter (mmol/kg)

c_j = concentration of component j in water (mmol/g)

NH_3, NH_4^+ = unionised ammonia, ionised ammonia

TAN = Total Ammoniacal Nitrogen

H^+ = H$^+$ ions

α_i, β_i = coefficients for degradation process and TAN concentration

k = Mass transfer coefficient for volatilisation of ammonia (g/m^2.h)

pH = acidity (-)

K_a = acid dissociation constant

pK_a = pH value with equal concentration of ionised and unionised particles

T = temperature (°C)

A_w = water activity (-)

P_{equi} = equilibrium water vapour pressure above litter (Pa)

P_0 = water vapour pressure above pure water (Pa)

RH_{equi} = equilibrium relative humidity above litter (%)

B, M = parameters of logistic growth curve

F_{NH_3} = function which determines the fraction of unionised ammonia

w_c = water content wet basis (g/kg litter)

W = effect of water on degradation rate

t = time (h)

L = layer thickness of litter (m)

ρ = mass concentration of litter (kg/ m^3)

δ = change or difference

indices

i = coefficient number

0 = standard or comparison level

If the unionised ammonia is dissolved in the water that is present in the litter, equation 3 can be rewritten as:

$$c_{NH_3} = \frac{F_{NH_3} \cdot C_{\text{TAN}}}{w_c} \tag{4}$$

For infinitely diluted solutions, Hashimoto (1972) derived the following relationship between the fraction of unionised ammonia and the H^+-concentration (10^{-pH}) whereas the effect of temperature on K_a was modelled (with $K_{a\,(20\,°C)} = 3.897 * 10^{-10}$):

$$F_{NH_3} = \left[1 + \frac{C_{H^+}}{K_{a,(20°C)} \cdot (1.074)^{T-20}} \right]^{-1} \tag{5}$$

Equation 5 is a logistic curve between 0 and 1, that can also be expressed as:

$$F_{NH_3} = \frac{1}{1 + e^{-B \cdot (pH - M(T))}} \tag{6}$$

with:

$$B = \ln 10 = 2.303 \tag{7}$$

$$M(T) = -\mathrm{LOG}(K_{a(20°C)}) - (T-20) \cdot \mathrm{LOG}(1.074) \tag{8}$$

M(T) represents the pH level for which F_{NH3} equals 0.5 for a temperature T and B/4 is the slope of the curve in point M. For concentrated chicken manure slurries, $K_{a(20\,°C)}$ was found to be $0.81 * 10^{-10}$ (Hashimoto, 1972). From equation 8 follows that the pK_a at 20 °C for water solutions and concentrated chicken manure, with $K_{a\,(20\,°C)}$ is $3.897 * 10^{-10}$ and $0.81 * 10^{-10}$ respectively, is 9.41 and 10.09. Thus the value of the pK_a for concentrated slurries differs from the pK_a for infinitely diluted solutions.

The mass flow of ammonia from the litter is assumed to be proportional to the concentration of unionised ammonia:

$$\Phi''_{NH_3} = k \cdot c_{NH_3,\,litter} \tag{9}$$

The concentration of ammonia in the air above the litter was assumed to be negligible compared to the ammonia concentration at the emitting surface. The mass flow of ammonia due to volatilisation depends on the unionised ammonia concentration in the litter, the air temperature, the litter temperature and the air velocity above the litter. In our volatilisation experiments temperature and air velocity were not varied and the pH of the litter was assumed to be constant.

Substitution of equation 4 and 6 into 9 and log-transformation results in the following equation for the mass flow of ammonia:

$$\ln \Phi''_{NH_3} = \ln k + \ln C_{\text{TAN},\,litter} - \ln\left(1 + e^{-B(pH - M(T))}\right) - \ln w_c \tag{10}$$

The mass balance of the TAN for a fixed amount of litter is:

$$\frac{\delta C(t)_{\text{TAN}}}{\delta t} = \Omega_{organic\,N}(t) - \frac{\Phi''_{NH_3}}{L \cdot \rho} \tag{11}$$

If the volatilisation rate is neglected and the degradation rate assumed to be constant, the solution of equation 11 is:

$$C(t)_{\mathrm{TAN}} = \Omega_{organic\,N} \cdot t \tag{12}$$

The degradation process is mainly influenced by the acidity (pH), the temperature and the water related properties in the litter. As long as the amount of substrate is not limiting the degradation process (theory of Michaelis-Menten), the degradation rate in the litter can be expressed as follows (Moore, 1972; Groot Koerkamp, 1994):

$$\Omega_{organic\,N} = e^{\alpha_0} \cdot e^{\alpha_1 \cdot (pH - pH_0)} \cdot e^{\alpha_2 \cdot (T - T_0)} \cdot e^{\alpha_3 \cdot (W - W_0)} \tag{13}$$

The effect of pH, temperature, and water in this equation is described relative to the mean level of these variables. W represents the effect of water on the degradation rate. This can be either the water content on wet base (g water/kg product), or the water content on dry base (g water/g dry matter) or the water activity. The water activity is a measure of the amount of water available for micro-organisms to perform essential functions and is defined as follows:

$$A_w = \frac{P_{equi}}{P_0} = \frac{RH_{equi}}{100\%} \tag{14}$$

Rewriting of equation 13 in 12 and assuming time period t to be constant, results in the following equation 0:

$$C_{\mathrm{TAN}} = e^{\beta_0} \cdot e^{\alpha_1 \cdot (pH - pH_0)} \cdot e^{\alpha_2 \cdot (T - T_0)} \cdot e^{\alpha_3 \cdot (W - W_0)} \tag{15}$$

with

$$e^{\alpha_0} \cdot t = e^{\beta_0} \tag{16}$$

In an experiment, litter samples were taken from commercial hen houses in order to meet the two goals of this research. Properties of the samples were determined and the volatilisation rate was measured. These data were used to estimate the mass transfer coefficient of equation 10 and the coefficients β_0 and α_1 to α_3 of equation 15.

3 Materials and Methods

3.1 Experimental set up

From January to March 1992, 66 samples of litter were taken from 12 commercial aviary houses. Depending on the size of the floor area, 3 to 5 samples were taken from each house, with the exception of the first two houses from which 9 samples were taken. The sampling places of the litter were randomly selected within stratified areas, obtained by dividing the total area of the house into 3 to 5 equal sub-areas based on visual differences in the litter structure. Litter samples taken within 2 meters of the outer walls of a house were classified as 'outer wall', all other samples were classified as 'middle'.

Before sampling, the temperature and thickness of the litter bed and the temperature and relative humidity of the air above the litter were measured. The temperature in the middle of the litter layer was measured with a standard mercury thermometer. The temperature and humidity of the air were measured by means of a Rotronic hygrometer (type I-100). This sensor was also used to measure outside temperature and humidity. Notes were taken on the type of aviary system and the strain and age of the hens.

The samples were transported to the laboratory within 3 hours after sampling and divided into three parts. The first part was used to determine the physical and chemical properties: the concentration of total nitrogen according to Kjeldahl (N_{kj}) and total ammoniacal nitrogen (TAN), pH, dry matter content, and inorganic matter content. Analytical procedures were essentially the same as described by Willers *et al.* (1993).

The second part was put in a plastic bottle to measure the water activity of the litter. The bottle was half filled with the litter, air-tight closed, stored at room temperature (about 20 °C), and shaken twice a day. The relative humidity of the air in the bottle was measured twice a day with a Rotronic sensor (type I-100). The equilibrium humidity, which was normally reached within 120 hours, was used for the calculation of the water activity.

The third part was put in a transparent perspex vessel for a volatilisation experiment. Ammonia volatilisation was measured in a laboratory scale set-up, schematically shown in figure 1. The equipment was placed in a climatic chamber where temperature and relative humidity were controlled (20 °C and 90%). The litter was poured in vessel A (5 cm height) which was covered with a lid. Air entered the vessel through small holes at the edge of the lid and left the vessel through the centre. By passing the air through 2 impingers (B), each containing 70 ml HNO_3 (0.5 M), ammonia was removed from this air. The second impinger served as a control and did not contain more than 5% of the amount of ammonia trapped in the first impinger. The air left the system after passing a water trap (C), a flow controller (D), and a pump (E). The flow rate was controlled to achieve an air exchange rate of 1 per minute. The system was tested on air leakage before each experiment. The first impinger was replaced 5 times at intervals of about 12 hours and after the experiment, both the concentration of ammonia (NEN 6472, 1983) and the volume of the liquid were determined. Each time the impingers were replaced, the pump was turned off and the vessels with the litter were shaken for approximately 1 minute.

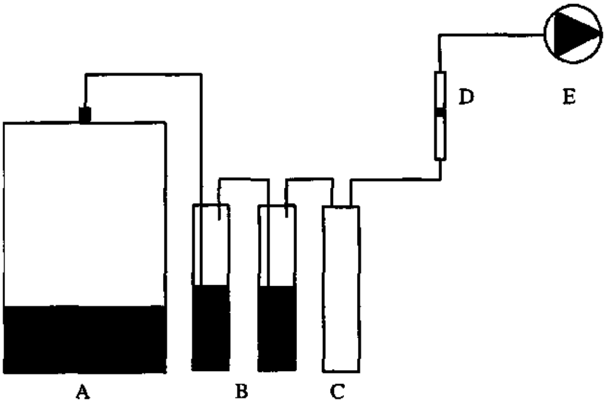

Figure 1 Schematic representation of the equipment used to measure the ammonia emission: A = Vessel with litter, B = Impingers, C = Water trap, D = Flow controller, E = Air pump (after Derikx and Aarnink, 1993).

The water content on wet basis of the litter (g/kg) was calculated from the dry matter content on wet basis. The relative TAN concentration was calculated from the TAN concentration divided by the total nitrogen concentration multiplied by 100. The density of the litter was calculated from the mass and the volume of the litter in the perspex vessels. The volatilisation rate of ammonia from the litter during the volatilisation experiments was calculated by means of linear regression of the cumulative volatilised ammonia versus time, using a model with intercept. Ammonia volatilisation rates were calculated as $mmol/m^2.h$.

3.2 Statistical analyses

A database was created with the results of all measurements of the litter samples. Statistical analyses were carried out with respect to the variation between samples. The litter samples were treated as independent measurements. Linear regression was used to estimate the mass transfer coefficient k of equation 10 and simultaneously the non-linear parameter M (pK_a) was estimated by means of the least squares method. A generalised linear regression model of the TAN concentration with the logarithm as link function was used to estimate the coefficients β_0 and α_1 to α_3 of equation 15. Variance inflation factors (VIF) of pH, temperature and water effects in this model were calculated as follows:

$$VIF = \left(1 - \frac{R^2_{adj.}}{100} \right)^{-1} \tag{17}$$

In an additional regression analysis the spatial variability of the volatilisation rate and the properties of litter samples within aviary houses was investigated. For this analysis the classification of the litter samples as 'outer wall' or 'middle' was used. All statistical analyses were carried out with the Genstat statistical program (Genstat 5 Committee, 1993).

4 Results

4.1 Properties

Table 1 gives the mean values, the range and the coefficient of variation of the properties of the litter used in this research and the circumstances under which they were taken. Eight samples were left out of this table and the statistical analyses because the structure of these samples was not granular, but clotted. As a result, the surface area of the litter samples in the vessel from which ammonia volatilisation took place was larger than of the samples where only the top layer was in contact with the air. Although the samples were taken during the winter period, the temperature of the air inside the houses was approximately 21 °C. The layer thickness varied strongly (0.5 to 10

Table 1 Mean values, range and coefficient of variation (c.v. = s.d.*100% / mean) of the measured variables of the litter from aviary housing systems and the circumstances under which the samples were taken (n=58).

Property	Unit	Minimum	Mean	Maximum	c.v.
N_{kj}	mmol/kg litter	477	1537	2643	24
TAN[1]	mmol/kg litter	21.4	182.6	318.6	39
TAN[1]	%	2.3	12.3	21.4	40
pH	-	7.4	8.8	9.2	4
Water content	g/kg litter	52	227	438	33
Ash content	% (dry matter)	24.5	40.2	84.7	39
Water activity	-	0.84	0.93	0.99	4
Density	kg/m^3	442	644	1169	25
Volatilisation rate	mmol/m^2.h	2.7	27.8	72.6	59
Temperature litter	°C	11.5	20.4	29.5	15
Layer thickness	cm	0.5	5.4	10	50
Aviary type (list)	type	TWF, TWF-F[2], Multifloor, Natura, Righs Boleg			
Type of hens, (list [3])	type	LSL w, Isabrown, Bovans w, Dekalb w, Lohman w, Hisex w			
Age of hens	weeks	20	34	66	32
Temperature house	°C	19.0	21.1	23.9	6
Relative humidity house	%	58	67	78	9
Temperature outside	°C	1.0	6.4	10.1	47
Relative humidity outside	%	70	86	92	9

[1] Total Ammoniacal Nitrogen

[2] TWF aviary with extra wire floor

[3] w indicates white type, otherwise brown

cm), like the temperature of the litter on the floor (11.5 to 29.5 °C). The physical and chemical properties showed a fair amount of variation around the mean values (table 1), except for the pH and the water activity which both had a coefficient of variation of 4.

4.2. Volatilisation of ammonia

Figure 2 shows three examples of the linear increase of the cumulative ammonia release versus time. Not all the lines go through the origin. The straight lines indicate that the volatilisation rate did not decrease during the experiment. This meant that the concentration of unionised ammonia (NH_3) in the top layer was not lowered during the experiment. The coefficient of variation of the volatilisation rate of the samples was 59 (table 1).

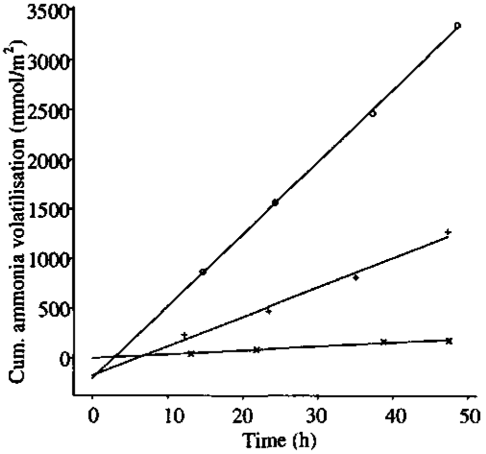

Figure 2 Three typical examples of the cumulative ammonia volatilisation versus time. Measurements for litter samples numbers. 39 (x), 55 (o) and 69 (+) and linear regression curves.

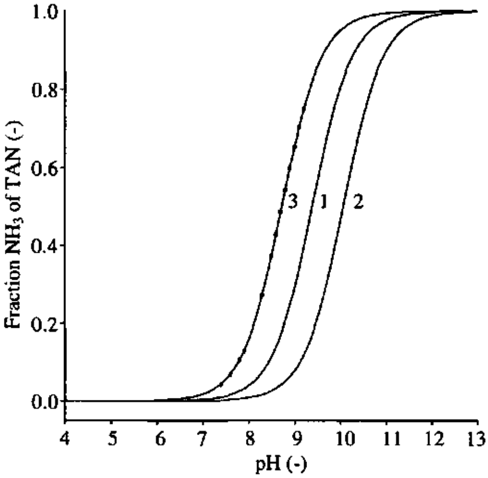

Figure 3 Two functions, F_{NH3}, for the fraction of unionised ammonia of the total ammoniacal nitrogen (TAN) (1 and 2) according to Hashimoto (1972) and the relationship found in this study (3). The calculated values of F_{NH3} for the pH measurements in this study are indicated in the curve (*). The pK_a-values are 9.41, 10.09 and 8.65 respectively. All curves valid for 20 °C.

Figure 3 shows the functions F_{NH3} according to Hashimoto (1972; equation 5) and the empirically determined function in this research (equation 6). The values of the pK_a (parameter M) for the three curves are also given. The pK_a found in this research, estimated at 8.65 with s.e. 0.10, was significantly lower ($P<0.01$) than the pK_a for ideal aqueous solutions (9.41). The value of F_{NH3} for the measured pH-values varied between 0 and 0.8. From figure 4 it can be concluded that the proposed model described the data satisfactorily (R^2=73%). The mass transfer coefficient k was found to be 53.0 ($e^{-3.97}$ with s.e. 0.105 on the log scale).

The amount of ammonia volatilised during the volatilisation experiment (about 60 hours) caused a decrease in the bulk TAN concentration of the litter in the vessel of about 5 to 145 mmol/kg (mean 55). This was 5 to 110% (mean 31%) of the initial TAN concentration and 0.3 to 22% (mean 4.0) of the total nitrogen concentration at the start of the experiment.

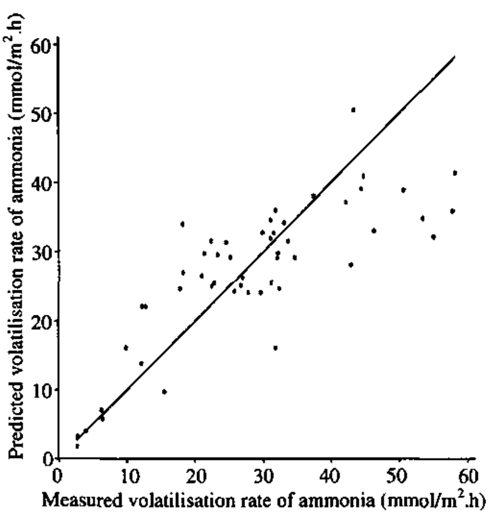

Figure 4 The predicted versus the measured volatilisation rate of ammonia (*) and the line with perfect predictions. Predictions from the linear regression model of equation 10.

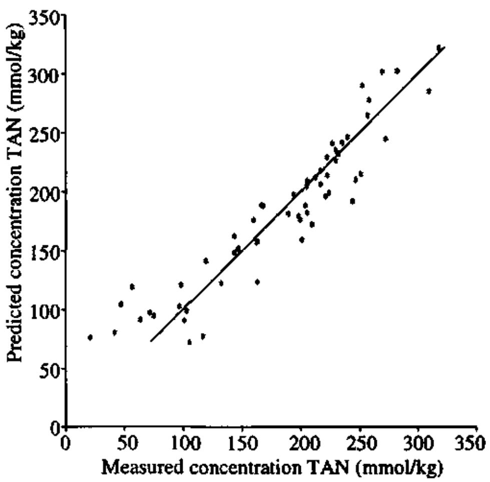

Figure 5 The predicted versus the measured Total Ammoniacal Nitrogen (TAN) concentration in the litter from aviary housing systems for laying hens (*) and the line with perfect predictions. Predictions from the linear regression model of equation 15.

The location of the litter within a house was found to have an effect on the volatilisation rate of ammonia ($P \leq 0.01$), the TAN concentration ($P \leq 0.01$) and the dry matter content ($P \leq 0.10$). The mean volatilisation rate from the litter samples taken in the middle of the houses was 43% lower, the mean TAN concentration was 25% lower and the mean dry matter content was 7% higher, all as compared to the mean level of the litter samples taken close to the outer walls of the same house.

4.3 Degradation of organic nitrogenous components

The regression coefficients of equation 15 were estimated as follows (standard error in brackets):

β_0	5.096	(0.041)
α_1	4.126E-3	(0.288E-3)
α_2	3.767E-2	(0.541E-2)
α_3	0.401	(0.091)

The relationship between the TAN concentration in the litter and the pH, temperature and water content, equation15, became:

$$C_{TAN} = 163 \cdot 1.041^{(pH-8.5)} \cdot 1.038^{(T-20)} \cdot 1.042^{(W-250)/10} \qquad (18)$$

This relationship is graphically shown in figure 5. This means that the TAN concentration in litter increased with approximately 4% per 1/10 unit of pH, approximately 4% per unit of temperature (°C), and approximately 4% per 10 units of water content (g/kg wet basis). The variance inflation factors for pH, temperature and water content in equation 18 were 1.09, 1.18 and 1.18 respectively.

5 Discussion

The values of the influencing factors on the volatilisation and degradation process were not set in this experiment, but accepted as they were found in the litter samples from the aviary houses at the time of sampling. The variance inflation factors of the explanatory variables pH, temperature and water content on the TAN concentration were just above 1.0, meaning that the correlation between them was negligible. The litter samples were treated as independent samples in the statistical analyses. However, possibly that samples from the same house were not always fully independent, because common factors like aviary system, age and type of hen might have affected the samples. Since these factors were randomly distributed over houses, samples from different houses were independent. It was assumed that the effect on the results was negligible. In this research twelve aviary houses, five types of aviary systems and six strains of hens of varying ages were examined and the measurements confirmed the hypothesised relationships well. The results of this research can therefore be accepted as a valid description of the volatilisation process and the ammoniacal nitrogen concentration in litter from aviary houses.

The mass transfer coefficient *k* is influenced by the temperature, the solubility of the gas, surface active agents, the type of mass transfer apparatus and the air velocity (Hashimoto, 1972). Temperature was not varied in our volatilisation experiments, while the effect of solubility and surface active agents was assumed to be constant and equal for all litter samples. The influence of apparatus was eliminated because all experiments were conducted with the same equipment. The volatilisation of ammonia in this study was measured under extreme conditions with respect to the air velocity. A ventilation rate of 1 per minute is high. The mass transfer of ammonia from the litter was therefore probably a combination of diffusion and convection. The mass transfer coefficient, and thus the volatilisation rate, for litter in animal houses, where air velocities of up to 0.5 m/s can occur (Ouwerkerk *et al.*, 1994), might therefore be considerably lower. The value of the mass transfer coefficient found in this study, 53.0 $g/m^2.h$, includes the influence of the Henry constant which gives the relationship between the concentration of unionised ammonia in the solution and the partial pressure of ammonia above the solution.

The adjustment of the pK_a value on the pH axis was essential for the function F_{NH3} and the description of the volatilisation process. The pK_a value of 8.65 found in this study for litter, was lower than the one found by Hashimoto (1972) for concentrated chicken slurries, which was 10.09, and the one for infinitely diluted water solutions (9.41). The shift of the pK_a found in this study can be explained by the fact that litter is not an infinitely diluted solution. The sensor used for pH measurements was not calibrated with solutions resembling the litter with its high concentrations of hydrogen ions (H^+). Furthermore, the pH measurements were conducted in a litter-water mixture while the volatilisation of ammonia was determined from the litter only. Also, the activity coefficient of the hydrogen ions was probably lower than unity, meaning that a part of the hydrogen ions was bound to the substrate. The combined effect of these three factors was that apparently in the measured pH range, higher concentrations of unionised ammonia were present in the litter than in a diluted water solution with the same pH. The assumption of a constant pH during the volatilisation experiment was not checked afterwards. However, changes of the pH were not expected because the properties of the litter during the experiment were kept close to the properties in the house (20 °C, little water evaporation).

Only a relatively small amount of the total nitrogen evaporated under the extreme conditions of this experiment. This amount could not have been measured accurately by means of a mass balance of nitrogen. The mean decrease of 31% of the TAN concentration at the end of the experiment did not decrease the volatilisation rate, as shown by the linear relationship between time and cumulative ammonia release (figure 2). This supports the theory that the unionised ammonia concentration (NH_3) in the top layer remained fairly constant during the volatilisation experiment. Degradation of organic nitrogen could have caused the supply of new ammonia.

The measurements of the volatilisation experiment confirmed the theory of the linear increase of the volatilisation rate with the unionised ammonia concentration in the litter. The assumption that the ammonia that volatilised was dissolved in the water seemed to be confirmed. This is consistent with the observations of other researchers (Groot Koerkamp *et al.*, 1994) who found an initial increase of the ammonia emission from litter in animal houses when the dry matter content increased.

The model for the TAN concentration in the litter gave a logical description for the effect of temperature, pH and water content. This model is theoretically also valid for the degradation rate of organic nitrogen under the assumption of a negligible volatilisation of ammonia, no effect of process time and a constant degradation rate for the temperature, pH and water content measured at the moment of sampling. Based on these three assumptions, the results could be compared with the degradation theory described by Groot Koerkamp (1994) and the empirical models on ammonia concentrations from broiler litter of Carr *et al.* (1990). The results of this study showed an exponential increase of the degradation rate with pH in the range of 7.4 to 9.2, whereas Elliot and Collins (1982) gave a linear relationship between pH 5.5 and 9.0. The exponential relationship between temperatures in the range of 12 to 30 °C and the degradation rate was also given by Elliot and Collins (1982). These temperatures were below the optimum temperature (35 °C; Elliot and Collins, 1982). The water activity of all litter samples in this study was higher than 0.84, whereas Groot Koerkamp (1994) indicated maximum degradation rates for A_w values above 0.7. It was evident that the small variation of the water activity at this level could not give a reasonable explanation for variations in the degradation rate. The large error in the measurement of the relative humidity (at least 1 to 2%) compared to the range of the measurements (84-99%) could be an additional explanation. The water content on wet basis gave a far better result in the linear regression analysis than the water content on dry basis or the water activity. Carr *et al.* (1990) found increasing ammonia concentrations from re-used broiler litter with an increasing temperature, pH and moisture content, indirectly pointing at higher degradation rates of organic material in the litter.

The lower dry matter content and higher TAN concentrations in the litter close to the outer walls of the aviary houses proved that properties of litter vary considerably with respect to their location in animal houses. The negative effect of the outer walls on the ammonia volatilisation from the litter samples was caused by higher TAN concentrations. These higher TAN concentrations may be caused by (higher) condensation (rates) of water vapour on the colder floor nearby the outer walls. Especially in winter periods, the effect of lower outside temperatures can decrease the floor temperature substantially if insulation is not present. This effect of non-insulated concrete floors was also suggested by Ouwerkerk and Voermans (1986) and found by Wachenfelt *et al.* (1993).

Reduction of ammonia emission from aviary houses with litter can be achieved by minimising the NH_3 concentration in the litter. The degradation of nitrogenous components must therefore be stopped as soon as possible after the excreta have been dropped in the litter or the pH must be lowered. Degradation can be stopped by controlling either the pH, the temperature or the water content of the litter or a combination of all three of these. From the review paper of Groot Koerkamp (1994), where a complete overview of possibilities to reduce emissions of ammonia is given, appears that it is not always possible or acceptable to control the pH, and that control of temperature conflicts with the climatic demands of the hens and the possibility of condensation of water vapour on the floor. Increasing the mean dry matter content of the litter is then left as the only possibility to reduce ammonia emission from aviary houses. A higher dry matter content of the bulk litter expresses a higher drying rate of fresh excreta dropped in the litter as compared to litter with a lower mean dry matter content. The sooner the dry matter content of these excreta have passed a critical level above which the degradation of organic nitrogen is minimised, the lower the TAN concentration and thus the emission of ammonia will be.

6 Conclusions

Both the volatilisation of ammonia and the concentration of total ammoniacal nitrogen could be described by the proposed theory. The volatilisation rate is mainly influenced by the NH_3 concentration in the litter and the value of the pH. The volatilisation process could be described when a pK_a value of 8.72 was assumed for the NH_3-NH_4^+ equilibrium instead of 9.41 for ideal water solutions. The TAN concentration in litter, which resulted from the degradation and volatilisation process, increased approximately 4% per unit of temperature (°C), approximately 4% per 1/10 unit of pH and approximately 4% per 10 units of water content (g/kg wet basis). The properties and volatilisation rate of ammonia from litter at different locations in houses for laying hens can vary greatly. The litter close to the outer walls of the aviary houses seemed to be negatively influenced by the low outside temperatures under winter conditions. The results of this research can be used to develop methods to reduce the emission from litter in aviary houses.

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CHAPTER 6

Litter Composition and Ammonia Emission in Aviary Houses Part I: Performance of a Litter Drying System

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Litter Composition and Ammonia Emission in Aviary Houses
Part I: Performance of a Litter Drying System

P.W.G. Groot Koerkamp, L. Speelman and J.H.M. Metz

Abstract

Research was carried out to study the effects of a litter drying system on the composition of the litter and the emission of ammonia in a TWF aviary housing system for laying hens. Air velocities above the litter were increased by means of air that was sucked from the top of the room and blown through holes in ducts at floor level. The dry matter content of the litter was higher (above 900 g/kg) and the total ammoniacal nitrogen (0.7 g/kg) and pH (7.3) of the litter were remarkably lower than in aviaries which did not have a system for forced drying of litter (dry matter 750-850 g/kg, total ammoniacal nitrogen 2-3 g/kg, pH about 8.6). Concentrations of ammonia in the exhaust air were below 5 ppm and the emission of ammonia from the house reached a stable emission level of about 2.0 mg/h per hen when hens were at the age of approximately 30 weeks. This emission level was a result of the litter on the floor and the manure on the belts, and it was reached when the belt manure was removed on a daily basis and approximately 500 m^3/h of air were blown evenly over the litter by means of three ducts. The litter drying system effectively maintained a high level of the dry matter content of the litter and minimised the degradation of nitrogenous components into ammonia. The increase of the volatilisation rate of ammonia from the litter through the higher air velocities was of minor importance because of the low TAN concentration.

1 Introduction

In the last decade, progress has been made in the development of welfare-based aviary housing systems for laying hens [1,2]. One of the most important drawbacks of these housing systems is the higher concentration of ammonia in the house than in battery cage systems, and consequently higher emissions of ammonia from the house [3]. Emission rates, processes and influencing factors of the emission of ammonia from poultry houses were reviewed by Groot Koerkamp [4]. As a result of the damaging effects of ammonia deposition on the environment (eutrophication and acidification)[5], ammonia emissions from livestock husbandry have to be reduced substantially [6,7].

Two main sources of production of ammonia can be distinguished in aviary houses, one being the manure on the belts and the other the litter-droppings mixture on the floor. Investigations revealed that the emission from aviary housing systems for laying hens, with manure belts, were about three times higher than from battery cage systems, with manure belts, for the same frequency of manure removal from the belts. This difference was caused by the volatilisation of ammonia from the litter [8, 9]. In one study, 22.5% of the droppings were deposited in the litter and caused 79% of the total emission of ammonia from the aviary system [10]. The production of ammonia by the litter consists of a degradation and a volatilisation process and depends primarily on the surface area, the amount of litter (layer thickness) and its composition, as found for aviary systems [11]. The water content, pH and temperature were identified as the most important parameters of the composition with respect to the degradation of nitrogenous components in litter into ammonia [12]. In particular, water plays a key role in the microbial degradation of nitrogenous components: the higher the water content, the higher the degradation rate. Two main sources of evaporation of water in an aviary house can be distinguished: respiration by the hens and the fresh droppings from the hens. The droppings become manure on the belts or they mix with the litter on the floor. The climatic parameters of temperature, vapour pressure difference and air velocity, influence the evaporation rate of water from the manure and litter, but temperature and air velocity also influence the volatilisation rate of ammonia from the litter. The means used to minimise the water content of the litter may therefore conflict with the aim to minimise the volatilisation of ammonia from the litter. Unfortunately, no ways are yet known how to enhance the evaporation of water from litter in poultry houses that are practically and economically feasible.

A study was carried out to find a practical way of enhancing the evaporation of water from litter in a Tiered Wire Floor aviary house for laying hens as a means to minimise degradation of nitrogenous components and to study the effect on the litter composition and emission of ammonia. In subsequent papers, the water flows from and to the litter will be described and modelled.

2 Experimental arrangements and methods

2.1 Housing system

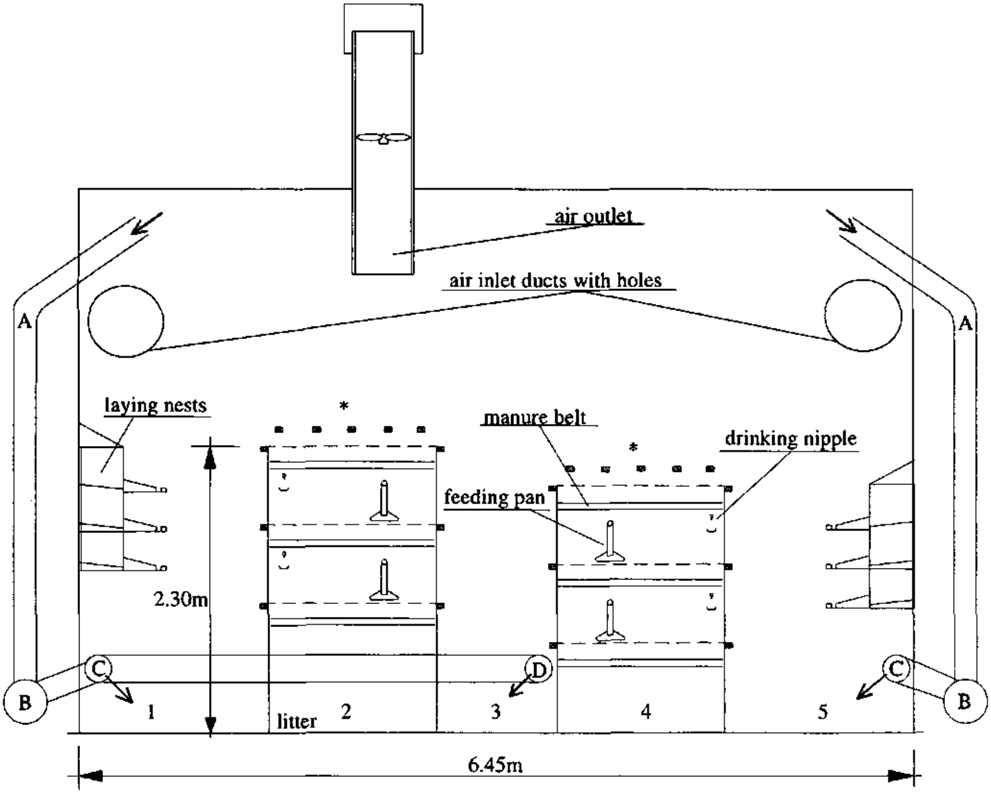

Figure 1 Cross-section of the Tiered Wire Floor (TWF) aviary system with the litter drying system. Pathways and stacks are numbered (1 to 5). A: closed ducts, B: centrifugal ventilators, C and D: ducts with holes, → : air flow direction, * temperature/relative humidity sensor.

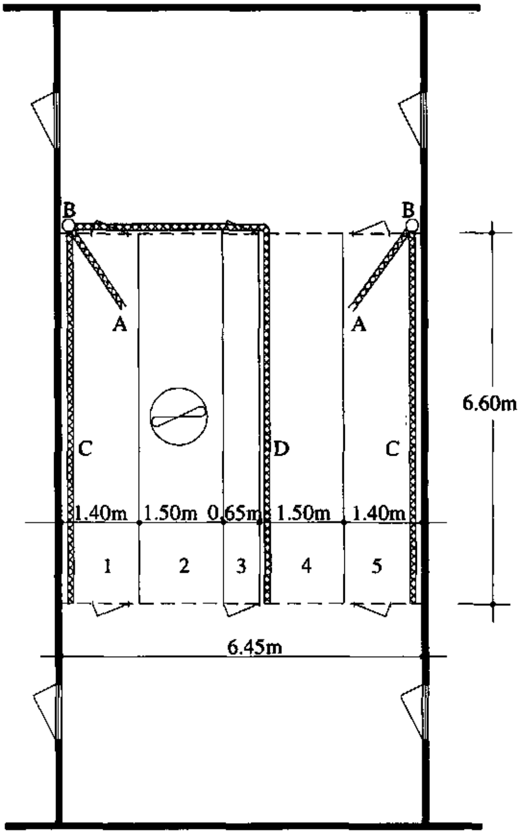

Figure 2 Top view of the Tiered Wire Floor (TWF) aviary system with the litter drying system. See figure 1 for legend.

The Tiered Wire Floor (TWF) aviary housing system in this experiment was assembled in a dark room of the experimental accommodation located at the Spelderholt Research Centre in Beekbergen (the Netherlands). The room was separated from the work areas by wire netting, which was covered with black plastic impermeable membrane. The room had a temperature controlled mechanical ventilation system (one ventilator in the roof, capacity about 4,500 m^3/h) with a temperature sensor about 50 cm above the perches of the upper tier, a water and feeding system and light regulation. A cross-section and a top view of the TWF system are shown in figures 1 and 2 respectively, and a detailed description of the TWF system is given in Groot Koerkamp and Bleijenberg [11]. The TWF system consisted of two rows of three stacked wire floors, two rows of laying nests and three pathways. Pathways and stacks are numbered successively from 1 to 5 in figures 1 and 2. The TWF system offered 976 cm^2 living area per hen, of which 33% was available as litter area (the whole floor area except stack number 4). The hens defecated part of their droppings on the conveyer belts beneath the wire floors of the tiers. This part of the droppings was removed from the house by the belts into a container outside the house. The hens deposited the other part of their fresh droppings in the litter.

2.2 Management and hens

One thousand hens of a commercial strain (Lohmann white LSL) were housed at 16 weeks of age. Room temperature was set at 22 °C. Hens were fed a commercial layer diet at a restricted level (168 g/kg crude protein; 11.93 MJ/kg metabolisable energy). Water was supplied *ad libitum* during the lighting period only with nipple drinkers with cups. The lighting scheme started with 11 h of light per day at 16 weeks of age and increased at 1 h per week up to 15 h per day. All hens were debeaked. Before placement of the hens, the litter area was filled with sand to a depth of 1 cm.

2.3 Treatments

At the start of the experiment, the hens were 17 weeks of age. The experiment lasted until 30 weeks of age (August 15th until December 20th 1993). During four treatment periods (1A-1D), of unequal lengths, treatments were carried out and measurements were made. The treatments involved manipulation of the evaporation of water from the litter and the amount and stay of the manure on the belts (table 1). Litter drying was practised during all periods. Warm air from the top of the room was sucked through two ducts (110 mm diameter) by two centrifugal fans (B) and blown to two ducts (C) (110 mm diameter) that distributed the air over the litter (see figures 1 and 2). The latter two ducts were placed about 20 cm above the litter along the whole length of the system and equipped with holes of 5 mm diameter (100 mm apart). During periods A and B, besides the litter drying arrangement described, a fan was mounted underneath the first floor of stack number 2 to enhance air turbulence above the litter (not shown in figure 1). Treatments during period 1A were the same as those during period 1B. However, they are distinguished separately because the emission of ammonia was stable during period 1B. The third tube of the litter drying system in the middle of the house (D) was installed at the start of period 1C. During periods 1A to 1C the manure on the belts was removed daily on Mondays to Fridays, whereas during period 1D it was removed on Saturdays and Sundays also. Manure on the belts was removed between 11 00 and 12 00 h.

Table 1 Treatment scheme for litter and manure handling.

Treatment period	Age of hens Weeks	Litter drying	Number of tubes with one row of holes	Presence of one fan under stack 2	Removal frequency of belt manure (number of times per week)
1A	17-19	on	2	Yes	5
1B	20-24	on	2	Yes	5
1C	25-26	on	3	No	5
1D	27-31	on	3	No	7

2.4 Measurements

Ammonia concentrations and ventilation rates of the house were continuously recorded during the four treatment periods in the ventilation shaft [13] in the roof of the house (figure 1). The outdoor concentration of ammonia was measured in one of the two air inlets. Ammonia in the air was transported from the ventilation shaft and air inlet through heated and insulated tubes via a thermal NH_3 converter to a NO_x chemiluminescence analyser [13]. Ventilation rates were measured with a measuring fan with the same diameter as the ventilation shaft. Temperature and relative humidity (r.h.) were measured with two combined sensors (Rotronic I-100) placed 20 cm above the upper tier (figure 1). At each side of the house a combined sensor was placed at a height of 2 m close to the air inlets to measure the outdoor temperature and humidity as well. The ventilation rate of the litter drying system was measured by two fan wheel anemometers (Lambrecht KG, type 1468) with a straightener placed upstream. Hourly averages of ammonia concentration, ventilation rate, temperature, r.h. and air velocity were automatically recorded [14]. The ammonia emission was calculated as the difference between the concentration of ammonia in the exhaust air and the inlet air multiplied by the ventilation rate. Egg production and feed and water intake of the hens were recorded daily.

Litter samples were taken weekly and analysed for dry matter (DM), ash, total ammoniacal nitrogen (TAN) and N-Kjeldahl (N_{kj}) content and pH. All chemical analyses were carried out according Dutch standards (NEN). A fixed amount of litter was taken from ten evenly distributed spots and mixed. The thickness of the litter layer was measured weekly at ten spots and averaged. Samples of belt manure were taken weekly in all treatment periods in the middle of the week.

During the removal of the manure from the belts, approximately five samples of manure were taken from the conveyer belt at a fixed time interval and mixed. The sample was then subject to analysis for the content of DM, N_{kj}, TAN, ash and pH.

2.5 Data analysis

Mean concentration, ventilation rate, emission, temperature, relative humidity and composition of litter and belt manure were calculated per treatment period. All analyses were treated with the Genstat 5 statistical package [15].

3 Results

3.1 Technical performance

The mean production results of the hens in the Tiered Wire Floor system from 21 to 32 weeks are summarised in table 2.

Table 2 Number of hens, mortality, egg production, feed consumption and water usage of the hens (age of hens 21 up to 32 weeks).

	Tiered Wire Floor
Number of hens housed (at 17 weeks)	1000
Rate of lay (eggs / housed hen day, %)	81.5
Feed consumption (g / hen d)	108.7
Feed conversion (kg feed / kg egg)	2.33
Water usage (ml / hen d)	211
Water / feed ratio (g / g)	1.94
Mortality (%)	0.60

3.2 Climatic conditions and ammonia concentrations

The temperature in the house was maintained during all four periods at about 22.5 °C. The temperature control system decreased the ventilation rate to compensate for the fall of the outside

Table 3 Mean and standard deviation (in brackets) of the temperature (T, outdoor and indoor), relative humidity (r.h., outdoor and indoor), ventilation rate of the house (Qhouse), ventilation rate of the litter drying system (Qlitter), ammonia concentration within the house and total emission of ammonia per treatment period (n=number of hourly values).

	Period			
Variable	1A (n=455)	1B (n=910)	1C (n=240)	1D (n=716)
T outdoor (°C)	11.3 (3.6)	6.6 (4.3)	1.7 (4.5)	1.4 (5.0)
R.h. outdoor (%)	86 (11)	86 (9)	87 (8)	88 (7)
Temperature indoor (°C)	23.1 (0.9)	23.0 (0.7)	22.8 (0.7)	22.2 (0.7)
R.h. indoor (%)	59 (4)	53 (7)	47 (5)	51 (7)
Qhouse (m^3/h per hen)	1.8 (0.69)	1.9 (0.42)	1.7 (0.30)	1.4 (0.29)
Qlitter (m^3/h)	423 (33)	398 (41)	524 (7)	470 (23)
Ammonia concentration (ppm)	0.7 (0.57)	3.3 (1.08)	2.5 (0.71)	2.4 (0.55)
Ammonia emission (g/h)	0.87 (0.72)	4.19 (1.50)	3.09 (1.23)	2.28 (0.71)

temperature until 1.4 °C was reached in period 1D (table 3). The ventilation rate of the litter drying system increased from about 400 m^3/h in periods 1A and 1B to about 500 m^3/h in periods 1C and 1D due to the installation of the third duct with holes in the middle of the house. A more equal distribution of the air over the litter was also achieved in this way. The ventilation rate slightly decreased with time due to settlement of dust in the ducts. Mean ammonia concentrations per period, within the house, were 3.3 ppm or lower. Mean outdoor concentrations per period varied between 0.03 and 0.08 ppm.

3.3 Litter and belt manure composition and layer thickness

The dry matter content of the litter decreased from 974 g/kg in period 1A to 917 g/kg in period 1D (table 4). The chemical composition of the sand initially present was about 100% ash. The sand mixed with droppings of the hens and the ash content decreased from 93% (1A) to 60% (1D) of the DM. Both the concentration of TAN and N_{kj} increased during the treatment periods, from 0.2 to 0.7 g/kg and from 2.8 to 18.0 g/kg, respectively. Both the TAN concentration relative to the N_{kj} concentration (4%) and the pH (7.3) were quite stable. The litter layer increased in thickness from 1.5 to about 3.4 cm. The dry matter content, the TAN and N_{kj} concentration of the manure on the belts were higher in period 1A than in the following periods (table 5). The TAN concentration (expressed as a percentage of the N_{kj}) decreased from 18 (1A) to 9% (1D). The pH was between 6.4 and 6.9.

Table 4 Mean and standard deviation (in brackets) of the composition of the litter during treatment periods 1A to 1D (n = number of measurements).

	Period			
	1A (n=3)	1B (n=5)	1C (n=2)	1D (n=4)
Dry matter (g/kg)	974 (14)	938 (12)	925 (6)	917 (10)
Ash (% of DM)	93 (5)	76 (6)	63 (1)	60 (5)
TAN (g/kg)	0.20 (0.10)	0.41 (0.09)	0.53 (0.07)	0.70 (0.11)
TAN (% of N_{kj})	5 (0.1)	4 (0.4)	3 (0.3)	4 (0.5)
N_{kj} (g/kg)	2.8 (2.6)	11.2 (3.2)	16.0 (0.8)	18.0 (1.1)
pH (-)	7.1 (0.5)	7.6 (0.3)	7.4 (0.1)	7.3 (0.1)
Layer thickness (cm)	1.50 (0.30)	2.58 (0.48)	2.65 (-)	3.39 (0.35)

Table 5 Mean and standard deviation (in brackets) of the composition of the manure on the belts during treatment periods 1A to 1D (n = number of measurements).

	Period			
	1A (n=2)	1B (n=5)	1C (n=2)	1D (n=4)
Dry matter (g/kg)	389 (27)	286 (26)	286 (21)	287 (7)
Ash (% of DM)	23 (4)	29 (4)	26 (0.1)	25 (1)
TAN (g/kg)	3.26 (1.8)	1.97 (0.9)	1.50 (0.1)	1.37 (0.2)
TAN (% of N_{kj})	18 (9)	13 (6)	10 (2)	9 (2)
N_{kj} (g/kg)	18.1 (0.7)	14.7 (2.0)	15.4 (2.3)	15.6 (2.1)
pH (-)	6.8 (0.2)	6.9 (0.6)	6.4 (0.3)	6.5 (0.3)

3.4 Emission of ammonia

Data on the emission of ammonia around 24 weeks of age (the break in figure 3) were missing due to technical problems. The emission of ammonia per hen (figure 3) increased strongly during period 1A, was highest during period 1B, decreased during 1C and stabilised during period 1D. The sharp peaks during periods 1B and 1C occurred during the weekends when manure on the belts was not removed. This was in contrast to period 1D with a levelled pattern and a small standard deviation (0.71) of the emission around the mean of 2.28 g/h (table 3). The peak between 28 and 30 weeks of age (period 1D) coincided with technical problems with the manure removal system. Part of the manure remained in the gutter of the removal system in the compartment.

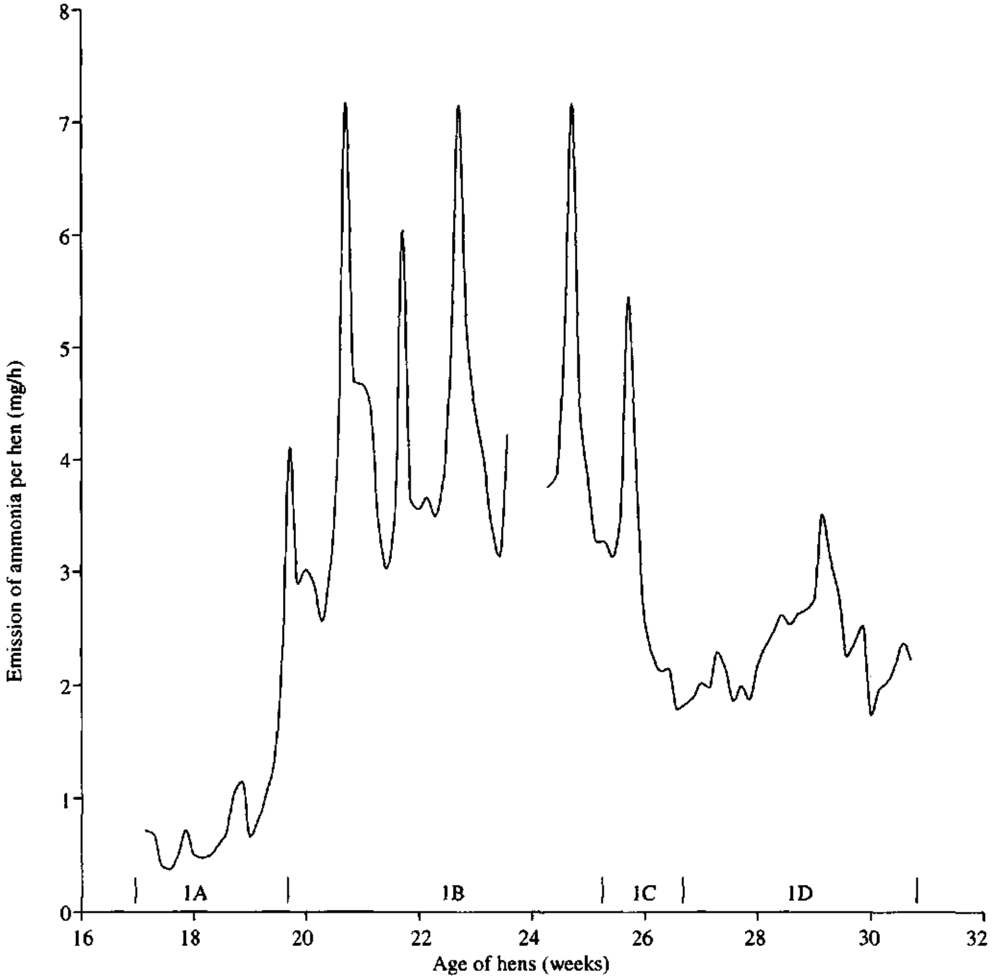

Figure 3 The course of the emission of ammonia (daily averages) from the Tiered Wire Floor (TWF) aviary system. Periods are numbered (1A to 1D).

4 Discussion

4.1 Technical performance

Mortality, egg production and feed consumption were comparable with results obtained in this and other aviary systems, considering the difference in the length of the laying cycles [3]. No obvious negative side-effects of the litter drying system on the production and behaviour of the hens were observed.

4.2 Climate

The climate was controlled satisfactorily despite small deviations from the set-point temperature. The ventilation rate of the litter drying system was about 0.5 m^3/h per hen and close to the ventilation rate that is commonly used for drying of manure on belts [16]. In the long run, pollution of the duct system by settlement of dust should be prevented to maintain the required air exchange rate. Ammonia concentrations were below the strict limit of 10 ppm that is applied in some countries for the working and living environment for men and animals. Ammonia concentrations were permanently low compared with the wide range of values measured in aviary systems without the application of litter drying (about 3-25 ppm) [10,11]. The lowest values within this range were found in a Multifloor aviary system, and the consequently low emission of ammonia is discussed in section 4.4.

4.3 Litter and manure

The composition of the litter in this experiment differed remarkably from the composition in TWF and other aviary systems without litter drying [8,10,11,12,18]. These differences of the composition were attributed to the litter drying which caused higher air velocities above the litter and improved the evaporation of water from the litter. The decrease of the DM content of the litter during the

Table 6 Overview of emissions of ammonia from different aviary systems with varying composition of the litter and a battery cage system (TWF = Tiered Wire Floor).

Aviary system / number of hens / type of hen [4]	Period [1]	DM litter (g/kg)	TAN litter (g/kg)	pH (-)	NH_3 emission (mg/h per hen)	Validity of emission [5]	Ref. nr.
TWF / 6040 / w	March – May	800	-	-	11.7	A	3
TWF / 6480 / w+b	March-Sept.(c)	750-850	1.9	8.5	12.5	B	10
Battery cage / 6480 /w+b	March-Sept.(c)	-	-	-	2.9	B	10
TWF / 25,700 / w	laying period	650-830	3.0	8.7	8.1	B	18
TWF / 998 / b	Aug.-Dec.	850	2.0 [2]	8.5	12.2	B	11
Natura / 807 / b	Aug.-Dec.	800	2.5 [2]	8.5	11.9	B	11
Righs Boleg / 994 / b	Aug.-Dec.	750	2.5 [2]	8.5	15.4	B	11
TWF / 1056 / b	Nov.-April	800	3.9	-	12.1	A	8
Natura / 806 / b	Nov.-April	771	4.2	-	12.5	A	8
Righs Boleg / 995 / b	Nov.-April	830	4.3	-	7.3	A	8
Multifloor [3] / 23,000 / w	laying period	780-830	1.9	8.0	3.0	C	17

[1] c: continuous measurements during whole period, otherwise partly with regular intervals; a laying period is 13 months

[2] stabilised level after 30 weeks of age

[3] belt manure was dried within about 40 h in a drying tunnel situated inside the house,
the exceptional ventilation pattern enhanced the air flow over litter.

[4] w indicates white type, b indicates brown type

[5] A: removal of belt manure twice per week, B: 1st day after removal of belt manure , C: general mean

beginning of the laying period was found before by other researchers, but the rate of decrease in this experiment was slower. The DM content remained above 900 g/kg, whereas values between 750 and 850 g/kg were found in other research for various ages of the hens (table 6). The limited availability of water for degradation of uric acid and proteins in the litter restricted the release of ammonia and resulted in 0.7 g TAN/kg litter only, whereas values between 2 and 3 g/kg were found in other research. The low pH of the litter, about 7.3 compared with about 8.6 in other research, also contributed to the slow degradation rate of nitrogenous components and increased the contribution of ammonium in the ammonia–ammonium equilibrium. The increase of the N_{kj} content and the layer thickness were caused by the deposition of droppings of the hens in the litter area and corresponded with results of other research [10,11]. The DM and TAN content and pH of the manure as sampled on the belts after one day were somewhat lower compared with other results where manure was sampled after a stay on the belts of three to five days. The peak in the ash content in period 1B was also found by others and the N_{kj} concentration was normal [11].

4.4 Emission of ammonia

The emission increased relatively slowly after placing of the hens in the aviary system at 16 weeks of age and did not show a typical peak around 21 weeks of age, as normally observed [8,11]. The increase of the emission during the weekends in periods 1B and 1C was attributed to the increase of the emission from the manure on the belts. The higher ventilation rate of the litter drying system and the more equal distribution of air over the litter since the start of period 1C (placement of the third tube) apparently improved the drying of the litter (only a slight decrease of the DM content) and consequently decreased the emission substantially. Little effect was found of the fan under stack number 2 on the drying of the litter during periods 1A and 1B; in fact, it hindered the hens in their movement and some hens preferred to lay eggs in the litter beneath this fan. A stable emission level of about 2.0 mg/h per hen was reached in period 1D, if the peak in the emission due to improper manure removal in this period, is neglected. This emission was the sum of the emission from the litter and the manure on the belts, and was very low compared with the emission from aviary systems without drying of litter (7.3 - 14.6 mg/h per hen for two frequencies of removal of belts manure) and even lower than the emission from a battery cage system with manure belts and daily manure removal (2.9 mg/h per hen), as summarised in table 6. The emission levels on the first day after manure removal, indicated with 'B' in table 6, were estimated with a regression model on the basis of measurements of the emission of ammonia under varying frequencies of removal of the manure from the belts. This enabled comparisons of emission rates of different studies for the same removal frequency of belt manure. Only in the case of the Multifloor system, was manure on the belts removed daily during the whole laying cycle. The low emission from the Multifloor aviary system, where the volatilisation of water from the litter was slightly enhanced, could be explained by the lower pH of the litter and the lower TAN concentration of the litter as compared with the composition of litter in other aviary systems. The TAN concentration (maximum 0.7 g/kg) and the pH (mean 7.3) of the litter in the TWF with litter drying in this study were substantially lower than was found in other aviary houses. These parameters of the litter composition caused lower volatilisation rates of ammonia from the litter, as shown by Groot Koerkamp and Elzing [12], and explain the low emission of ammonia from the whole TWF system. The litter drying system minimised the degradation process effectively and possible effects on the volatilisation process of ammonia from the litter were thereby of minor importance. The mean emission of ammonia during period 1A to 1D amounted to 2.85 g/h, which was equivalent to a nitrogen volatilisation of 1.94% of the nitrogen intake by the hen.

5 Conclusions

A technically simple but effective litter drying system was successfully applied. It was concluded that enforced air movement above the litter in aviary houses, by using 0.5 m^3/h per hen, enhanced the evaporation of water from the litter substantially. In this way, the DM content was maintained above 900 g/kg and the TAN concentration (0.7 g/kg) and pH (7.3) were decreased, as compared with the composition of litter in aviary houses without forced drying of litter. This change in the composition of the litter lowered the emission of ammonia from the litter. Lowest emissions of ammonia from the aviary house (2.0 mg/h per hen) were reached when manure on the belts was removed every day and three instead of two ventilation tubes were used. By means of litter drying the emission of ammonia from aviary houses can be as low as or below the typical level for battery cages with daily removal of manure on the belts.

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CHAPTER 7

Litter Composition and Ammonia Emission in Aviary Houses Part II: Modelling of the Evaporation of Water

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Litter Composition and Ammonia Emission in Aviary Houses
Part II: Modelling of the Evaporation of Water

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Abstract

Experimental research was carried out with laying hens that were 47 to 60 weeks of age to validate a physical model of the evaporation rate of water from litter in a Tiered Wire Floor aviary system. Changes in the evaporation rate of water from the litter was achieved by varying air velocities above the litter between 0.07 and 0.28 m/s, by naturally changing weather conditions and by removing belt manure once a week, once a day or two times a day. An evaporation model was developed and used to predict the water content of the litter on a specific day. The water content increased with 126.8 g/kg litter per day (s.e. 19.4) due to the water input through fresh droppings defecated in the litter by the hens. The evaporation rate of water from the litter was positively influenced by the air velocity ($v_{air}^{0.287}$) and the difference between the water vapour pressure in the litter and the water vapour pressure of the air above the litter. The water activity of the litter was estimated to be 0.86 (s.e. 0.07) and caused a decrease in the saturated water vapour pressure in the litter. The water vapour pressure of the air indoor highly depended (79%) on the vapour pressure of the outside air. It was predicted that in this way drying conditions above the litter worsen from April to October under Dutch circumstances. This can, however, be compensated by increasing the litter temperature and the air velocities. The emission of ammonia was modelled with the following influencing parameters: manure removal interval (0.76%/h), indoor temperature (8.1%/°C), water content of the litter (0.32% per (g/kg)) and air velocities above the litter (103% per (m/s)). The mean emission in the case of daily removal of the belt manure amounted 2.85 mg/h per hen.

1 Introduction

The development and use on commercial farms of welfare friendly systems with litter for laying hens may be hampered by the negative effects of ammonia on the indoor climate and the environment [1,2]. Water plays an important role in the release of ammonia from litter. In a previous paper was found that the emissions of ammonia from the litter can be reduced substantially when the dry matter content of the litter is kept above 900 g/kg [3]. However, more knowledge of the effect of water content of the litter on the emission of ammonia and factors that influence the evaporation of water from the litter is necessary to be able to control the dry matter content of the litter at a desired level.

The volatilisation rate of ammonia from litter in aviary houses for laying hens is linearly related to the unionised ammonia concentration in the water of the litter [4]. The release of ammonia from degradation processes can be reduced by lowering the pH, the temperature or the water content of the litter. Control of acidity and temperature is either difficult or is not acceptable under most practical circumstances. The dry matter content, that is the complement of the water content, of litter found in various aviary systems varied between 700 and 850 g/kg and affected the degradation rate of nitrogenous components substantially [4]. The two major flows of the water balance of the litter are the water input by means of fresh droppings of the hens and the water output by means of evaporation of water from the litter. The evaporation of water is influenced by the air velocity above the litter, the temperature of the litter-air boundary and the water vapour pressure difference between the litter and the air. The water vapour pressure in an aviary results from the water content of the outside air, the latent heat production of the hens and the evaporation of water from the manure on the belts and the litter.

The objective of this research was to model and validate, by means of data obtained in a Tiered Wire Floor aviary system, the evaporation rate of water from litter. Additionally the interrelations between the indoor and outdoor climate, characteristic parameters of litter and belt manure, and the volatilisation of ammonia from the litter and the belt manure were studied.

2 Materials and Methods

2.1 Housing system

The Tiered Wire Floor (TWF) aviary housing system in this experiment was placed in a dark room located at the Spelderholt Research Centre in Beekbergen. It was the same one as the one used by Groot Koerkamp *et al.* [3] (Chapter 6), except that the whole floor area (42.2 m^2) was now covered with litter and available for dust bathing of the hens. The litter drying system was adapted to this situation. The middle tube of the system was equipped with two rows of holes so that air was also blown over the litter under stack number four (see figure 1 of Groot Koerkamp *et al.* [3]). This experiment was done in the second half of the laying cycle of the hens that were used by Groot Koerkamp *et al.* [3]. The management with respect to feeding, lighting, climate control and handling of belt manure was the same as in this former experiment.

2.2 Treatments

At the start of the experiment the hens were 47 weeks of age. They were housed until 60 weeks of age (April 19th until July 13th 1994). During five periods of two to three weeks (2A-2E) treatments were carried out and measurements were made. The treatments involved manipulation of 1) the evaporation rate of water from the litter and 2) the amount and period of stay of the manure on the belts (table 1). The litter drying system was used to increase air velocities above the litter from about 0.07 m/s to 0.28 m/s to enhance evaporation of water [3]. The litter drying system was switched on (2A and 2D) and off (2B, 2C and 2E), and the manure on the belts was removed once a week (2A and 2B), every day (2C and 2D) or two times a day (2E). Manure on the belts was removed between 11 00 and 12 00 h and during period 2E also between 16 00 and 17 00 h. The thickness of the litter layer was reduced to one cm by removing litter at the start of treatment period 2A.

Table 1 Treatment scheme for litter and manure handling (the litter drying system consisted of 3 ducts with holes).

Treatment Period	Age of hens (weeks)	Litter drying	Removal frequency of belt manure
2A	48-50	on	once per week
2B	51-53	off	once per week
2C	54-55	off	once per day
2D	56-57	on	once per day
2E	58-59	off	twice per day

2.3 Measurements

Hourly averages of the ammonia concentration, the ventilation rate of the house, the temperature, the relative humidity and the ventilation rate of the litter drying system were continuously recorded as described by Groot Koerkamp *et al.*[3] Temperature and relative humidity (r.h.) were measured by means of four combined sensors (Rotronic I-100): two above the upper tier and two above the litter. Four temperature sensors were placed in the litter. Three air velocity sensors (Schmidt, type SS 20.011) were placed about ten cm above the litter. Two Rotronic sensors were placed outside the house at a height of two m to measure the outdoor temperature and relative humidity.

The emission of ammonia was calculated as the difference between the concentration of ammonia in the exhaust air and the inlet air multiplied by the ventilation rate. Air temperature and r.h. were used to calculate the saturated and the actual water vapour pressure of the indoor and outdoor air [5]. Egg production and feed and water intake of the hens were daily recorded.

Litter samples were taken daily and analysed on dry matter (DM). A fixed amount of litter was taken from ten evenly distributed spots and mixed. A part of this mixture was analysed. Once per treatment period the concentration of total ammoniacal nitrogen (TAN), N-Kjeldahl (N_{kj}), pH, and ash content were determined in a mixture of the daily taken litter samples.

Samples of belt manure were taken weekly in all treatment periods. During the removal of the belt manure on average five samples of manure were taken from the conveyer belt at a fixed time interval and mixed. This sample was taken for analysis for the content of DM and ash. The measurements during period 2E were all missing.

2.4 Statistical analysis

Hourly values of temperature, r.h., ventilation rate, ammonia concentration, and total emission of ammonia were used to calculate a mean value and standard deviation per treatment period. Daily means of all variables were calculated from noon until noon and a database was created which was used to validate the models for the evaporation rate of water and the emission of ammonia. Mean values and standard deviation of the composition were calculated per period. Significance of estimates of regression coefficients were tested under the assumption of the Student's t-distribution. Significant differences are indicated as follows: ˜: $P<0.10$; *: $P<0.05$; **: $P<0.01$; ***: $P<0.001$ (two sided). All statistical analyses were carried out with the Genstat 5 statistical package [6].

2.5 Model development

From the mass balance of water in litter follows equation (1) that gives the relation between the evaporation rate of water and the water content of the litter on two consecutive days:

$$C_{H_2O,t} = \frac{I_{H_2O,t} \cdot 1day}{M_t} - \frac{A \cdot 1day}{M_t} \cdot \Phi_{H_2O,t} + C_{H_2O,t-1} + \mathrm{Rest}_{H_2O,t} \tag{1}$$

The water content of the litter is the complement of the dry matter content:

$$C_{H_2O,t} = 1000 - C_{DM,t} \tag{2}$$

The influence of temperature, air velocity and water vapour pressure difference on the evaporation rate of water can be described as follows:

$$\Phi_{H_2O} = k \cdot (T_{boundary,t} + 273.15)^{\gamma_1} \cdot v_{air}^{\gamma_2} \cdot (P_{H_2O,litter,t} - P_{H_2O,air,t}) \tag{3}$$

Parameter k represents the constant of the mass transfer coefficient. The water activity (A_w) of litter is less than one. This means that the water vapour pressure in the boundary layer of the litter is smaller than the saturated vapour pressure because a certain amount of the water is bound to the litter:

$$P_{H_2O,litter,t} = A_w \cdot P_{sat,H_2O,litter,t} \tag{4}$$

Using equation (3) and (4) in equation (1), assuming $I_{H20,t}$ and M_t to be constant, and the rest term transposed into a partial dependency on the water content of the litter on the previous day (λ), yields:

$$C_{H_2O,t} = \frac{I_{H_2O}}{M} - \frac{A}{M} \cdot k \cdot T^{\gamma_1}{}_{boundary,t} \cdot v_{air,t}^{\gamma_2} \cdot (A_w \cdot P_{sat,H_2O,litter,t} - P_{H_2O,air,t}) + \lambda \cdot C_{H_2O,t-1} \tag{5}$$

The parameters of the partly non-linear equation (5) were solved by using the database of the required variables of daily averages. The influence of the boundary temperature $T_{boundary}$ was expected to be small and set to zero.

The water vapour pressure of the air above the litter influences the evaporation rate of water and depended on the vapour pressure of the outside air, the indoor temperature and the evaporation of water from the manure on the belts. This empirical relation was solved by linear regression techniques and looked like:

$$P_{H_2O,air,t} = \beta_0 + \beta_1 \cdot P_{H_2O,air\ outside,t} + \beta_2 \cdot T_{air\ house,t} + \beta_3 \cdot Time_{bm,t} \tag{6}$$

The emission of ammonia was analysed as follows:

$$Z_t = \eta_t + \varepsilon_t \tag{7}$$

The deviation ε_t was assumed to follow an auto-regressive process of order one and was the weighed sum of past innovations:

$$\varepsilon_t = \phi \cdot \varepsilon_{t-1} + a_t \tag{8}$$

The model for the emission of ammonia was:

$$\eta_t = \alpha_0 + \alpha_1 \cdot (Time_{bm,t} - 12.5) + \alpha_2 \cdot (T_{air\ house,t} - 22.5) + \alpha_3 \cdot (C_{H_2O,t} - 80) + \alpha_4 \cdot (v_{air,t} - 0.26) \tag{9}$$

The effects of $Time_{bm,t}$, $T_{air,house}$, $C_{H20,t}$ and v_{air} were relative to the mean values of these parameters during the first part of this laying period [3]. This linear model on the log scale meant a multiplicative model for the emission itself. The variance was assumed to be constant on the log scale and time-series analysis was used for the time-dependent processes [7]. The relationship between σ^2_ε the variance of ε_t, and σ^2_a is: $\sigma^2_\varepsilon = \sigma^2_a / (1-\phi^2)$. The directive 'BJIDENTIFY' of Genstat was used to check the innovations a_t.

Notation

$\Phi_{H_2O,t}$ = evaporation rate of water from litter at day t (g/d m^2)
$I_{H_2O,t}$ = water input to litter from fresh dropping at day t (g/d)
$C_{H_2O,t}$ = water content of litter at day t (g/kg litter)
$C_{DM,t}$ = dry matter content of litter at day t (g/kg litter)
$\mathrm{Rest}_{H_2O,t}$ = residual term of the water balance of litter (g/kg litter)
A = litter area (m^2)
M_t = total mass of the litter at day t (kg)
$T_{boundary,t}$ = mean temperature of the litter - air boundary at day t (°C)
$T_{air\ house,t}$ = mean temperature of the air in the TWF system at day t (°C)
$v_{air,t}$ = mean air velocity above the litter at day t (m/s)
$P_{H_2O,litter/air,t}$ = mean water vapour pressure in the litter / the air above litter at day t (Pa)
A_w = water activity (-)
$Time_{bm,t}$ = mean duration of stay of manure on the belts in the TWF system at day t (h)
z_t = natural logarithm of the measured emission of ammonia (mg/h per hen) at day t
η_t = mean emission of ammonia at day t
ε_t = deviation at day t
ϕ = correlation parameter of the autoregressive process of order 1
$\gamma_{1,2}, \lambda$ = regression coefficients
$\beta_{0,1,2,3}$ = regression coefficients
$\alpha_{0,1,2,3,4}$ = regression coefficients
k = mass transfer coefficient

3 Results

3.1 Technical performance

The mean egg production results of the hens from 20 to 60 weeks are summarised in table 2. The rate of lay amounted 88.1%, and feed consumption and feed conversion ratio were 108.53 g/d per hen and 1.99 kg feed/kg eggs respectively.

Table 2 Number of hens, mortality, egg production, feed consumption and water usage of the hens (age of hens 21 up to 60 weeks).

	Tiered wire floor
Number of hens housed at 17 weeks	1000
Mortality, cumulative (%)	2.8
Rate of lay (%)	88.1
Feed consumption (g / hen day)	108.53
Feed efficiency (kg feed / kg egg)	1.99
Water usage (ml / hen day)	213.90
Water / feed ratio (g / g)	1.97

3.2 Climatic conditions and ammonia concentrations

The mean outdoor temperature per treatment period increased, from 10.9 in period 2A up to 20.5 °C in period 2E (table 3). The ventilation rate per hen increased with the outdoor temperature. The mean indoor temperature rose above 25 °C during periods 2D (26.7 °C) and 2E (28.1 °C) with the higher outdoor temperatures. The temperature above the litter was 3.0 to 3.5 °C lower than in the upper part of the TWF house. About 600 m^3/h of air was blown over the litter when the litter drying system was switched on (period 2A and 2D). This resulted in air velocities of 0.24 to 0.28 m/s, compared with 0.07 m/s during periods without forced drying of the litter. Mean ammonia concentrations in the exhaust air were between 2.1 (period 2E) and 6.4 ppm (period 2B).

Table 3 Mean and standard deviation (in brackets) of the temperature (T, outdoor, indoor, above and in the litter), relative humidity (r.h., outdoor, indoor and above the litter), ventilation rate of the house (Qhouse), ventilation rate of the litter drying system (Qlitter), air velocity above the litter, ammonia concentration in the exhaust air and total emission of ammonia per treatment period (n = number of hourly values).

	Treatment period				
Trait and system	2A (n=539)	2B (n=505)	2C (n=335)	2D (n=360)	2E (n=322)
T outdoor (°C)	10.9 (5.2)	12.7 (4.7)	12.8 (4.3)	16.9 (5.2)	20.5 (6.3)
R.h. outdoor (%)	68 (18)	71 (18)	75 (16)	69 (17)	64 (19)
Temperature indoor (°C)	25.0 (0.8)	24.7 (1.1)	24.9 (1.2)	26.7 (1.7)	28.1 (2.6)
R.h.indoor (%)	52 (6)	54 (7)	54 (7)	54 (7)	52 (7)
Temperature above litter (°C)	21.4 (1.9)	20.5 (2.5)	20.4 (2.7)	24.3 (2.4)	25.0 (3.1)
R.h.above litter (%)	56 (6)	61 (6)	64 (5)	58 (5)	59 (5)
Temperature of litter (°C)	21.3 (1.6)	20.8 (1.9)	20.6 (2.0)	24.0 (2.2)	25.1 (2.5)
Qhouse (m^3/h per hen)	1.6 (0.61)	2.0 (0.70)	2.0 (0.69)	2.7 (1.16)	3.3 (1.11)
Qlitter (m^3/h)	588 (19)	0 (0)	0 (0)	586 (22)	0 (0)
Air velocity above litter (m/s)	0.28 (0.06)	0.07 (0.03)	0.08 (0.03)	0.24 (0.04)	0.08 (0.03)
Ammonia concentration (ppm)	6.2 (2.47)	6.4 (2.68)	3.0 (0.53)	2.7 (0.48)	2.1 (0.40)
Ammonia emission (g/h)	6.97 (3.23)	8.57 (3.98)	4.24 (1.65)	5.19 (2.35)	4.99 (2.18)

3.3. Litter and belt manure composition and layer thickness

The mean dry matter content of the litter varied between 799 (period 2C) and 856 g/kg (period 2A), see table 4. The ash content slightly decreased in the course of time from 33 to 29%. The absolute TAN concentration varied between 1.22 (2E) and 1.66 (2B) g/kg, while the relative TAN concentration was between 3.9 and 5.5%. The N_{kj} concentration was stable at about 30 g/kg. The pH ranged between 7.2 and 7.9. The dry matter content of the manure on the belts was during periods 2A and 2B (weekly removal) higher than during the other periods when manure on the belts was daily removed (table 5).

Table 4 Mean and standard deviation (in brackets) composition of the litter during treatment periods 2A-2E (n=number of measurements per period; n=1 for total ammoniacal nitrogen (TAN), N_{kj} and pH).

	Period				
	2A (n=15)	2B (n=20)	2C (n=14)	2D (n=13)	2E (n=13)
Dry matter (g/kg)	856 (14)	807 (19)	799 (12)	855 (15)	835 (11)
Ash (% of DM)	33 (2.8)	30 (1.9)	30 (1.2)	29 (1.8)	29 (0.9)
TAN (g/kg)	1.35	1.66	1.48	1.25	1.22
TAN (% of N_{kj})	4.5	5.5	5.0	3.9	4.1
N_{kj} (g/kg)	29.7	30.1	29.9	31.9	29.9
pH (-)	7.2	7.8	7.9	7.4	7.6

Table 5 Mean and standard deviation (in brackets) of the composition of the manure on the belts during treatment periods 2A-2E (n = number of measurements).

	Period				
	2A (n=1)	2B (n=3)	2C (n=2)	2D (n=2)	2E (n=0)
Dry matter (g/kg)	361 (-)	352 (24.4)	290 (5.4)	279 (21.1)	- (-)
Ash (% of DM)	25.0 (-)	24.3 (1.35)	23.7 (1.82)	21.6 (1.41)	- (-)

3.4 Evaporation of water

The regression of the partly non-linear function of equation (5) resulted in a residual mean square of 80.0 and the percentage of variance accounted for was 90%(R^2_{adjusted}). Figure 1 shows the results graphically. The constant and regression coefficients were estimated as follows (s.e. in brackets):

I_{H2O}/M	126.8 (19.4) ***
$(A/M).k$	94.4 (16.9) ***
γ_l	0
γ_2	0.287 (0.070) ***
A_w	0.864 (0.069) ***
λ	0.488 (0.067) ***

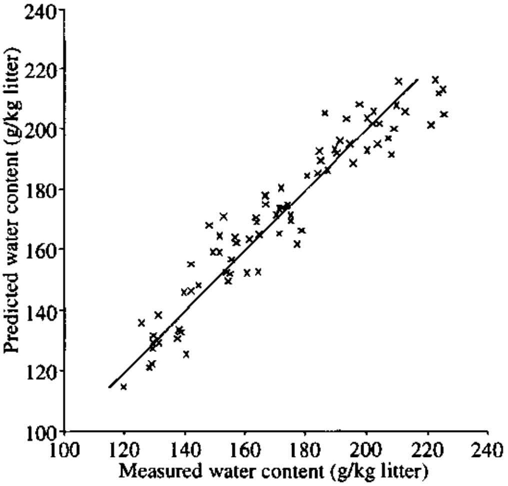

Figure 1 The predicted versus the measured water content of the litter per day during treatment period 2A-2E (x) and the line with perfect predictions. Predictions according equation 5.

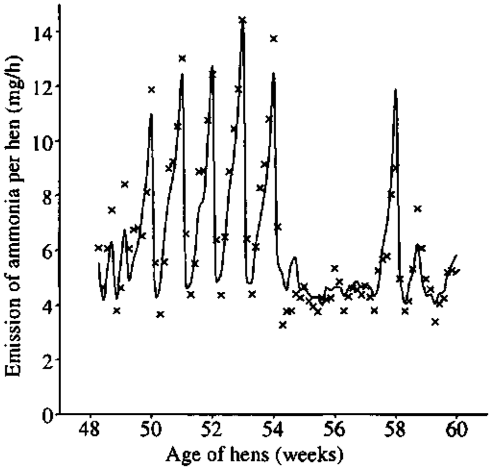

Figure 2 The course of the emission of ammonia from the Tiered Wire Floor aviary house. Daily average measurements (x) and fitted values (——) according to equation 9 during period 2A-2E.

The standard error of all coefficients were small compared with the mean value. The effect of temperature (γ_l) was set to zero. The regression of equation (6) resulted in a residual mean square of 0.0034 and the percentage variance accounted for amounted 95%. The regression coefficients were estimated as follows (s.e in brackets):

β_0	0.700	(0.042) ***
β_1	0.792	(0.036) ***
β_2	0.0090	(0.0050) $^{-}$
β_3	2.55E-4	1.50E-4

This meant that the indoor vapour pressure amounted 0.700 Pa plus 79% of the value of the outside air. Both indoor temperature (β_2, 0.009 kPa/°C) and the stay of manure on the belts (β_3, 2.55E-4 kPa/h, h ranging from 5 to 150 h) influenced the indoor vapour pressure positively, but these effects were small.

3.5 Emission of ammonia

The regression of the emission of ammonia resulted in a residual mean square of 0.0219 and the percentage variance accounted for amounted 80%. Figure 2 shows the variation of the emission during periods 2A to 2E together with the predictions. The regression coefficients were estimated as follows (s.e. in brackets), together with the effects on the linear scale:

α_0	(constant)	1.0470	(0.1172) ***	2.850 mg/h per hen
α_1	(time belt manure)	0.0076	(0.0004) ***	0.763% / h
α_2	(temperature house)	0.0781	(0.0157) ***	8.123% / °C
α_3	(water content litter)	0.0032	(0.0012) **	0.321% / (g/kg)
α_4	(air velocity)	0.7085	(0.3477) *	103% / (m/s)
ϕ	(ar-1 parameter)	0.2386	(0.1080) *	-

The mean emission amounted 2.85 g/h per hen ($e^{1.047}$) for daily removal of belt manure ($Time_{bm}$ = 12.5), for a mean indoor temperature of 22.5 °C, for a water content of the litter of 80 g/kg and an air velocity above the litter of 0.26 m/s. These levels were chosen to be identical to the circumstances during the first part of this laying cycle [3]. The emission increased with the stay of the manure on the belts, the indoor temperature, the water content of the litter and the air velocity above the litter.

4 Discussion

4.1 Technical Performance

Egg production in the TWF aviary system with the litter drying system was close to what could be expected for hens kept in battery cages. Feed consumption was lower than the results obtained in other aviary systems in the Netherlands [1] and feed efficiency was even better than expected for these hens when kept in battery cages (2.14). These results could partly be explained by the relatively young age of the hens at the end of the experiment. However, the hens still had a higher energy demand due to a higher activity compared with hens in battery cages [1].

4.2 Climatic conditions and ammonia concentrations

Mean indoor temperatures were during all periods above the set-point temperature of 22 °C. Despite these deviations, no negative effects on the egg production were found. The amount of air blown over the litter was 0.1-0.2 m^3/h per hen higher than the ventilation rate used in the first part of this laying cycle [3]; this was to compensate for the larger area of litter. The ammonia concentrations were low with values below 10 ppm.

4.3 Litter and belt manure composition

The DM content of the litter varied considerably due to the treatments applied, and can be explained by the variation of the evaporation of water from the litter (next paragraph). The TAN concentration (1.22-1.66 g/kg) was remarkably higher than in the first part of this laying cycle (0.20-0.70 g/kg) [3], but still below values of litter in aviaries without forced drying of litter. These higher TAN concentrations (1.22-1.66 g/kg) were caused by higher degradation rates of nitrogenous components during days with higher water content of the litter. The relative TAN concentration and pH were similar to the levels found in the first part of this laying cycle.

4.4 Evaporation of water

The regression results of equation 5 meant that the water content of the litter on day t was for 48.8% based on the water content at the previous day ($\lambda = 0.488$). On top of this, the water content increased every day with 126.8 g/kg (I_{H2O}/M) due to the water input by the excreta dropped in the litter by the hens. This amount is high compared with water content generally found in litter, being

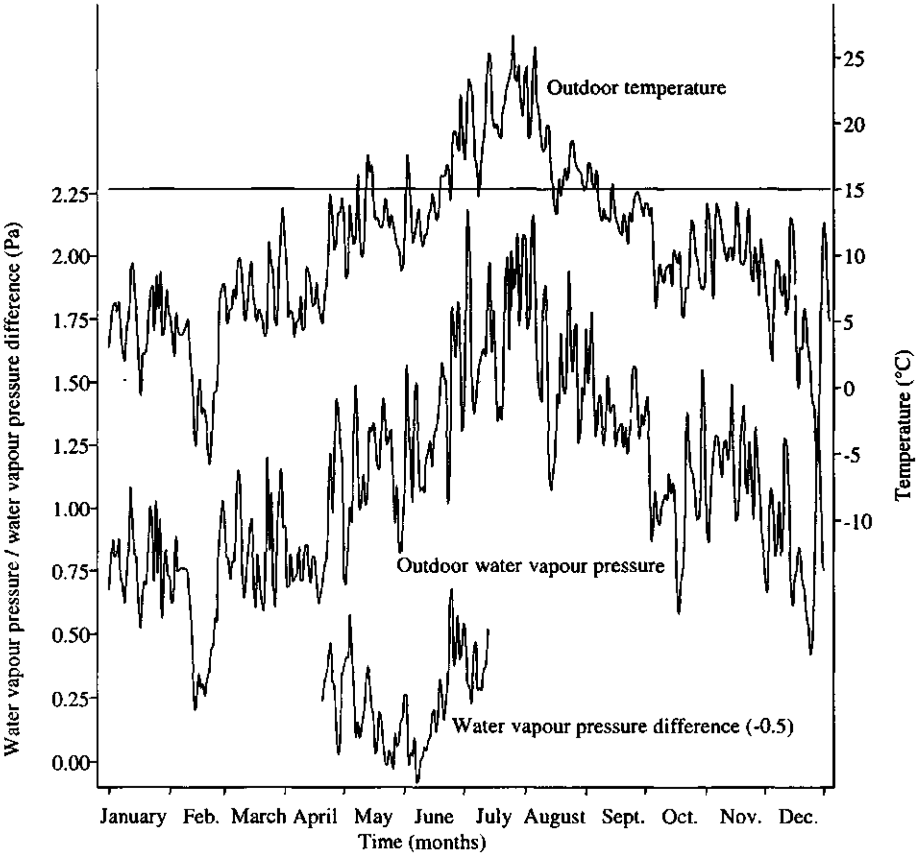

Figure 3 Course of the water vapour pressure and temperature of the outside air in 1994 at De Bilt in the Netherlands (daily averages; KNMI, 1995). The actual water vapour pressure difference between the litter and the air above the litter during this experiment is shown by the lower line. The pressure difference was scaled down 0.5 in the figure for ease of reading.

100-250 g/kg. The evaporation of water decreased the water content with 94.4 g/kg ((A/M).k) at an air velocity of 1.0 m/s and 1.0 Pa water vapour pressure difference. The estimated water activity (A_w, 0.864) was in good agreement with results of other research [8].

The water content of the air above the litter was strongly influenced by the water vapour pressure of the outside air. This implies a strong dependency on the outdoor climate. Figure 3 shows the patterns of the daily average water vapour pressure and temperature of the outdoor air in 1994 [9]. Both the temperature and water vapour pressure were highest during the summer (July). Figure 3 also shows the water vapour pressure difference between the litter and air above the litter during period 2A to 2E (corrected downward 0.5 in the figure). This varied between 0.5 and 1.25 Pa. The rise of the outdoor water vapour pressure during May decreased the water vapour pressure difference. However, this trend altered in the beginning of June. From the beginning of June daily mean outside temperatures rose above 15 °C and increased the temperature of the litter above 20 °C, as shown in table 3. The higher temperatures of the litter increased the saturated water vapour pressure in the litter, and consequently the water vapour pressure difference raised until 1.0 Pa again. It was assumed that in the same way also during August and September drying conditions deteriorate due to a decrease of the water vapour pressure difference.

4.5 Emission of ammonia

The emission of ammonia during this part of the laying cycle (2.85 mg/h per hen) was higher than during the first part (2.0 mg/h per hen [3]), for a comparable removal frequency of belt manure, indoor temperature, water content of the litter and air velocity above the litter. The higher emission of ammonia was attributed to the larger area of litter (about 30%) and the higher TAN concentrations of the litter (1.22-1.66 compared with 0.2-0.7). The emission of ammonia from the manure on the belts increased the total emission of ammonia with 20% per day (24 h). The indoor temperature influenced both the emission from the belt manure as the litter, while the air velocity and water content solely describe the effect on the emission from the litter. The water content of the litter positively influenced the degradation rate of nitrogenous components and thus the TAN concentration of the litter. This day-to-day variation of the TAN concentration was not measured, but the effect on the emission was modelled by the water content of the litter.

5 Conclusions

It was concluded that useful knowledge of the evaporation rate of water from litter was obtained. With this knowledge the air velocity above the litter and the litter temperature can be used to develop a control system to compensate for the effect of the outdoor climate and maintain the dry matter content of the litter at a desired level. In this way the emission of ammonia from the litter can be minimised and the use of aviary housing systems for laying hens on commercial farms is not hampered by higher emissions from aviary houses compared with battery cages.

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CHAPTER 8

Litter Composition and Ammonia Emission in Aviary Houses Part III: Flow of Water to the Litter through Fresh Droppings

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Abstract

An observational study was carried out to investigate the level and variation of water input through fresh droppings to the litter in a Tiered Wire Floor aviary housing system from hens aged 17 through 30 weeks. The mass balances of droppings (all excreta), manure on the belts and litter on the floor were modelled and measurements were made of concentrations and flows and quantities of droppings, belt manure and litter. From the differences in the concentration levels of ash, nitrogen, phosphorus and potassium between droppings, belt manure and litter it was concluded that the transport of litter between the feathers of the hens to the belts was negligible. The relative amount of excreta deposited in the litter by the hens yielded a peak of approximately 50% at 22 weeks of age. Thereafter the flow of droppings to the litter decreased to a stabilised level of approximately 10%. The flow of water through the droppings to the litter showed the same pattern, with a peak of approximately 45 g/d per hen and a stabilised level of approximately 7 g/d per hen. The measured water concentrations of the droppings were 40-90 g/kg lower than the water concentration of freshly excreted droppings, therefore the actual peak might have been 10 to 30 g/d per hen higher. It was hypothesised that the peak in the water flow to the litter was caused by a change in the behaviour of the hens which was indicated by the relative number of measured weights that were registered by the scales which had been placed in the litter area and on a feeding tier. After hens reached the age of 20 weeks, they spent less time scratching and dust bathing in the litter area. Presumably this was so because they spent more time laying eggs in the nests and eating and drinking on the tiers.

1 Introduction

In the last decade, progress has been made in the development of welfare-based aviary housing systems for laying hens [1,2]. One of the most important drawbacks of these housing systems is the higher concentration of ammonia in the house compared with battery cage systems and consequently, higher emissions of ammonia from the house [3]. As a result of the damaging effects of ammonia deposition on the environment (eutrophication and acidification)[4], governmental regulations, especially in the Netherlands, prescribe a substantial reduction of the emissions of ammonia from livestock husbandry [5,6].

Emission rates, processes and influencing factors of the emission of ammonia from poultry houses were reviewed by Groot Koerkamp [7]. Two main sources of production of ammonia can be distinguished in aviary houses, one being the manure on the belts and the other the litter-droppings mixture on the floor for scratching and dust bathing (further indicated as litter). Experimental research showed that the emission of ammonia from the litter is the major source [8,9], which is influenced by the effect of water content, pH and temperature on the degradation process of uric acid and undigested proteins [10], as well as by the effect of temperature, pH and air velocity on the volatilisation process of ammonia [10,11]. The effect of the water content on the emission of ammonia was established [12], and a practical and effective way to control the water content of the litter was tested [13]. Not only the water flow from the litter, but also the flow of water to the litter by means of fresh droppings is of interest for control of the water content of the litter. The variation of the flow of water to the litter through fresh droppings after placement of the hens in an aviary system and the stabilised flow after 30 weeks of age may explain the problems and experiences with wet and cake-like litter under practical circumstances [11,14].

The objective of this study was to investigate the level and variation of the water input by means of fresh droppings to the litter in a Tiered Wire Floor aviary house after placement of the hens in the aviary system. The mass balances of droppings, belt manure and litter were modelled and these equations were used together with the measurements of concentrations and newly developed measuring methods of flows and quantities of droppings, belt manure and litter. In preceding papers [12, 13], factors that affected the water flow from the litter and the effect of water content on the emission of ammonia were presented.

2 Materials and methods

2.1 Housing system and management

A Tiered Wire Floor (TWF) aviary housing system was placed in a dark room of the experimental facilities of the Spelderholt Research Centre in Beekbergen, the Netherlands. This room was the same one as the one used by Groot Koerkamp *et al.* (figure 1 of chapter 6). The aviary system

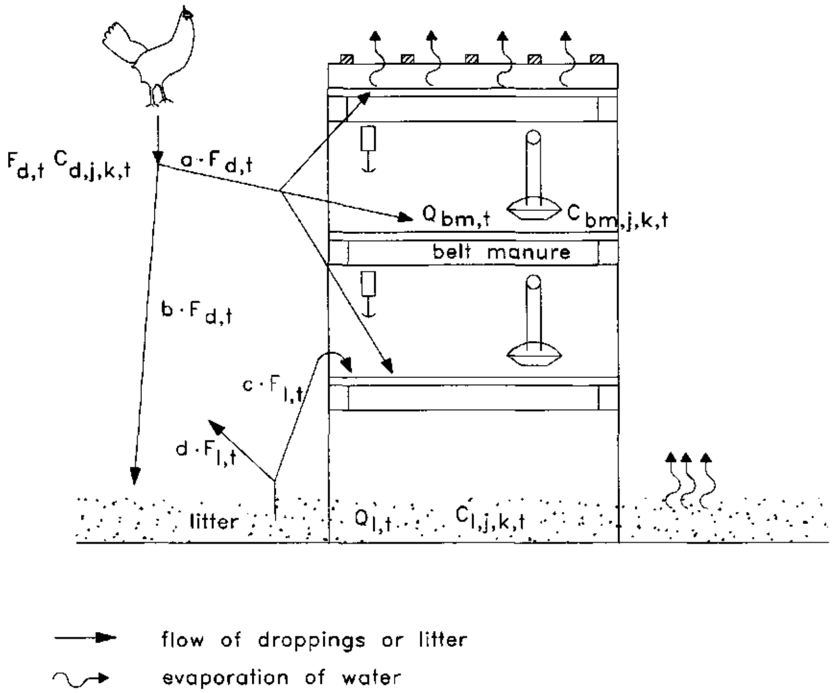

Figure 1 Schematic representation of the model of the flows (F) and quantities (Q) of droppings (suffix d), litter (suffix l) and belt manure (suffix bm) in an aviary system. Composition of flows and quantities with respect to variable j on basis of variable k are given as concentrations (C) (see Notation).

offered 976 cm^2 per hen, of which 33% was floor area for the litter (31.0 hens/m^2 litter). The hens defecated part of their droppings on the conveyer belts beneath the wire floors of the tiers. This manure was called 'belt manure' and will also be referred to with suffix 'bm'. It was removed from the house by the belts into a container outside the house. The hens defecated the remaining part of their fresh droppings in the litter on the floor, which will also be referred to with suffix 'l'. For reference measurements, a part of the lowest tier of stack number 4 (figure 1of chapter 6) was used to make a cage for ten hens that could be separated from the flock (length * height * width = ca. 1.0 * 0.5 * 1.5 m). The excreta from these ten hens were called 'droppings' and will also be referred to with suffix 'd'.

A detailed description of the management procedures of this study (climatic control, water and feed supply and lighting scheme) have been reported in chapter 6 [13]. In brief, one thousand white leghorn hens of a commercial strain (Lohmann LSL) were housed at 16 weeks of age. The hens were 17 weeks of age at the start of this study, which lasted through 30 weeks of age (August 15th until December 20th 1993). Prior to placement of the hens, the litter area was filled with sand to a depth of 1 cm, and litter drying was practised as described in the previous paper. The manure on the belts was removed daily on Mondays to Fridays from 16 to 26 weeks of age, whereas from weeks 27 to 30 it was removed on Saturdays and Sundays as well. Rate of lay, egg weight and feed and water usage (including waste) were recorded daily to calculate data on a weekly basis.

2.2 Measurements

Measurements were made to determine the flow of droppings, the flow of belt manure, and the quantity of litter, in combination with the composition of these three types of manure. These measurements were used in the equations of section 2.3.

The collection period of the droppings on the plates underneath the separation cage with ten hens generally started on Monday and Tuesday at approximately 12 00 h, and lasted approximately 24 h. The amount of droppings per hen per day (exact 24 h) was calculated. After the droppings collection on Wednesday, ten 'fresh' hens were placed in the separation cage. After the droppings collection on Tuesday, the droppings were mixed, and a sample was taken for analysis of the dry matter (DM), ash, N-Kjeldahl (N_{kj}), phosphorus (P) and potassium (K) content. All chemical analyses were carried out according to Dutch NEN standards.

At four moments during the experiment (age of hens 23, 24, 28 and 29 weeks of age) the DM content of freshly excreted droppings was determined. After removal of the belt manure, fresh droppings from the whole flock were scraped from the running belts and put into a can until at least 200 g of droppings were gathered.

The amount of manure on the belts was determined, four times a week (from 17 to 20 weeks of age), two times a week (from 21 to 24 weeks of age) or once a week (from 25 to 30 weeks of age). The collection period started at approximately 12 00 h, and lasted approximately 24 h. The amount of manure on the belts per hen per day (exact 24 h) was calculated. During the belt manure collection on Tuesday, approximately five samples of manure were evenly taken from the conveyer belts, mixed, and a sample was taken for analysis of DM, ash, N_{kj}, P and K content.

The amount of litter per unit of floor area was determined every week from 9 evenly distributed spots. Per spot, about one square meter with litter was levelled off, a metal square (29.9 * 29.9 cm) was pressed into the litter down to the concrete floor, and the litter within the square was taken out, weighed and put back in the litter. At the end of the experiment (week 30) all litter was taken out of the aviary system and weighed for a control measurement. In week 30 the amount of litter per square meter was determined 5 times from the 9 spots. Each week a sample of litter was taken from the nine evenly distributed spots and was mixed, and a sample was taken for analysis of DM, ash, N_{kj}, P and K content.

An Individual Poultry Weighing System (IPWS) was used to have some measure of the presence and activity of the hens on the litter and on the first floor of a feeding tier [15]. The mean number of weights of the hens measured by the four scales in the litter area (daily averages) were calculated relative to the sum of the number of weights of the one scale on the feeding tier and the mean number of weights of the four scales in the litter area.

2.3 Model development

Figure 1 shows the schematic representation of the flows and quantities of excreta, droppings, litter and belt manure in an aviary system. The droppings of the hens are deposited on the belts beneath the wire floors or in the litter. This mass balance gives the following equation:

$$a_t + b_t = 1 \tag{1}$$

Coefficient a_t represents the part of the droppings found on the belts compared with the total production of droppings (see Notation). Coefficient b_t represents the part of the droppings defecated in the litter compared with the total production of droppings. Both coefficients are time dependent, as indicated with suffix t. Litter between the feathers of the hens can be deposited on the belts by the hens, and become belt manure, as represented by $c_t{*}F_{l,t}$. The amount of belt manure accumulates during a certain time period (τ) and is related to the flow of the droppings and from the litter as follows:

$$Q_{b,t} = \int_0^{\tau} (a_t \cdot F_{d,t} + c_t \cdot F_{l,t}) d\tau \tag{2}$$

The total flow of excreta and litter deposited on the belts can be calculated as follows

$$F_{bm,t} = \frac{Q_{b,t}}{\tau} \tag{3}$$

and can be written as the sum of two flows:

$$F_{bm,t} = a_t \cdot F_{d,t} + c_t \cdot F_{l,t} \tag{4}$$

Due to the evaporation of water from droppings, belt manure and litter the mass balance of these three types of manure is not very precise. The mass balance of the dry matter is accurate if the degradation of organic material is negligible. Equation 4 then becomes:

$$F_{bm,t} \cdot C_{bm,DM,pro,t} = a_t \cdot F_{d,t} \cdot C_{d,DM,pro,t} + c_t \cdot F_{l,t} \cdot C_{l,DM,pro,t} \tag{5}$$

The mass balance of dry matter of the litter is:

$$F_{l,t} \cdot C_{l,DM,pro,t} = b_t \cdot F_{d,t} \cdot C_{d,DM,pro,t} - \frac{\delta(Q_{l,t} \cdot C_{l,DM,pro,t})}{\delta t} \tag{6}$$

Combining equation 5 and 6 yields:

$$F_{bm,t} \cdot C_{bm,DM,pro,t} = (c_t \cdot (1 - a_t) + a_t) \cdot F_{d,t} \cdot C_{d,DM,pro,t} - c_t \frac{\delta(Q_{l,t} \cdot C_{l,DM,pro,t})}{\delta t} \tag{7}$$

Equation 7 contains two unknown parameters a_t and c_t, so the parameters can not be solved uniquely. If c_t equals zero, a_t can be solved as follows:

$$a_t = \frac{F_{bm,t} \cdot C_{bm,DM,pro,t}}{F_{d,t} \cdot C_{d,DM,pro,t}} \qquad (8)$$

The flow of litter from the dust bathing area, $F_{l,t}$ in figure 1, is divided into two streams: one stream to the belts (fraction c_t) and one remainder (fraction d_t), e.g. litter eaten by the hens or discharged by the ventilation air as dust. Due to transport of litter to the belts, the concentration of component i in the belt manure differs from the droppings. Coefficient e_t represents the relative contribution of DM of litter in the total amount of DM of manure on the belts, as expressed by equation 9:

$$C_{bm,i,DM,t} = e_t \cdot C_{l,i,DM,t} + (1 - e_t) \cdot C_{d,i,DM,t} \qquad (9)$$

Equation 9 can be rewritten to solve parameter e_t:

$$e_t = \frac{C_{d,j,DM,t} - C_{bm,j,DM,t}}{C_{d,j,DM,t} - C_{l,j,DM,t}} \qquad (10)$$

The value of e_t can be calculated for the components (i) ash, N, P and K, if a reasonable concentration difference exists between the droppings and the litter. The concentration of ash in the litter was initially about 1000 g/kg (pure sand), while the concentrations of N, P and K in the litter were initially zero. If C_{bm} equals C_d, no litter was deposited on the belts and coefficient e_t equals zero. When C_{bm} equals C_l, all droppings are deposited in the litter and all manure on the belts comes from the litter. From the value of e_t the value of c_t can be calculated. If e_t equals zero, c_t also becomes zero.

Notation

$F_{d,t}$ = Flow of dropping produced by the hens at time t, g/d per hen
$F_{bm,t}$ = Flow of belt manure (droppings, litter) deposited on the manure belts at time t, g/d per hen
$F_{l,t}$ = Flow of litter from the dust bathing area at time t, g/d per hen
$C_{i,j,k,t}$ = Concentrations in flow or quantity i of variable j on base of variable k at time t, g/kg
$Q_{l,t}$ = Quantity of the litter at time t, g/kg litter
$Q_{bm,t}$ = Quantity of the manure on the belts at time t, g
t = age of hens, days (d)
τ = time, h
a_t = time - dependent coefficient representing the partial flow of dropping to the manure belts
b_t = time - dependent coefficient representing the partial flow of dropping to the litter
c_t = time - dependent coefficient representing the partial flow of litter to the manure belts
d_t = time - dependent coefficient representing the remainder flow of litter
e_t = time - dependent coefficient representing relative contribution of litter to the belt manure
i = type of manure : d = droppings, l = litter, bm = belt manure
j = DM = dry matter, ash = inorganic matter, N = nitrogen, P = phosphorus, K = potassium
k = pro = product, litter, belt manure and dropping as sampled, DM = dry matter

2.4 Calculations and analyses

The value of e_t (equation 10) was estimated together with the s.e. from the four values of e_t on the basis of the concentrations of ash, N, P and K in the droppings, belt manure and litter. The measurements of the flows of droppings and belt manure were used to model these flows in time with 'critical exponential' and 'exponential' lines respectively. These daily predictions and the weekly measurements of the concentrations of DM were used to model the DM flow of droppings and belt manure.

The measured amount of litter per square meter from the nine spots in the dust bathing area were averaged per week and the trend was modelled with a linear relation in time. Together with the concentration of DM this yielded a linear relation in time for the amount of DM per square meter in the dust bathing area. In week 30 the measurements from the nine spots were compared with the total amount of litter to have some idea of the accuracy of the spot measurements. The measurements of the amount of litter per square meter were averaged per spot and for the whole floor and multiplied by the total area of the dust bathing area (32.67 m^2). All the litter from the floor was removed and weighed to determine the total amount.

All analyses were performed with the Genstat 5 statistical package [16].

3 Results

3.1 Bird performance

Production performance of the hens in the Tiered Wire Floor system from 21 to 32 weeks of age is summarised in table 2 of chapter 6 [13]. The rate of lay increased from zero at 18 weeks of age to an almost stable level of 90% at 28 weeks of age. The feed conversion ratio decreased during the same period down to a stable level of about 2.0.

3.2 Composition of droppings, belt manure and litter and solution of equation 10

Table 1 shows the composition of the droppings, belt manure and litter. Some measurements of the concentration of droppings (e.g. in week 17) and belt manure were missing. The DM content of the droppings did not show a trend in time, but the DM content of the belt manure decreased during the first three weeks of the experiment from about 400 to the mean level of about 300 g/kg (not shown). The ash content and N_{kj}, P and K concentrations on basis of the DM of the droppings and belt manure were quite stable. The DM and ash content of the litter started both at about 1000 g/kg and decreased in course of time, while N_{kj}, P and K concentrations in the litter increased from zero until approximately 20, 10 and 12 g/kg respectively (not shown). Table 1 shows that the concentrations of ash, N_{kj}, P and K in the litter differed strongly from the droppings, so that

Table 1 The mean and standard deviation (in brackets) of the composition of the droppings, belt manure and litter from 17 to 30 weeks of age (n = number of measurements).

	Droppings (n=12)		Belt manure (n=13)		Litter (n=14)	
Dry matter (g/kg)	282	(18)	302	(43)	935	(25)
Ash (g/kg DM)	253	(31)	265	(35)	722	(136)
N_{kj} (g/kg DM)	54.3	(6.9)	51.8	(4.9)	13.6	(7.0)
P (g/kg DM)	16.4	(5.2)	17.5	(1.6)	5.6	(3.4)
K (g/kg DM)	18.2	(4.0)	19.9	(1.4)	7.4	(3.5)

equation 10 could be applied. The estimated value of e_t varied between –0.24 and 0.17 with s.e. between 0.02 and 0.18. The estimated weekly values of e_t did not significantly differ from zero. This meant that the amount of litter in the belt manure was negligible. Coefficient c_t of equation 7 was therefore set to zero, and equation 8 was used to estimate coefficient a_t.

3.3 Flows of droppings, belt manure and litter and the solution to equation 7

The results of the regression lines of the flow of the product itself and the DM of droppings and belt manure are summarised in table 2. Figure 2 shows the flow of the dry matter in the droppings and belt manure. The prediction of the flow of DM of droppings in week 17 is unrealistic, because it is even lower than the predicted flow of belt manure. The flow of droppings increased rapidly until 22 weeks of age, and then decreased to a stabilised level (estimated at 0.033 kg/d per hen). The flow of belt manure slowly increased to a stabilised level of 0.036 kg/d per hen, which was higher than the stabilised level of the droppings. However, these levels were not estimated very accurately due

Table 2 The results of the regression analyses of the flow of droppings (A + (B + C * Age of hens) * $R^{\text{age of hens}}$) and belt manure (A + B * $R^{\text{age of hens}}$), for the total quantity (kg/d per hen) and the dry matter (kg DM/d per hen). Standard errors of estimates are given in brackets (n = number of measurements, age of hens in days).

Type of manure	Droppings				Belt manure			
Material	Total quantity		Dry matter		Total quantity		Dry matter	
A	0.125	(0.006)	0.033	(0.001)	0.104	(0.005)	0.036	(0.008)
B	-6749	(19465)	-5317	(9110)	-4.1	(2.9)	-0.09	(0.06)
C	49	(141)	400	(68)		-		-
R	0.93	(0.02)	0.93	(0.01)	0.97	(0.01)	0.99	(0.01)
R^2_{adjusted}, %	73.6		81.2		91.8		90.0	
σ^2_{rest}	0.107 E –3		1.616 E -6		37.4 E –6		1.71 E –6	
n	25		12		29		13	

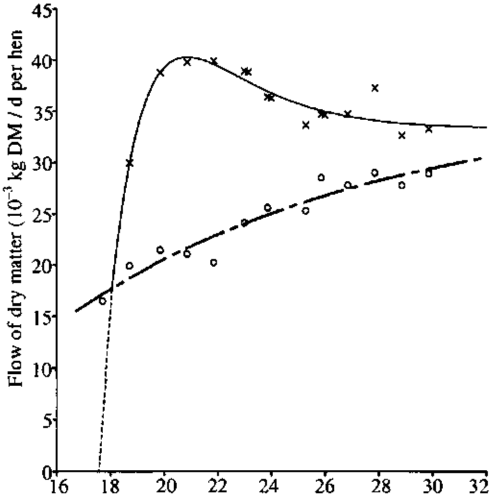

Figure 2 The course of the flow of dry matter of the droppings (measurements: x, predictions: line) and the belt manure (measurement: o, predictions: line) from 17 until 30 weeks of age.

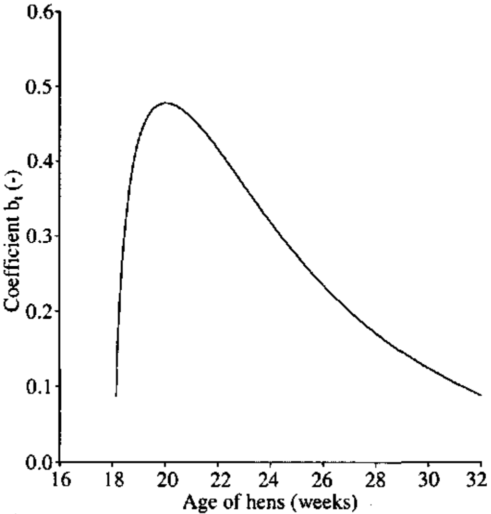

Figure 3 The course of coefficient b_t from 17 until 32 weeks of age.

to a lack of measurements after 30 weeks of age. Application of equation 8 and 1 yielded the magnitude of coefficient b_t in course of time, as shown in figure 3. Predictions of week 17 were left out of this figure for the reason given above.

The linear model for the amount of litter (kg) per square meter was (s.e. in brackets):
8.77 (2.30) + 0.093 (0.014) * age of hens (days)

The linear model for the amount of DM in the litter (kg) per square meter was (s.e. in brackets):
11.11 (2.27) + 0.070 (0.014) * age of hens (days)

The deviation between the total amount of litter in the dust bathing area, measured by weighing all litter (983 kg), and the amount calculated from the spot sampling mass measurements (952.4 kg), amounted to 30.6 kg or 3%.

The total flow of DM from the litter was calculated with equation 6. This flow increased from about 2 g/d per hen to a peak around 20 weeks of age of 18 g/d per hen, and subsequently decreased to a level of about 3 g/d per hen around 30 weeks of age.

3.4 Flow of water to the litter

Combining the results of figure 3 and the water content of the droppings resulted in the water flow to the litter, as shown in figure 4. A strong increase after placement of the hens in the aviary system of up to 45 g water per day per hen, followed by a decrease to a stabilised level (estimated at 7.3 g/d per hen). The DM content of fresh droppings appeared to be 40-90 g/kg lower than the DM content of the droppings on the plates sampled after about 24 h. This implied that the actual peak of the flow of water to the litter was 10 to 30 g/d per hen higher than shown in figure 4.

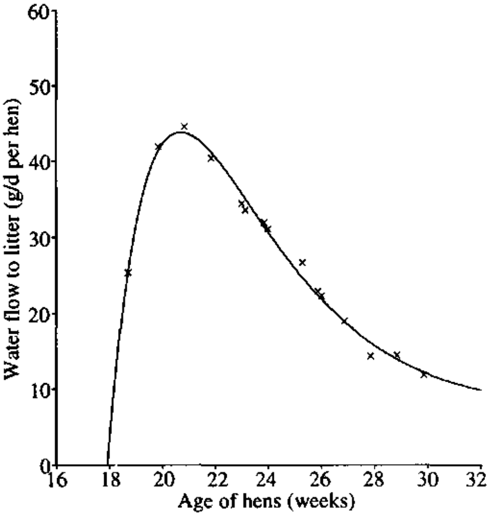

Figure 4 The calculated water flow to the litter (calculations: x, trend: line) from 17 until 32 weeks of age.

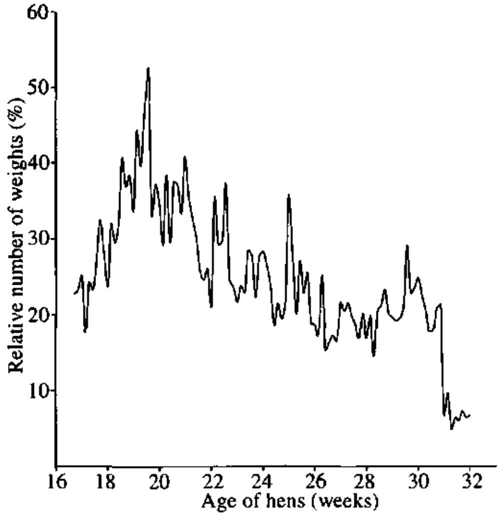

Figure 5 The course of the relative number of weights (daily averages) of the hens on the weighing scales in the litter from 17 until 32 weeks of age.

3.5 Activity of the hens

Figure 5 shows the relative number of weight measurements of the hens on the weighing scales in the litter area. The relative number of visits to the scales in the litter increased to a maximum of 40-50% around 20 weeks of age, and then decreased. The sharp fall of the number of weights at 30 weeks of age was caused by the work needed to take out all the litter for the control measurement. The total number of weight measurements of the hens on the weighing scales, to which the relative number was calculated, increased until 18 weeks of age and subsequently did not show a trend in time.

4 Discussion

Production features of all hens in the Tiered Wire Floor aviary system from 17-32 weeks of age were comparable to those found under practical circumstances [3]. The amount of feed taken in by the hens was partly used for egg production and partly for growth and maintenance. The unused amount was excreted. After 30 weeks of age, growth of hens becomes negligible, and egg mass production stabilises [15].

The DM flow of droppings showed a peak around 20 to 22 weeks of age, and then decreased to a stable level. The DM flow of belt manure increased slowly, and consequently almost 50% of the droppings was deposited in the litter at 20 weeks of age (figure 3). After 20 weeks of age, the flow of droppings and belt manure came closer to each other, so that around 30 weeks of age only about 10-15% of the droppings were defecated in the litter. The pattern of the water flow to the litter (figure 4) was a logical result of these processes.

The pattern of coefficient b_t as a function of age of the hens, and hence the water flow to the litter, could be related to the behaviour of the hens in the aviary system. The relative number of measured weights of the hens in the litter per day (figure 5) can be seen as a measure for the number of hens present in the litter area to exhibit scratching and dust bathing behaviour. The higher the relative number of weights, the more hens were present in the litter area, the more droppings were deposited there. The pattern of the relative number of weight measurements was the same as for coefficient b_t: an increase to a maximum around 20 weeks of age, followed by a slow decrease to a stabilised level. The hens apparently discovered the scratching and dust bathing area after placement in the system at 16 weeks of age, and used the litter more and more. But at around 20 weeks of age egg production started and increased until 28 weeks of age. Consequently, the hens probably spent more time on the tiers eating and drinking and in the nests for laying eggs [15], and less time in the litter area. This resulted in the registered decrease of the number of measured weights of hens in the litter area.

The peak of the water flow to the litter through fresh droppings around 20 weeks of age was extremely high compared with the stable level around 30 weeks of age. The water balance of the litter is determined by the water flow to the litter by fresh droppings and the water evaporation from the litter. Climatic conditions, which were normal during this study [13], and physical properties of the building influence these water flows, e.g. by condensation of water on the floor [17]. The water balance is crucial for the condition of the litter, which can vary from dry and friable to wet and cake-like. Litter drying was applied during this experiment, so the evaporation rate of water was high enough to keep the litter dry and prevent high concentrations of ammonia in the air, as well as welfare and hygienic problems caused by wet and cake-like litter [13]. However, under experimental and practical circumstances [18] (without litter drying) the DM content of the litter dropped sharply many times during the first few weeks after the hens were placed in the aviary system. The DM content of the litter was generally normal again around 30 weeks of age. Farmers often complain about the condition of the litter (wet and cake-like) and often they plough the litter with a fork, add new litter or replace it all with new litter. These problems with the condition of the litter typically occur during the first part of the laying period. The peak of the water flow to the litter that was found in this experiment gives a plausible explanation for the problems mentioned above. Sometimes the DM content of the litter remains low after even 30 weeks of age and problems with the condition of the litter continue. In such cases the stabilised level of the water flow to the litter is probably still higher than the evaporation rate of water from the litter.

The flow of litter from the dust bathing area amounted to 2 to 3 g DM/d per hen, with a peak of 18 g/d per hen around 20 weeks of age. A part of this flow was transported to the belts by the hens. Litter between the feathers of the hens after dust bathing was deposited on the belts if hens spread out their feathers when they were on the wire floors again. A litter flow of 3 g/d per hen was about 10% of the flow of belt manure (figure 2). However, this amount of litter could not be determined precisely. Either the actual flow was almost zero, or the flow was not zero, which is more likely, but the sampling error of belt manure and the error of the chemical analyses were too large compared with the amount of litter deposited on the belts. The hens in the TWF aviary in this study had to fly from the litter to the lowest tier, and consequently lost most of the litter between their feathers before they reached the wire floor. In other aviary systems, where the lowest wire floor was only 20 cm above the concrete floor, the flow of litter to the belts must have been substantial [3]. In case of such aviaries with low positioned tiers, the hens can jump from the litter on a tier. Litter remains between the feathers until the hens spread out their wings when they are on a tier above a manure belt. Other possible explanations for the flow of litter from the litter area (2 tot 3 g DM/d per hen) could be that litter was transported out of the house as dust by the ventilation system, or the litter was eaten by the hens. The emission of litter dust would amount to 0.4 g/d per hen, when a ventilation rate of 1.7 m^3/h per hen (chapter 6) and an inhalable dust concentration of 10 mg/m^3 was used [19]. This is not a negligible amount, but it is likely that the hens also take in a few grams of DM of litter per day during their visit to the litter area.

5 Conclusions

A useful method with mass balances and measurements was applied to determine the changes in the total production of droppings by the hens, the flow of belt manure, the flow of droppings deposited in the litter, and finally the flow of water to the litter by means of droppings deposited there. The pattern of the water flow to the litter coincided with the changing behaviour of the hens related to the increasing egg production during the first 14 weeks after placement of the hens in the aviary system at 17 weeks of age. The peak (45 g/d per hen) and the stabilised level (7 g/d per hen) of the water flow to the litter could explain the variation of the water content of the litter that occurs in practical houses during different parts of the laying period.

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CHAPTER 9

General Discussion

General Discussion

1 Aviary houses as an alternative to battery cages

The starting point of this thesis was the need for welfare-friendly housing systems for laying hens as an alternative to the battery cage system which is said to impair the welfare of the birds to an unacceptable low level (EU-SVC, 1996). Welfare-friendly housing systems will in practice only have a chance of survival, however, if all related aspects are considered. Many initiatives which were based on just ethological aspects failed because these other aspects were neglected. This thesis deals with aviary houses, a housing system that emerged as the most likely alternative to battery cages in the Netherlands in terms of animal welfare, the costs, production efficiency and the climatic and disease control (Blokhuis and Metz, 1992). The main differences of aviary systems in comparison to battery cages are the larger living area for the hens, the presence of litter, separate laying nests and resting perches. There was a drawback however. At the start of the research of this thesis, it was already clear that the level of ammonia emission from aviary houses could be considerably higher than the emission level from battery cages. The objective of the research for this thesis was therefore, to establish the level of emission from aviary houses (inventory), to understand the processes and factors involved in the emission (characteristics) and finally, to find technical solutions to control and minimise the emission.

The laying hens in aviary houses can move freely between the litter area on the floor, the feeding and drinking tiers, the rest tiers with perches (the highest ones) and the laying nests. Consequently, they can deposit their droppings with 20-25% dry matter in all of these places. Usually, however, the laying nests will remain clean. The ammonia emission from these houses is therefore mainly caused by two sources: the manure on the conveyor belts underneath the feeding, drinking and rest tiers (indicated as belt manure) and the litter-droppings mixture on the floor (indicated as litter). The manure on the belts is inaccessible for the hens; they do however, have access to the litter-droppings mixture on the floor since the litter is meant to be used by the hens as substrate for the pecking, scratching and dust bathing behaviour of the hens (Liere, 1991).

2 Emission processes and its influencing factors

The micro-biological process of the degradation of uric acid and undigested proteins occurs in both belt manure and litter, and is influenced by water content, pH and temperature. The total ammoniacal nitrogen ($NH_3 + NH_4^+$) concentration, pH and temperature determine the concentration of volatile ammonia (NH_3) available for volatilisation into the air (qualitatively described in chapter 2). This volatilisation of ammonia is positively influenced by temperature and air velocity above the manure and litter surfaces. Besides these degradation and volatilisation processes of nitrogenous components, the volatilisation process of water from belt manure and litter is essential as it strongly affects the water content of both belt manure and litter. This water content strongly affects the degradation of nitrogenous components into ammonia.

The first descriptions of the ammonia emission from both sources in aviary houses (chapter 3 and 4) were based on a combination of influencing factors, such as of fundamental, empirical and practical nature. The physical models of the degradation and volatilisation processes of ammonia (chapter 5) and the water flows to and from the litter presented in this thesis (chapter 7 and 8) have a strong explanatory character.

The droppings that the hens deposit on the belts become belt manure. Water in this manure evaporates into the air, a process which can be amplified through the use of a manure drying system which increases the dry matter content of the manure up to about approximately 45% during a collection period of one week. The emission from the belt manure appeared to be positively influenced by the storage time on the belts, the water content of the manure and the temperature of the air in the house, and negatively by the water vapour pressure of the air in the house (chapter 3 and 4). After removal of the belt manure the emission from the new manure increased exponentially in time. If the manure is removed at a higher frequency than once a week, the ammonia emission decreases. The positive effect of temperature and the difference of water vapour pressure between the manure and the air will enhance the evaporation of water from the manure. A lower water content of the manure decreases the degradation process and thus lowers the rate of increase of the emission during the collection period of manure on the belts. A decrease in the length of the collection period is favourable for lower emissions, but it hampers the evaporation of water, which is favourable for the dry matter content, which in turn is favourable for lower emissions. An optimum collection period of 4 to 5 days was found for battery cages with an improved manure drying system. In this case the dry matter content of the manure, which is an important criterion of the manure quality, could be raised up to 55% while the increase in the emission was still acceptable (Niekerk and Reuvekamp, 1997).

The droppings of the hens deposited in the litter area will mix with the present litter. The dry matter content of the litter generally varies between 75 and 85% and is preferably kept friable. The emission from the litter appeared to be positively influenced by the temperature and water vapour pressure of the air above the litter, the unionised ammonia concentration in the litter and the depth of the litter layer (chapter 3 and 4). Next, the influence of this mixture on the degradation and volatilisation processes was established. The degradation rate of nitrogenous components in the litter is positively influenced by the water content (4% per 10 units of water content, g/kg), the pH (4% per 1/10 unit of pH) and the temperature (4% per unit of temperature, °C) of the litter (chapter 5). Control of the litter temperature offers a limited opportunity to minimise the degradation rate because the set-point temperature of hen houses ranges from 20 to 25 °C. Control of pH might bring along negative side-effects, e.g. increase of the mineral content and/or the amount of litter. The concentration of total ammoniacal nitrogen (NH_3+NH_4^+), pH and temperature of the litter determine the concentration of volatile ammonia (NH_3) available for volatilisation into the air (chapter 5). This volatilisation is positively influenced by temperature and velocity of the air above the litter (chapter 7). The best way to control and minimise the ammonia emission from litter under Dutch circumstances was to interfere in the degradation process by means of control over the water content. The evaporation of water from the litter is positively influenced by the temperature of the litter (top layer), the difference in water vapour pressure between the litter and the air, and the velocity of the air above the litter (chapter 7). Both the volatilisation rate of water from the litter as well as the water input to the litter through fresh droppings affect the water content of the litter (chapter 8).

3 Levels of emission and strategy for control

Simply put, the solution to the problem of ammonia emission from aviary houses for laying hens is *regular removal* when referring to belt manure and *drying* when it is the litter on the floor we are referring to. Although the emission processes are the same for both sources, important differences between them do exist. All belt manure can be removed regularly; regular removal and renewal of litter has its practical drawbacks. Manure on the belts is inaccessible to the hens; litter, however is 'used' by the hens. The relative amount of droppings deposited on the belts is much higher than the relative amount deposited in the litter (about 20%). Finally, the dry matter content of litter (75-85%) is much higher than that of manure on the belts (25-55%).

The strategy of *regular removal* to reduce the ammonia emission from belt manure on conveyor belts in battery cages has already been implemented on a large scale on commercial farms in Western Europe (Middelkoop, 1994). Additional drying of the manure is possible by means of warm air blown through ducts with holes which are located above the belts in houses for laying hens. This drying process decreases the ammonia emission of the manure during its temporary stay in the house. If however, the belt manure is removed from the house on a more frequent basis, there is less need to dry the manure in order to minimise the ammonia emission. Once the belt manure is outside the house, it can be treated to reach its final destination, and may become slurry, dried manure (e.g. in drying tunnels) or composted manure. It is of course necessary to control the ammonia emission during storage (e.g. closed stores) and application (e.g. injection or ploughing) if the efforts put into reducing the emissions from the house are to have a durable effect.

The strategy of *drying* the litter was tested with a newly developed litter drying system which blows air over the litter instead of through the litter as was done by the system that is used in broiler houses (Groenestein, 1993). Through the use of this systems the dry matter content of litter in aviary houses which generally ranges from 75 to 85% could be raised to more than 90%. Although the water content of the litter still influenced the emission from the Tiered Wire Floor aviary system (0.32% per unit of water content, g/kg), the emission level was reduced substantially (chapter 7). Frequent removal of all litter from the house and renewal with fresh litter, e.g. every fortnight, will reduce the emission of ammonia (chapter 3 and 4), but it also will lead to an increase in the amount of waste and the work load. Therefore this does not seem to be the best solution. Instead, a method had to be found to control the emission from the litter that remains in the aviary house during the whole laying period, effectively. By using the drying system the dry matter content of the litter can be kept at a high level; hence, the emission of ammonia from the litter can be minimised (chapter 6). A thin layer of litter can be kept dry and friable by using a litter drying system which adequately dries the top layer of the litter and by the scratching and dust bathing behaviour of the hens which regularly turns the litter allowing the water from the sub-layers to evaporate. This means that regular removal of the redundant amount of litter is therefore crucial. A thick layer of litter will not be turned adequately by the hens, and condensed water on the floor cannot evaporate. Insulation of the outer walls of the house and the concrete floor of the litter area may therefore contribute to the prevention of water condensation. A thin layer of litter can be maintained by application of wire floors at a low level, or manual or mechanical removal of the litter (Smits and Migchels, 1992).

The degradation of nitrogenous components into ammonia starts immediately after excretion of the droppings. The rate of degradation is, however, relatively slow and it takes at least 24 h before a substantial amount of ammonia is present in the manure and litter. The dilemma that we are confronted with in case of belt manure and litter drying is the positive effect of warm air which is blown over the manure and litter with high air velocities, on both the evaporation of water and the volatilisation of ammonia. Therefore, the rate in which the belt manure and litter is dried is crucial to maintain the emission of ammonia at a minimum, both during the drying time in the house as well as thereafter during the handling of the manure and litter outside the house. The drying must be carried out in such an effective way that substantial release of ammonia from uric acid and undigested proteins in the manure and litter is prevented; otherwise, emissions will even be greater due to drying with a warm air flow over the two sources of ammonia.

The implementation of a strategy of *regular removal* of the belt manure and *drying* of the litter resulted in an emission level of 2.0 (at the start of the laying period, chapter 6) and 2.85 mg/h per hen (at the end of the laying period, see chapter 7). Manure on the belts was removed daily and a litter drying system was used. The higher emission of ammonia at the end of the laying period was due to the higher concentration of total ammoniacal nitrogen in the litter. This in turn, was a result of the higher degradation rates of nitrogenous components during the experimental periods without litter drying. The emission level of 2.0 mg/h per hen was lower than the emission level per hen in a battery cage with the same belt manure removal schedule (2.9 mg/h per hen, see chapter 3), and also lower than the Dutch standard emission level for battery cages with manure belts, 4.2 mg/h per hen (35 g/yr per hen place, with and without drying of belt manure). Recent investigations have, however, shown that the emission from battery cages can be decreased to 1.2 mg/h per hen (10 g/yr per hen place) by an improved drying of manure on the belts and a more frequent removal of the belt manure as compared with the standard management (Niekerk and Reuvekamp, 1997). In summary, the emission from welfare-friendly aviary houses can thus be reduced from a level of three to four times the standard level of battery cages to more or less the same level. Unfortunately, the emission from the litter cannot be stopped completely and will therefore result in a higher emission of ammonia from aviary houses, even if this is only a fraction higher, in comparison to the emission from battery cages. Nevertheless, aviary houses equipped with a litter drying system are a favourable solution to the problem of ammonia emissions into the environment, especially as compared with other welfare-friendly housing systems with litter in north-western Europe (Groot Koerkamp *et al.*, 1998).

4 Other aspects

Besides the two sources of ammonia in aviary housing systems discussed, there is a third source, namely the manure on perches, wire floors and strips as a result of fouling. The influence of this source on the total emission of ammonia was originally neglected is this study, as its contribution to the total emission of ammonia in standard aviary systems was expected to be relatively low. However, in the case of low emission levels there was proof that its contribution could be substantial (Groot Koerkamp, 1998). A detailed layout of an aviary system and the choice of material type for the elements (sticky) could then be of importance.

During the inventory of ammonia emissions levels from standard aviary houses a wide variation was found in the levels (chapter 6): 1) variance between different types of aviaries, 2) variance between different houses of the same type, and 3) variance (kinetics) in time. These three types of variation are due to differences in the following factors: *the housing system* (design of the system, stocking density), *the animal* (type and age of hen, water and food intake, dietary protein level and type of proteins, behaviour), *the climatisation* (outside weather conditions, actual and set-point temperature, air velocities above manure and litter) and *the management* (manure removal, hygiene, disease control, lighting scheme). Several of these factors were only partly included or not included at all in the analyses of the emission rates in the preceding chapters. This does not necessarily mean that they do not influence the emission of ammonia, but with the limited data that was available and the existence of confounded variables, e.g. indoor temperature, ventilation rate and activity of the hens, characterisation of all the influencing factors was not possible.

Special note should be given to the possibilities of reducing the emission of ammonia through feeding strategies. The following changes in feed composition to diminish the emission were summarised (Wever en Slijpe, 1997): decrease of nitrogen concentration and addition of essential amino-acids, decrease of the salt concentration (K and Na), addition of denitrifying bacteria and addition of components that stimulate a specific part of the fermentation. A change of the nitrogen concentration and composition of the feed is indicated as the most realistic with possible ammonia emissions reductions of up to 50%. Despite the fact that the role of water is acknowledged (water intake is proportional to nitrogen excretion), expected reductions are based on a reduced amount of uric acid in the excreted droppings. Based on the theory of Michaelis-Menten and the fact that only a small amount of uric acid is degraded into ammonia, it can be deduced that it is unlikely that the limiting factor is formed by the amount of degradable substrate (uric acid and undigested proteins). The enzyme concentration (uricase) or enzyme activity which is influenced by water content, temperature and pH, forms the limiting factor (chapter 5). Effects of changes in the nitrogen concentration and composition were found (Harn and Middelkoop, 1996), but the key role of water in the emission process is strongly underestimated.

5 Practical considerations

It is expected that the public concern for the welfare of hens in the Netherlands will result in new legislation, favouring the application of welfare friendly systems. The production costs of eggs in alternative systems (e.g. aviaries) are, however, approximately 10% higher in comparison to battery cage eggs (Horne, 1997), which hampers the transfer to such systems in practise. The development and implementation of alternative systems has already taken place in Switzerland, Sweden and the Netherlands, but only in Switzerland battery cages are now officially banned. A European ban on battery cages is not expected in the short term. Although recent EU proposals aim at a substantial increase of the area per bird in battery cage systems (up to 800 cm^2 per hen). Cost price differences between battery cage and alternative systems may then become negligible.

In general, welfare friendly housing systems for laying hens are and will be equipped with a litter area. Manure and litter handling in those poultry houses is strongly related to the actual housing design, the hens, the climatisation and the management. In addition, the manure and litter handling in the house is part of the total chain of waste handling from the excretion of droppings to the application and use of manure as fertiliser. Drying and regular removal of belt manure and litter should, therefore, fit the individual situation of a poultry farmer. A poultry farmer will base his choice for a certain housing system and certain manure and litter handling techniques not only on conditions (legislation) and aspects related to welfare and economics (Appleby, 1997), but also on other aspects (EU-SVC, 1996), e.g. related to environment, labour and management (Lokhorst, 1997).

The implementation of a litter drying system in aviary houses for laying hens as described in chapter 6, enables poultry farmers to attain a substantial reduction in the emission of ammonia. The litter drying system is in itself rather simple and it does not hamper the hens in their scratching and dust bathing behaviour. The litter drying system may, therefore, be well applicable in other types of poultry houses, e.g. loose housing systems and traditional houses with litter for broilers. The knowledge of the physical processes enables us to control effectively the dry matter content of litter in any poultry house with the use of a drying system. A combination of various control parameters can be used, such as the temperature, relative humidity and velocity of the air which is blown over the litter as well as the temperature of the floor (insulated concrete floor, possibly equipped with floor heating).

Other positive effects of the use of litter drying are: the improved local climate in the house (lower ammonia concentrations and more equal temperature distribution), a possible way to combat the laying of eggs in the litter, a possible decrease in the occurrence and survival of micro-organisms causing infectious diseases in the litter, and an expected decrease in the disorders of feet, legs and plumage of the hens. A negative side-effect of the higher dry matter content of litter is the risk of increased dust concentrations in the air of the poultry house, and hence, the emission of dust to the environment. Dust concentrations in poultry houses with litter range anywhere between 2 and 10 mg/m^3. This is generally above the level which is acceptable for human working environments (Takai *et al.*, 1998). Protection of the respiratory system of workmen during their stay in aviary houses by means of personal filter equipment is already a necessity, even without the use of a litter drying system. This aspect will need further attention in the future.

The question remains whether the amount, type and composition of the litter-droppings mixture as found in aviary houses today can fulfil the demands of the hens for their dust bathing behaviour as given by Liere (1991). Control of the emission of ammonia from litter requires that it has a high dry matter content (about 90%) and is spread out in a thin layer (maximum of about 5 cm). Both two requirements may possibly conflict with the needs of the hens.

The application of litter drying requires extra investments and operational costs (electricity) for the poultry farmer. Although detailed information on investment and operational costs is not yet available, these additional costs are expected to be marginal to the total investments in a housing system and counterbalance the reduction of ammonia. The drying of manure on the belts, also in aviary systems, is already common practice. In the beginning of 1998 two commercial aviary houses for laying hens were equipped with a combined drying system for manure on the belts and the litter on the floor (Pluimveehouderij, 1998).

6 General conclusions

In conclusion, from the results of this study can be concluded that the most relevant knowledge for the control of the ammonia emission from poultry houses with litter is available now. This knowledge improves fundamentally the prospects of sustainable housing systems for poultry that combine poultry welfare and environmental goals.

From all kinds of possible measures to reach low ammonia emissions from poultry houses, the control of the dry matter content of the litter appears to be most crucial, apart from belt manure drying and removal. This study has shown that dry litter can be reached through the implementation of modern yet simple techniques. Optimisation of litter drying is, however, still possible in various ways, such as the improvement of the design of the aviary system and the management and the application of floor insulation and/or floor heating.

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Summary

1 Introduction

The developments in the egg production sector since the Second World War can be characterised by an increase in the scale of the farms, in the productivity of the hens and in the number of layers per unit of labour. This was possible due to a number of technological advancements in this sector, such as (1) the development of battery cages, (2) the mechanisation of feed and water distribution, the egg collection and the manure handling and (3) the improved hygiene, nutrition, breeding and health care of the hens. These developments were, however, also a source of criticism, both in the Netherlands as well as in other north-western European countries. In the late 1980s research which was done on welfare friendly housing system for laying hens led to the development of the first prototype of an aviary housing system in the Netherlands. This prototype was basically a traditional floor housing system equipped with extra wire floor tiers thereby increasing the use of the vertical space. In aviary systems each hen disposes over an area of approximately 1000 cm^2 and the hens can move around freely, scratch and dust bath in the litter on the floor and rest on perches and lay their eggs in the nests. However, further development and testing of aviary housing systems remained desirable. In 1990 the Dutch research programme 'Aviary Housing for Laying Hens' was initiated, in which an integrated approach was followed. One of the subjects addressed in this research programme was the emission of ammonia. The higher ammonia emission from aviary housing systems in comparison with battery cages formed a major bottle-neck for the successful continuation of development and the practical application of welfare friendly aviary housing systems for laying hens.

2 Objectives of this thesis

The objectives of this thesis (chapter one) were to acquire knowledge on the levels of ammonia emission from the various types of aviary houses for laying hens (inventory), to describe the kinetics of the ammonia emission, as well as the processes and factors that are involved in this process (characteristics) and finally, to use this knowledge in the development of technical solutions to lower the emission. The level of emission of ammonia from battery cages equipped with belts which allow for the regular removal of the manure, is the lowest of all the types of housing systems for hens. In the Netherlands it has therefore been certified with a Green Label certificate. It was, therefore, this level of emission that was set as the goal in the development of sustainable, welfare friendly housing systems for laying hens.

3 Review on housing systems and emissions of ammonia

This thesis begins in chapter two with a review of the state-of-the-art at the start of this study. In this chapter the housing systems for laying hens were described and classified as *battery cages* or *alternative systems*. In traditional battery cage systems and alternative, welfare oriented, housing systems for laying hens two types of waste can be distinguished, namely *manure* and *litter*. Manure is encountered as *slurry* or as *dry manure*. Litter on the floor is a dry and granular mixture of droppings and e.g. sand. It is used by the hens for dust bathing and scratching.

In the processes involved in the emission of ammonia, the most important process parameters are temperature, pH and water activity, that is the availability of water for micro-organisms in the substrate. Air temperature, relative humidity and air velocity best define the influencing climatic conditions. Despite the effectiveness of pH control, it cannot be applied because of the many negative side-effects. Forced drying of manure seems to be the only way to control its emission of ammonia while it is in the house which is effective as well as accepted. Regular removal of the manure from the house will always be necessary.

A reduction of the emissions of ammonia can be achieved by changing from a housing systems with composting to a battery cage systems with manure belts below the cages, thereby allowing the manure to dry and simplify its regular removal. The emissions of these two housing systems are 386 and 34 g NH_3/yr per hen respectively. The drying rate of the manure and the frequency of removal are crucial in relation to the emission. A minimal emission from the manure is achieved if a dry matter content of 60% is reached within 50 h after excretion of the droppings. The emission from battery systems with belts can be reduced to 10 g NH_3/yr per hen if the manure is removed from the house two times a day instead of two times a week. The emissions of ammonia from alternative housing systems with litter are several times higher in comparison with battery cages with belts. This is due to the long stay of the litter inside the house. A higher dry matter content of litter slows down the volatilisation of ammonia, but a practical way to actually reduce the emission from litter in this way were not yet available at the start of this thesis. Besides this, a good understanding of water activity of litter was still not available.

4 Comparison of the ammonia emission from a battery cage and an aviary housing system

Chapter three describes a comparative study on the effect of manure handling on the emission of ammonia in a battery cage and the effect of both manure handling and litter treatment on the emission in a Tiered Wire Floor (TWF) aviary system. The manure handling consisted of variation in the drying and removal frequency and the litter treatment consisted of removal of most of the litter. Each system housed 6480 hens, manure and litter treatments were varied in time, and effects were analysed by means of time-series analysis. The hens in the TWF system deposited 22.5% of their droppings in the litter and the remaining part was dropped on the manure belts. In the battery cage system all manure was dropped on the belts. The estimated emission from the manure on the belts in both systems was 18.8 g/h (daily mean, manure removal twice a day), whereas the emission from the litter in the TWF system amounted to 62.5 g/h. Emission from the belt manure on a typical day increased with 14, 39, 109 and 177% from the 1st until the 4th day after manure removal. The effect of temperature and water vapour pressure difference on the emission was +17 and -22% per degree and per kPa, respectively. Drying the manure on the belts increased its dry matter content and seemed to lower the emissions. The dry matter content of the litter varied between 780 and 840 g/kg, the mean total nitrogen content was 3.3% of the dry matter, and the layer thickness varied between 2 and 9 cm. Both the unionised ammonia content, which ranged between 20 and 190 mg/kg, and the layer thickness of the litter had a positive influence on its emission.

5 Comparison of the ammonia emission from three types of aviary systems

In chapter four an experiment with laying hens of 16 to 36 weeks of age is described. This experiment was carried out to investigate the differences in ammonia emission between three commercially available aviary housing systems and what additional effect the manure and litter handling had on these emission levels. The ammonia emission from the TWF, the Natura and the

Boleg aviary system increased rapidly after placement of the hens in these systems and reached its peak at 20 weeks of age. Equilibrium levels were found at 11.55, 11.24 (not significant as compared to TWF) and 14.55 ($P<0.001$ compared to TWF) mg ammonia per h per hen. After removal of the belt manure the emission increased 5.6% on the first day and 11% on the following days. The litter layer was allowed to increase up to approximately 7 cm in all three aviary systems, after which 6.5 cm were removed. This resulted in a 20% reduction of the emission level ($P<0.001$). Ammonia concentrations varied between 1 and 16 ppm, while ventilation rates varied between 1 and 4 m^3/h per hen in order to maintain the inside temperature at approximately 22 °C. Some 82% of the droppings produced by the hens was found on the belts: either because it was excreted there directly by the hens or because it was dropped there by the hens as litter material. The composition of both the belt manure and the litter, which was a sand-droppings mixture, changed significantly in time during the first 20 weeks after placement of the hens in the three aviary systems. Differences in the composition of the belt manure and litter between the three aviary systems were found with respect to the DM, pH, ash, N_{kj} and the total ammoniacal nitrogen concentration. The different levels of ammonia emission and the differences that were found in the composition of the belt manure and the litter between the three aviary systems were related to the design of the aviary systems, the behaviour of the hens and the degradation and the volatilisation processes.

6 Degradation of nitrogenous components and volatilisation of ammonia from litter

In chapter five the physical and chemical relationships of both the volatilisation and the degradation processes in litter from aviary houses for laying hens were analysed and verified by means of experimental data, consisting of 66 litter samples taken from 12 commercial aviary houses. The volatilisation rate of ammonia from the litter was linear to the NH_3 concentration in the water of the litter, whereas the pK_a of the NH_3-NH_4^+ equilibrium was adjusted to 8.65. The concentration of the total ammoniacal nitrogen ($NH_3+NH_4^+$) in the litter found in the aviary houses, which is the result of the degradation of organic material, was approximately 4% higher per 1/10 unit of pH, 4% higher per unit of temperature (°C) and 4% higher per 10 units of water content (g/kg). It appeared that the cold winter weather had an adverse effect on the litter which was near the outer walls of the aviary houses. Emissions of ammonia from litter can be reduced by maintaining a high dry matter content, a low pH or low a temperature, thereby minimising the degradation rate of organic nitrogen and thus decreasing the volatilisation of ammonia. However, it may not always be feasible nor always acceptable to control the pH level and the temperature in aviary houses.

7 Effect of litter drying on the composition of litter and the ammonia emission

The effects of a litter drying system on the composition of the litter and the emission of ammonia in a TWF aviary housing system for laying hens are described in chapter six. Air velocities above the litter were increased by means of air that was sucked from the top of the room and blown through holes in ducts at floor level. The dry matter content of the litter was higher (above 900 g/kg) and the total ammoniacal nitrogen (0.7 g/kg) and pH (7.3) of the litter were remarkably lower than in aviaries which did not have a system for forced drying of litter (dry matter 750-850 g/kg, total ammoniacal nitrogen 2-3 g/kg, pH about 8.6). Concentrations of ammonia in the exhaust air were below 5 ppm and the emission of ammonia from the house reached a stable emission level of about 2.0 mg/h per hen when hens were at the age of approximately 30 weeks. This emission level was a result of the litter on the floor and the manure on the belts, and it was reached when the belt manure was removed on a daily basis and approximately 500 m^3/h of air were blown evenly over the litter by means of the three ducts. The litter drying system effectively maintained a high level of the dry matter content of the litter and minimised the degradation of nitrogenous components into ammonia. A possible increase of the volatilisation rate of ammonia from the litter through the higher air velocities was of minor importance because of the low total ammoniacal nitrogen concentration in the litter.

8 Influencing factors on the evaporation of water from litter

Next, in chapter seven, experimental research was performed using hens aged 47 to 60 weeks to validate a physical model of the evaporation rate of water from litter in a TWF aviary system (chapter seven). Changes in the evaporation rate of water from the litter was achieved by using different air velocities above the litter (from 0.07-0.28 m/s), by naturally changing weather conditions and by removing the belt manure once a week, once a day or two times a day. An evaporation model was developed which predicted the water content of the litter on a specific day. The water content increased with 126.8 g/kg litter per day (s.e. 19.4) due to the water input through fresh droppings defecated in the litter by the hens. The evaporation rate of water from the litter was positively influenced by the air velocity ($v_{air}^{0.287}$) and the difference between the water vapour pressure in the litter and the water vapour pressure of the air above the litter. The water activity of the litter was estimated to be 0.86 (s.e. 0.07) and caused a decrease in the saturated water vapour pressure in the litter. The water vapour pressure of the air in the house was largely dependent (79%) on the vapour pressure of the air outside. Consequently, prediction were made that in the Netherlands the drying conditions above the litter would worsen from April until October. This can, however, be compensated by increasing the litter temperatures and the air velocities. The emission of ammonia was described by a model with the following influencing parameters: manure removal interval (0.76%/h), indoor temperature (8.1%/°C), water content of the litter (0.32% per (g/kg)) and air velocities above the litter (103% per (m/s)). The mean emission in the case of daily removal of the manure on the belts amounted 2.85 mg/h per hen.

9 Flow of water to the litter through fresh droppings

Finally, chapter eight describes the results of research into the levels and the variations of the water flow to the litter in a TWF system as a result of fresh droppings in the litter from hens aged 17 to 30 weeks. The model which was developed of the mass balances of droppings (all excreta), manure on the belts and litter on the floor was used in combination with measurements of concentrations and newly developed measuring methods of flows and quantities of droppings, belt manure and litter. From the differences in the concentration levels of ash, nitrogen, phosphorus and potassium between droppings, belt manure and litter, it was concluded that the transport of litter between the feathers of the hens to the belts was negligible. The relative amount of excreta deposited in the litter by the hens yielded a peak of approximately 50% at 22 weeks of age. Thereafter the flow of droppings to the litter decreased to a stabilised level of approximately 10%. The flow of water through the droppings to the litter showed the same pattern, with a peak of approximately 45 g/d per hen and a stabilised level of approximately 7 g/d per hen. The measured water concentrations of the droppings were 40-90 g/kg lower than the water concentration of freshly excreted droppings, therefore the actual peak might have been 10 to 30 g/d per hen higher. It was hypothesised that the peak in the water flow to the litter was caused by a change in the behaviour of the hens which was indicated by the relative number of measured weights that were registered by the scales which had been placed in the litter area and on a feeding tier. After hens reached the age of 20 weeks, they spent less time scratching and dust bathing in the litter area. Presumably this was so because they spent more time laying eggs in the nests and eating and drinking on the tiers.

10 General discussion

Chapter nine summarises the previous chapters and structures and discusses this issue in a broader context in order to find practical solutions to reduce and minimise the ammonia emissions from aviary housing systems for laying hens (solutions for reduction). The laying hens in aviary houses can move freely between the litter area on the floor, the feeding and drinking tiers, the rest tier with perches (the highest one) and the laying nests. Consequently, they can deposit their droppings with 20-25% dry matter in all of these places. The ammonia emission from these houses is therefore mainly a result of two sources: the manure on the conveyor belts underneath the feeding, drinking and rest tiers (*belt manure*) and the litter-droppings mixture on the floor (*litter*). The microbiological process of the degradation of uric acid and undigested proteins occurs in both belt manure and litter, and is influenced by water content, pH and temperature. The total ammoniacal nitrogen (NH_3 + NH_4^+) concentration, pH and temperature determine the concentration of volatile ammonia (NH_3) available for volatilisation into the air. This volatilisation of ammonia is positively influenced by temperature and air velocity above the manure and litter surfaces. Besides these degradation and volatilisation processes of nitrogenous components, the volatilisation process of water from belt manure and litter is essential as it strongly affects the water content of both belt manure and litter. This water content strongly affects the degradation of nitrogenous components into ammonia. The emission from the *belt manure* appeared to be positively influenced by the storage time on the belts, the water content of the manure and the temperature of the air in the house, and negatively by the water vapour pressure of the air in the house. After removal of the belt manure, the emission from the new manure increased exponentially in time. The degradation rate of nitrogenous components in the *litter* is positively influenced by the water content, the pH and the temperature of the litter. The volatilisation of unionised ammonia (NH_3) into the air is positively influenced by the temperature and velocity of the air above the litter.

Simply put, the solution to the problem of ammonia emission from aviary houses for laying hens is *regular removal* when referring to belt manure and *drying* when it is the litter on the floor we are referring to. The strategy of *regular removal* to reduce the ammonia emission from belt manure on conveyor belts in battery cages has already been implemented on a large scale on commercial farms in Western Europe. The strategy of *drying* the litter was tested with a newly developed litter drying system which blows air over the litter. This system raised the dry matter content of the litter from 75 to 85% to more than 90%. The implementation of a strategy of *regular removal* of the belt manure and *drying* of the litter in a TWF aviary system resulted in an emission level of 2.0 (at the start of the laying period, chapter 6) and 2.85 mg/h per hen (at the end of the laying period, chapter 7). The emission level of 2.0 mg/h per hen was lower than the emission level per hen in a battery cage with the same belt manure removal schedule (2.9 mg/h per hen, see chapter 3), and also lower than the Dutch standard emission level for battery cages with manure belts, 4.2 mg/h per hen (35 g/yr per hen place, with and without drying of belt manure). The emission from welfare friendly aviary houses can thus be reduced from a level of three to four times the standard level of battery cages to more or less the same level. But the emission from battery cages can be further reduced, while the emission from the litter cannot be stopped completely. This will therefore result in a higher emission of ammonia from aviary houses, even if this is only a fraction higher, in comparison to the emission from battery cages.

It is expected that the public concern for the welfare of hens both in the Netherlands as well in Europe will result in new legislation, favouring the application of welfare friendly housing systems. The use of aviary systems for laying hens and the implementation of a litter drying system in these housing systems will enable poultry farmers to achieve a substantial reduction in the emission of ammonia as compared with traditional welfare friendly floor systems. Other positive effects resulting from the use of a litter drying system are an improved local climate in the house, a method to combat the laying of eggs in the litter and, possibly less infectious diseases and disorders of the feet, legs and plumage. A negative side-effect of the higher dry matter content of litter is the risk of increased dust concentrations in the air of the poultry house, and hence, the emission of dust to the environment. The additional costs of investments and electricity are expected to be marginal compared to the total investments in a housing system and counterbalance the reduction of ammonia.

11 Conclusions

In conclusions, the most relevant knowledge for the control of the ammonia emission from poultry houses with litter is presently now. This knowledge fundamentally improves the prospects of sustainable housing systems for poultry which combine poultry welfare with environmental goals. This study has shown that dry litter can be reached through the implementation of modern yet simple techniques. Optimisation of litter drying is, however, still possible.

Samenvatting

Samenvatting

1 Inleiding

De ontwikkelingen in de West-Europese leghennenhouderij sinds de tweede wereldoorlog worden gekenmerkt door schaalvergroting op de primaire bedrijven, toegenomen productiviteit per hen en een toename van het aantal gehouden hennen per arbeidskracht. Dit was onder andere mogelijk door de ontwikkeling van batterijkooien, de mechanisatie van de voer- en waterverstrekking, van de eierverzameling en van de mestbehandeling. Daarnaast droegen ontwikkelingen op het gebied van de hygiëne, de voersamenstelling, de fokkerij en de gezondheidszorg hieraan bij. Ondanks de positieve aspecten voor de sector ontstond er in de jaren zestig maatschappelijke kritiek, zowel in Nederland als in andere West-Europese landen. Deze kritiek richtte zich op de intensieve wijze van het houden van leghennen in batterijkooien. Het welzijn van leghennen in batterijkooien wordt geschaad omdat de hennen niet in staat zijn een aantal natuurlijke gedragingen uit te voeren, zoals scharrelen, stofbaden en zich afzonderen om een ei te leggen. Onderzoek naar welzijnsvriendelijke huisvestingssystemen voor leghennen leidde in Nederland eind jaren tachtig tot een prototype van een volièresysteem. Een volièresysteem onderscheidt zich van traditionele scharrelsystemen door het gebruik van de verticale ruimte. Een leghen in een volièresysteem beschikt over ca. 1000 cm^2 leefoppervlak, terwijl zij zich vrij kan bewegen tussen de scharrel- en stofbadruimte, de voer- en drinketages, de rustetages en de legnesten. Verdere ontwikkeling en beproeving van volièresystemen waren nodig. Dit werd in 1990 opgestart binnen het DLO-onderzoekprogramma 'Volièrehuisvesting voor leghennen'. Binnen dit onderzoekprogramma werden verschillende aspecten onderzocht, zoals de eierproductie van de hennen, de kostprijs, de werkomstandigheden, het management en de milieubelasting. Reeds bij aanvang van het onderzoekprogramma was bekend dat de ammoniakemissie uit volièrestallen hoger was dan uit batterijstallen met mestbanden. Deze hogere milieubelasting zou een belangrijke bottleneck kunnen vormen bij de verdere ontwikkeling en toepassing van de welzijnsvriendelijke volièrestallen in de praktijk.

2 Doel van het onderzoek

Het doel van dit proefschrift was het verwerven van kennis over de hoogte van de ammoniakemissie uit verschillende typen volièrestallen (inventarisatie), het modelleren van de variatie van de emissie in de tijd en het beschrijven van de effecten van de invloedsfactoren op de onderliggende fysische en chemische processen (karakterisering). En tenslotte om met behulp van deze kennis technische oplossingen te ontwikkelen om de emissie te verminderen. Bij batterijsystemen met mestbanden (met bandmestdroging en wekelijkse verwijdering; zonder bandmestdroging en twee maal per week verwijdering) is de ammoniakemissie het laagst (35 gram NH_3 per dierplaats per jaar). In Nederland is dit systeem gecertificeerd als een Groen Label systeem. Dit emissieniveau was derhalve het doel voor de ontwikkeling van een milieu- èn welzijnsvriendelijk huisvestingssysteem voor leghennen.

3 Stand van zaken bij aanvang van het onderzoek

Dit proefschrift begint in hoofdstuk twee met een overzicht van de beschikbare kennis ten tijde van de aanvang van het onderzoek. Huisvestingssystemen voor leghennen werden onderverdeeld in *batterijsystemen* en (welzijnsvriendelijke) *alternatieve systemen*. De verse uitwerpselen van de hennen in al deze systemen worden, afhankelijk van waar zij terechtkomen, onderscheiden als *mest* of *strooisel*. Met 'mest' kan zowel *natte mest* of *drijfmest* als *droge* of *voorgedroogde mest* aangeduid worden. Mest die wordt opgevangen op banden onder kooien of onder roostervloeren wordt aangeduid als *bandmest*. Het 'strooisel' op de vloer is doorgaans droog en korrelig van structuur. Het is eigenlijk een mengsel van uitwerpselen en zand of zaagsel dat bij het begin van een legronde in de scharrelruimte wordt gebracht. De hennen scharrelen in het strooisel en gebruiken het om in te stofbaden.

Bij de emissie van ammoniak uit pluimveestallen speelt de afbraak van urinezuur en onverteerde eiwitten in de mest tot ammoniak een belangrijke rol. De belangrijkste invloedsfactoren zijn de temperatuur, de pH en de wateractiviteit in de mest (een maat voor de beschikbaarheid van water voor micro-organismen). Daarnaast hebben de luchttemperatuur, de luchtvochtigheid en de luchtsnelheid grote invloed hebben op de vervluchtiging van zowel ammoniak als water uit de mest en het strooisel. Beheersing van de pH van mest op een laag niveau (<6) door bijvoorbeeld het toevoegen van zuur stuit op nogal wat praktische bezwaren, ondanks dat dit een zeer effectieve maatregel zou zijn om de ammoniakemissie te verlagen. Verlaging van de staltemperatuur tot onder normale praktijkwaarden (20-25 °C) is strijdig met de klimaatbehoeften van de hen, zodat ook hiermee geen werkelijke ammoniakreductie bereikt kan worden. Het geforceerd drogen van mest op de banden is eigenlijk de enige en meest effectieve manier om de ammoniakemissie van de mest in de stal te beperken. Regelmatig verwijderen van de mest blijft daarbij noodzakelijk voor een lage emissie. Maatregelen tijdens de opslag en de aanwending van mest in het veld kunnen voor een verdere, duurzame reductie van de ammoniakemissie zorgen.

Vermindering van de ammoniakemissie uit de leghennensector kan dus worden bereikt door over te schakelen van traditionele systemen met compostering (deep-pit- en kanalenstallen, 386 g NH_3 per dierplaats per jaar) naar batterijsystemen met mestbanden (35 g NH_3 per dierplaats per jaar), zodat regelmatige verwijdering en droging van de mest mogelijk is. De snelheid waarmee mest wordt gedroogd en de verblijftijd in de stal (omgekeerd evenredig met de verwijderingsfrequentie) zijn van cruciaal belang voor de hoogte van de emissie. Door optimalisatie van de mestdroging is een kortere verblijftijd van de mest in de stal mogelijk en kan de emissie van een batterijsysteem met mestbanden zelfs worden verlaagd tot 10 g NH_3 per dierplaats per jaar. De ammoniakemissie uit alternatieve huisvestingssystemen met strooisel, zoals scharrel- en volièresystemen, is onder gebruikelijke praktijkomstandigheden vele malen hoger dan uit batterijsystemen (respectievelijk ca. 90 en 315 g NH_3 per dierplaats per jaar). Het vermoeden bestond reeds dat het drogestofgehalte van het strooisel een grote invloed heeft op de emissie uit het strooisel. Echter, het vereiste inzicht en praktische mogelijkheden om de emissie uit het strooisel te beperken waren bij het begin van dit onderzoek niet aanwezig.

4 Vergelijking van de emissie uit een batterij- en een volièresysteem

In hoofdstuk drie wordt de ammoniakemissie uit een batterijstal vergeleken met de emissie uit één van de volièresystemen, namelijk het Etagesysteem. Daarbij is tevens het effect van de behandeling van de bandmest in het batterijsysteem (variatie in drogen en verwijderingsfrequentie) en het effect van de behandeling van de bandmest (gelijk aan het batterijsysteem) en verwijdering van het strooisel in het Etagesysteem onderzocht. Beide huisvestingssystemen huisvestten 6480 hennen, behandelingen werden gevarieerd in de tijd en tijdreeksanalyse werd toegepast om effecten statistisch te kunnen schatten. In het Etagesysteem kwam 22,5% van de uitwerpselen van de hennen in het strooisel terecht. De rest van de uitwerpselen, zoals alle mest in het batterijsysteem, kwam terecht op de mestbanden. De emissie van de mest op de banden (daggemiddelde) werd in beide systemen geschat op 18,8 g/uur bij tweemaal daags verwijderen van de bandmest. De emissie van het strooisel bedroeg 62,5 g/uur. De emissie van de bandmest steeg met 14, 39, 109 en 177% op de eerste tot en met de vierde dag na het afdraaien van de banden (verwijderen van de bandmest). Het effect van de staltemperatuur en het waterdampdrukverschil tussen mest en strooisel enerzijds en de stallucht anderzijds bedroeg +17% per graad Celsius en –22% per kPa. Drogen van de mest op de banden verhoogde het drogestofgehalte van de bandmest en de emissie leek daarbij te dalen. Het drogestofgehalte van het strooisel varieerde tussen 78 en 84%, het gemiddelde stikstofgehalte bedroeg 3,3% van de drogestof en de laagdikte van het strooisel varieerde tussen 2 en 9 cm. Het ammoniakgehalte in het strooisel, dat varieerde tussen 20 en 190 mg/kg, en de laagdikte van het strooisel hadden een positieve invloed op de emissie uit het strooisel.

5 Vergelijking van de emissie uit drie verschillende typen volièresystemen

In hoofdstuk vier wordt de ammoniakemissie uit drie verschillende typen volièrestallen vergeleken. Hierbij is tevens het effect van de behandeling van de bandmest (variatie in de verwijderingsfrequentie) en het strooisel (verwijderen) onderzocht. Na het plaatsen van de hennen op 17 weken leeftijd in het Etagesysteem, het Naturasysteem en het Bolegsysteem nam de ammoniakemissie snel toe. De hoogste emissie werd in alle drie systemen gemeten op 20 weken leeftijd en daalde vervolgens tot stabiele niveaus van respectievelijk 11,6, 11,2 (niet significant verschillend t.o.v. Etagesysteem) en 14,6 ($P<0{,}001$ t.o.v. Etagesysteem) mg NH_3 per uur per hen (daggemiddelden). De emissie steeg met 5,6% op de eerste dag na verwijderen van de bandmest en vervolgens met 11% per dag daarna. De laagdikte van het strooisel steeg tot 7 cm. Door verwijdering van 6,5 cm van deze strooisellaag daalde de emissie met 20% ($P<0{,}001$). De ammoniakconcentraties in de uitgaande lucht varieerden tussen 1 en 16 ppm, terwijl het ventilatiedebiet werd geregeld tussen 1 en 4 m^3/uur per hen om de staltemperatuur te handhaven op ca. 22 °C. Ongeveer 82% van de uitwerpselen van de hennen werd teruggevonden op de mestbanden, hetzij direct uitgescheiden boven de banden, hetzij daar terecht gekomen als strooisel dat de hennen uit hun veren hadden geschud. De samenstelling van het strooisel, een mengsel van zand en uitwerpselen, veranderde sterk tijdens de eerste 20 weken na opzet van de hennen. Tussen de drie volièresystemen werden verschillen gevonden met betrekking tot het drogestofgehalte, de pH, het asgehalte, totaalstikstof (N_{kj}) en ammoniumgehalte. De veranderingen in de tijd en de verschillen tussen de drie systemen ten aanzien van de strooiselsamenstelling en de ammoniakemissie konden in relatie worden gebracht met het ontwerp van de drie systemen, het gedrag van de hennen en de afbraak- (van stikstofcomponenten) en vervluchtigingsprocessen (ammoniak en water).

6 Afbraak van stikstofcomponenten en vervluchtiging van ammoniak uit het strooisel

Om een beter inzicht te krijgen in de afbraak- en vervluchtigingsprocessen in strooisel werden deze processen beschreven met fysische modellen en geverifieerd aan de hand van 66 strooiselmonsters uit 12 verschillende volièrestallen (hoofdstuk 5). De vervluchtiging van ammoniak uit strooisel bleek lineair te verlopen met het ammoniakgehalte (NH_3) in het water van het strooisel. De

pK_a waarde van het NH_3-NH_4^+ evenwicht bleek te zijn verschoven van pH 9,41 naar pH 8,65. De concentratie van ammoniakale stikstof (NH_3+NH_4^+) in de strooiselmonsters, ontstaan door afbraak van urinezuur en eiwitten, steeg 4% per 1/10 eenheid van de pH, 4% per graad Celsius en 4% per 10 eenheden van het watergehalte (g/kg). De lage buitentemperaturen tijdens het verzamelen van de monster, het was winter, bleken een negatieve invloed te hebben op de samenstelling en de emissie uit de strooiselmonsters die dicht bij de buitenmuren genomen werden. Geconcludeerd werd dat de emissie uit strooisel het best kan worden verminderd door de afbraaksnelheid van urinezuur en eiwitten te verlagen. Dit is mogelijk door de pH en de temperatuur te verlagen of door het drogestofgehalte te verhogen (equivalent met verlagen van het watergehalte).

7 Het effect van strooiseldrogen op de strooiselsamenstelling en de ammoniakemissie

In hoofdstuk zes is het effect van een strooiseldroogsysteem op de samenstelling van het strooisel en de ammoniakemissie uit een Etagesysteem beschreven. Met het droogsysteem werd lucht uit de nok van de stal aangezogen en over het strooisel geblazen via buizen met gaatjes erin. Dit resulteerde in een hoger drogestofgehalte (boven 90%), een lager ammoniakaal stikstofgehalte (0,7 g/kg) en een lagere pH (7,3) dan in strooisel van volièrestallen zonder geforceerde droging van strooisel (75-85% drogestof, ammoniakaal stikstof 2-3 g/kg, pH 8,6). De ammoniakconcentraties in de uitgaande lucht waren lager dan 5 ppm en de emissie bereikte een stabiel niveau van ongeveer 2,0 mg/uur per hen op een leeftijd van de hennen van 30 weken. Dit emissieniveau werd bereikt bij dagelijks verwijderen van de bandmest (geen droging) en een gelijkmatige verdeling van de lucht over het strooisel (debiet ca. 500 m^3/uur). Het effect van de hogere luchtsnelheden boven het strooisel op de vervluchtiging van ammoniak uit het strooisel bleek van ondergeschikt belang.

8 Invloedsfactoren op de verdamping van water uit strooisel

In een volgend experiment, hoofdstuk 7, wordt de verdamping van water uit strooisel beschreven met fysische modellen en gevalideerd met behulp van experimentele data verkregen uit metingen in het Etagesysteem. De verdampingssnelheid van water werd gemanipuleerd door de luchtsnelheden boven het strooisel tussen 0,07 en 0,28 m/s te variëren, door natuurlijke variatie van het buitenklimaat en door de bandmest éénmaal per week, éénmaal per dag of tweemaal per dag te verwijderen. Met het model kon het watergehalte van het strooisel op een bepaalde dag worden voorspeld, afhankelijk van het watergehalte op de vorige dag, de luchtsnelheid ($v_{air}^{0,287}$) en het waterdampdrukverschil tussen het strooisel en de lucht boven het strooisel. Het watergehalte steeg dagelijks met 126,8 g/kg door de toevoer van water in de verse uitwerpselen van de hennen. Een deel van dit water, of zelfs meer, vervluchtigde weer in de loop van de tijd. De wateractiviteit van het strooisel bedroeg 0,86 (s.e. 0,07) en verlaagde de verzadigde dampspanning van het water in het strooisel. De waterdampdruk van de lucht in het Etagesysteem bleek sterk afhankelijk (79%) van de waterdampdruk van de buitenlucht. Hierdoor zou onder Nederlandse omstandigheden gedurende de maanden april tot oktober de droging van strooisel sterk kunnen verslechteren. Dit zou kunnen worden gecompenseerd door verhoging van de luchtsnelheden boven het strooisel (strooiseldroging) of verhoging van de strooiseltemperatuur (vloerverwarming). De ammoniakemissie uit de stal bedroeg 2,85 mg/uur per hen bij dagelijks verwijderen van de bandmest. Hierbij werd het effect van de verwijdering van de bandmest (0,76%/uur), staltemperatuur (8,1%/°C), watergehalte van het strooisel (0,32% per (g/kg)) en de luchtsnelheid (103% per (m/s)) gecorrigeerd naar de gemiddelde niveaus (hoofdstuk 6).

9 Variatie van de watertoevoer naar het strooisel met de uitwerpselen van de hennen

In hoofdstuk acht wordt het niveau en de variatie beschreven van de watertoevoer naar het strooisel als gevolg van de uitwerpselen die de hennen in het strooisel uitscheiden. De massabalansen van de verse uitwerpselen, de bandmest en het strooisel zijn beschreven. Daarnaast werden metingen aan hoeveelheden, massastromen en samenstelling van uitwerpselen, bandmest en strooisel gedaan. Op basis van de concentratieverschillen van as, stikstof, fosfor en kalium tussen de verse uitwerpselen, bandmest en strooisel werd geconcludeerd dat het transport van strooisel tussen de veren van de hennen naar de bandmest verwaarloosbaar klein was. Op ongeveer 22 weken leeftijd kwam ca. 50% van de verse uitwerpselen van de hennen in het strooisel terecht. Vervolgens daalde het aandeel van de verse uitwerpselen dat in het strooisel terecht kwam tot een stabiel niveau van ongeveer 10%. De hoeveelheid water die per dag in het strooisel terechtkwam liet hetzelfde patroon zien, waarbij de piek ca. 45 g water per dag per hen bedroeg en het stabiele eindniveau op ongeveer 7 g water per dag per hen uitkwam. De piek zal in werkelijkheid 10 tot 30 g/dag per hen hoger zijn geweest, omdat op het moment van monstername reeds een hoeveelheid water uit de verse uitwerpselen was verdampt. De piek in de watertoevoer naar het strooisel zou kunnen worden verklaard door het gedrag van de hennen tijdens dit deel van de legperiode (eerste 10 weken na plaatsing in het volièresysteem). Het relatieve aantal gewichtsbepalingen van de hennen met weegschaaltjes in de strooiselruimte vertoonde namelijk hetzelfde patroon als de watertoevoer naar het strooisel. De hennen brachten na 20 weken leeftijd steeds meer tijd door in de legnesten en hadden steeds meer tijd nodig voor voer- en wateropname. Hierdoor bleef er steeds minder tijd over voor scharrelen en stofbaden in de strooiselruimte.

10 Discussie

In hoofdstuk negen wordt de informatie uit de voorgaande hoofdstukken samengevat en gestructureerd met als doel om praktische oplossingen te bespreken waarmee de ammoniakemissie uit volièresystemen kan worden verminderd. Omdat de leghennen vrijelijk kunnen bewegen tussen de verschillende functionele ruimten in een volièresysteem, komen de uitwerpselen (20-25% droge stof) wisselend terecht bij één van beide ammoniakbronnen, de mest onder de banden van de drink-, voer- en rustetages (*bandmest*) en het strooiselmengsel in de scharrel- en stofbadruimte (*strooisel*). Door microbiële afbraak van urinezuur en onverteerde eiwitten ontstaat in beide mestsoorten ammoniak. Naast het afbraak- en vervluchtigingsproces is de verdamping van water uit bandmest en strooisel van eminent belang.

De ammoniakemissie van de bandmest neemt (exponentieel) toe na het afdraaien van de mestbanden, en wordt tevens verhoogd door hogere watergehalten van de mest en temperatuur van de stallucht. De emissie van de bandmest daalt bij een lagere waterdampdruk van de stallucht door een betere droging van de mest. De afbraaksnelheid van stikstofcomponenten in strooisel wordt positief beïnvloed door het watergehalte van het strooisel, de temperatuur en de zuurgraad. De vervluchtiging van ammoniak is rechtevenredig met de concentratie ammoniak in het strooisel en wordt positief beïnvloed door luchtsnelheid en temperatuur.

De oplossing ter vermindering van de ammoniakemissie uit volièrestallen voor leghennen is *regelmatig verwijderen* van de bandmest en *drogen* van het strooisel in de scharrel- en stofbadruimte. De strategie van *verwijderen* van bandmest wordt reeds breed toegepast in batterijsystemen met mestbanden in West-Europa. Ten behoeve van de mestkwaliteit (drogestofgehalte) en verdere verlaging van de ammoniakemissie wordt additioneel de mest op de banden gedroogd. De strategie van *drogen* van strooisel is getest met een nieuw ontwikkeld droogsysteem waarmee stallucht over het strooisel wordt geblazen. Hierdoor kan het drogestofgehalte van het strooisel van 75-85% tot minimaal 90% worden verhoogd. Door toepassing van de strategie van *regelmatig verwijderen* van bandmest en *drogen* van strooisel in een Etagesysteem daalde de emissie tot 2,0 mg/uur per hen aan het begin van de legronde (hoofdstuk 6) en 2,85 mg/uur per hen aan het einde van de legronde (hoofdstuk 7). Beide emissieniveaus waren lager dan die van een batterijsysteem met dezelfde afdraaifrequentie van de mestbanden (2,9 mg/uur per hen, hoofdstuk 3) en waren tevens lager dan de gestandaardiseerde emissie voor batterijsystemen met mestbanden, 4,2 mg/uur per hen (of 35 g/jaar per dierplaats, met en zonder droging van de bandmest). De emissie van welzijnsvriendelijke volièresystemen voor leghennen kan dus worden verminderd van een niveau van 3 tot 4 keer de emissie van een mestbandbatterij tot een niveau dat gelijk is of lager dan dat van een mestbandbatterij. Echter, de emissie van een standaard batterijsysteem met mestbanden kan worden verlaagd tot 1,2 mg/uur per hen (of 10 g/jaar per dierplaats) door betere droging van de bandmest en een hogere afdraaifrequentie. Omdat het nagenoeg onmogelijk is om de emissie uit strooisel volledig te stoppen, zal de ammoniakemissie uit volièresystemen, hoe klein ook, altijd hoger zijn dan uit een batterijsysteem met dezelfde behandeling van de bandmest (verwijderen en drogen).

Anno 1998 staat het welzijn van leghennen volop in de belangstelling, zowel in Nederland als in de rest van Europa. Vele groeperingen en instanties zijn betrokken bij de discussies hoe leghennen op een welzijnsvriendelijke wijze kunnen worden gehouden. De keuzes die gemaakt gaan worden zullen bepalend zijn voor het imago van het product en de sector als geheel in de toekomst. Nationale en Europese wetgeving op het gebied van de huisvesting van leghennen zal geen direct verbod betekenen van de legbatterij. Getracht zal echter worden om via een combinatie van maatregelen welzijnsvriendelijke huisvestingssystemen economisch aantrekkelijker te maken dan batterijsystemen. Door toepassing van de strategie van *regelmatig verwijderen* van mest en *drogen* van strooisel kan de ammoniakemissie uit welzijnsvriendelijke systemen met strooisel dusdanig worden verlaagd dat de milieubelasting geen belemmering hoeft te zijn bij toepassing van deze systemen in de praktijk. Bijkomende voordelen van strooiseldroging zijn het betere stalklimaat (lagere ammoniakconcentraties en gelijkmatige temperatuurverdeling), de mogelijkheid om grondeieren tegen te gaan, een mogelijke verlaging van de ziektedruk vanuit het strooisel en waarschijnlijk minder borstblaren en pootgebreken. Nadelen van strooiseldroging zijn de kans op hogere stofconcentraties in de stal en de emissie daarvan naar buiten. De extra investeringen en elektriciteitskosten van een strooiseldrooginstallatie zijn klein ten opzichte van de totale bouwkosten en zullen waarschijnlijk opwegen tegen de voordelen van de lagere ammoniakemissie.

11 Conclusies

Geconcludeerd kan worden dat de meest relevante kennis voor beheersing en vermindering van de ammoniakemissie uit leghennenstallen met strooisel beschikbaar is. Met deze kennis is een basis gelegd voor duurzame huisvestingssystemen voor leghennen die het welzijn van de hennen combineren met een acceptabele milieubelasting. Het onderzoek in het proefschrift heeft aangetoond dat het probleem van de ammoniakemissie uit strooisel kan worden opgelost met een technisch eenvoudig en goed in stallen inpasbaar systeem. Optimalisatie van strooiseldroging is mogelijk door het gebruik van meerdere technieken naast elkaar (afgezien van beluchten bijvoorbeeld ook vloerverwarming), aanpassingen aan het huisvestingssysteem en verbetering van het management van de pluimveehouder.

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Curriculum Vitae

Petrus Willibrordus Gerardus Groot Koerkamp was born on 23 December 1964 in the present municipality Dronten in the province of Flevoland in the Netherlands. He grew up with dairy cattle and arable farming on the parental farm. After his primary school in Biddinghuizen and the secondary school in Elburg he started his studies in Agricultural Engineering in 1983 at the Wageningen Agricultural University. In 1990 he graduated to Master of Science *cum laude* with thesis work on mathematics and the control of natural ventilation in animal houses. He started in 1990 as a research scientist at the Institute of Agricultural and Environmental Engineering (IMAG-DLO) at Wageningen. During several years he studied the emission of ammonia from houses for laying hens, in particular welfare friendly aviary systems. Besides, he co-ordinated the IMAG-DLO contribution in an international research project for the European Union into aerial pollutants in and from animal housing systems. Nowadays he is leader of a research programme on the measurement of emissions of ammonia and odour from traditional and newly developed housing systems for livestock financed by the Ministry of Agriculture, Nature Management and Fisheries. He is also involved in other research projects related to environmental aspects of livestock housing.

Petrus Willibrordus Gerardus Groot Koerkamp werd geboren op 23 december 1964 in de toenmalige Zuidelijke IJsselmeerpolders (thans gemeente Dronten). Hij bracht zijn jeugd door op het gemengde bedrijf met melkvee en akkerbouw van zijn ouders. Na de lagere school 'De Wingerd' te Biddinghuizen en het V.W.O. 'Lambert Franckens College' te Elburg doorlopen te hebben, werd in 1983 met de studie Landbouwtechniek gestart aan de toenmalige Landbouwhogeschool te Wageningen. Tijdens zijn studie verzorgde hij studentassistentschappen voor wiskunde, liep stage aan de Landbouwuniversiteit van Gödöllö (Hongarije) en was secretaris van de werkgroep 'Pluimvee' van het Financieringsoverleg Mest- en Ammoniakonderzoek (FOMA). In 1990 studeerde hij *cum laude* af op een afstudeervak landbouwbedrijfsgebouwen (regeling van natuurlijke ventilatie in stallen) en een gecombineerd vak wiskunde. In datzelfde jaar werd hij aangesteld als wetenschappelijk onderzoeker bij het toenmalige Instituut voor Mechanisatie, Arbeid en Gebouwen (IMAG-DLO) te Wageningen, het latere Instituut voor Milieu- en Agritechniek. Tot 1994 verrichtte hij voornamelijk onderzoek naar de ammoniakemissie uit welzijnsvriendelijke volièrestallen voor leghennen. Mede door deelname aan een vierjarig EU-project verbreedde het onderzoeksterrein zich naar andere parameters van de luchtkwaliteit in stallen (stof, andere gassen), de emissie daarvan naar het omringende milieu en naar andere diersoorten (rundvee en varkens). Thans is hij programmaleider van het DLO-onderzoekprogramma 'Emissiemetingen ammoniak en geur in de veehouderij'.