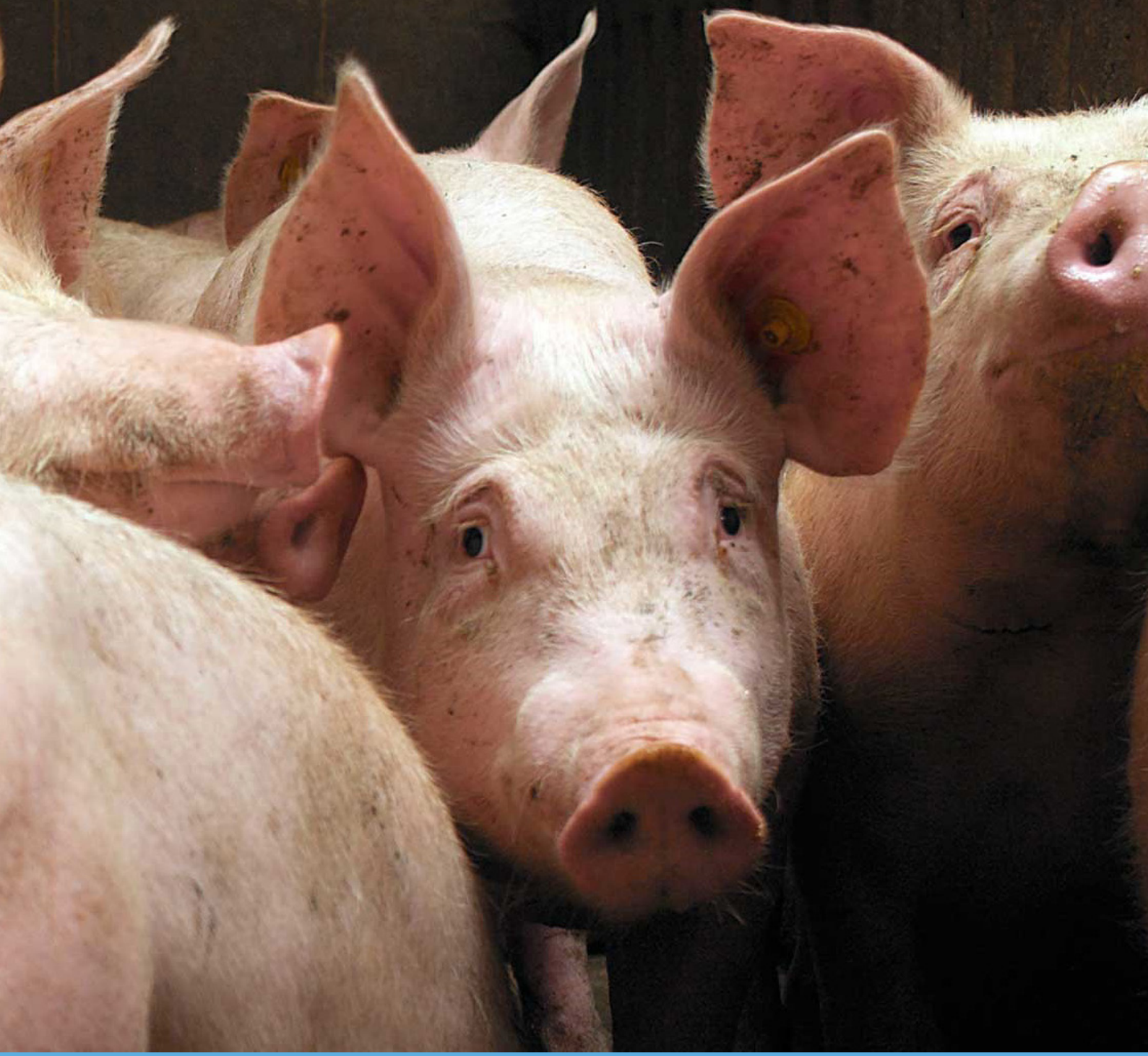


Improvement of nitrogen efficiency in pigs via dietary and feeding interventions

A.K. Kies, P. Bikker, A.J.M. Jansman

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WAGENINGEN
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Improvement of nitrogen efficiency in pigs via dietary and feeding interventions

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Samenvatting.
Dit rapport is het resultaat van een literatuuronderzoek naar de mogelijkheden om via de voeding de stikstofuitscheiding en ammoniakemissie van varkens te verminderen. Verlaging van het ruw eiwitgehalte in voeders kan de stikstofuitscheiding aanzienlijk reduceren, mits wordt voldaan aan de aminozuurbehoefte van het dier. De grootste kansen liggen bij verbetering van de stikstofefficiëntie van vleesvarkens, onder meer door verdere optimalisatie van voersamenstelling, toepassing van precisievoedings concepten en verbetering van dierprestatie. Eiwitarme voeders kunnen voordelen bieden voor milieu en darmgezondheid, maar brengen ook risico's en mogelijk hogere voerkosten met zich mee.

Summary UK
This report is the result of a literature review investigating opportunities to reduce nitrogen excretion and ammonia emissions from pigs through nutritional strategies. Lowering the crude protein content of pig diets can substantially reduce nitrogen excretion, provided that the animals' amino acid requirements are adequately met. The greatest opportunities lie in improving nitrogen use efficiency in growing-finishing pigs through further optimization of diet composition, implementation of precision feeding concepts, and further enhancement of animal performance. Low-protein diets can offer benefits for the environment and gut health, but they may also entail certain risks and possibly increased feed costs.

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Foreword

In the Netherlands, the emission of nitrogen (N) is considered an important source of environmental pollution, as its deposition deteriorates the biodiversity and health-status of vulnerable nature-areas. Nitrogen oxides (NO_x) and ammonia (NH_3) are the main nitrogenous compounds emitted, with transportation and agriculture, especially animal production, as the most contributing sectors (PBL, 2025). Therefore, the Dutch government and the industry and agriculture sectors develop and apply strategies to reduce N-deposition in the environment, especially for protecting sensitive natural areas. Within the agricultural sector, research has been carried out over the past decades aiming to reduce NH_3-emission. In pig production, modification of the nutrient composition of the diets, especially reduction of the dietary protein content, and development and application of precision feeding concepts may contribute to the further reduction of N-excretion of pigs and related NH_3-emission.

Further reduction of the protein (crude protein; CP) content of pig diets can principally further improve N-efficiency in the sector. However, there are important unknown factors related to such measures, such as the effects on animal performance and health, and the effects on N-excretion and NH_3-emission. In addition, the economic effects related to potential increased feeding costs need to be considered as well. The subject has been discussed with representatives of the Ministry of Agriculture, Fisheries, Food Security, and Nature (LVVN), stakeholders of the pig production sector, and Wageningen Livestock Research. It was agreed that instead of focussing only on the options to further reduce the protein content of diets, to consider other options to improve N-efficiency in the pig sector in practice as well. Not only the protein content of pig diets influences N-efficiency, but also, e.g., the application of feeding strategies and management factors that affect animal performance and health.

To explore variation in N-efficiency at farm level, data need to be collected allowing to calculate more precisely variation in N-efficiency and the factors contributing to its supposed variation (e.g., farm-characteristics, level of animal performance and health status, animal management and feeding strategies). This approach would allow a better judgement of which diet and feeding related measures contribute to further improvement of N-efficiency and justify further research in relation to feeding management on the one hand and animal performance, animal health, and occurrence of undesired behaviour on the other. The former should also be considered in relation to developments and ambitions related to sustainability and animal-friendlier farming of pigs. In addition, it would also enable the possibility to define research aimed to further improve N-efficiency in the Dutch pig sector and its practical consequences and potential trade-offs.

The Dutch ministry LVVN has asked for a desk study to present an overview of the literature on the relationship between reduction of dietary protein content of pig diets and N-excretion and NH_3-emission of pigs. The current desk study evaluates the opportunities and limitations of improving N-efficiency of pigs via diet composition and feeding strategies based on a concise evaluation of scientific literature. In case gaps in knowledge were identified, scientific and/or practical research questions were formulated.

Samenvatting

Stikstofemissie (N) is een belangrijke bron van milieubelasting in Nederland, omdat depositie van stikstof in het milieu onder meer leidt tot aantasting van biodiversiteit en de kwaliteit van kwetsbare natuurgebieden. Daarom zijn maatregelen nodig om de uitstoot en depositie van stikstof verder te verminderen. Ammoniak (NH_3) vormt een belangrijke component van de stikstofemissie, waarbij de dierlijke productie een belangrijke bron is. Binnen de landbouwsector worden daarom aanvullende initiatieven genomen om de NH_3-emissie verder te reduceren.

Voor de varkenshouderij kunnen aanpassingen in de voersamenstelling en toepassing van precisievoeding bijdragen aan vermindering van stikstofuitscheiding en NH_3-emissie. Een eerste mogelijkheid is verdere verlaging van het ruw eiwitgehalte (RE) en daarmee het stikstofgehalte (aangezien RE = N × 6,25) van voeders voor verschillende categorieën varkens (zeugen met biggen en vleesvarkens). Het Planbureau voor de Leefomgeving (PBL, 2020) schatte dat een verdere verlaging van het RE-gehalte van varkensvoeders kan leiden tot een jaarlijkse reductie van de NH_3-emissie van 1,2–2,4 kton. Verlaging van het RE-gehalte kent echter ook risico's en beperkingen, zoals negatieve effecten op dierprestaties en diergezondheid. Daarnaast kan het leiden tot hogere voerkosten. Daarom lijkt het effectiever om te focussen op verbetering van de stikstofefficiëntie van varkens, omdat daarbij meerdere factoren die bijdragen aan stikstofuitscheiding worden meegenomen.

In dit rapport is de beschikbare literatuur geëvalueerd over de relaties tussen verlaging van het RE-gehalte in varkensvoeders, stikstofuitscheiding en NH_3-emissie. Daarnaast is gekeken naar het reductiepotentieel van veranderingen in de samenstelling van varkensvoeders (nutriëntsamenstelling, grondstofsamenstelling en gebruik van specifieke voederadditieven), evenals combinaties daarvan. Ook is aandacht besteed aan mogelijke negatieve effecten van deze aanpassingen op dierprestaties, diergezondheid en dierenwelzijn, en op de productiekosten van biggen en varkensvlees.

Uit de literatuur blijkt dat er een sterke relatie bestaat tussen het RE-gehalte van het voer, stikstofefficiëntie, stikstofuitscheiding en de potentiële NH_3-emissie uit mest. Per procentpunt verlaging van het RE-gehalte kan de stikstofuitscheiding met circa 8–10% worden verminderd. Omdat dit samengaat met een verbetering van de stikstofefficiëntie, is de afname van de uitscheiding van stikstof via de urine (TAN: totaal ammoniakale stikstof) relatief groter. Dit is relevant omdat TAN het substraat vormt voor NH_3-vorming in mest. In gecontroleerde onderzoeksomstandigheden werd gemiddeld 28% van de TAN in mest omgezet naar NH_3-emissie. In de praktijk varieert dit percentage echter sterk, afhankelijk van mestmanagement, huisvesting, genetica, gezondheidsstatus, hygiëne, grondstofkeuze, voersamenstelling en voerstrategie.

Voor vleesvarkens (25–125 kg lichaamsgewicht) lijkt het mogelijk het gewogen gemiddelde RE-gehalte over de verschillende groeifasen te verlagen van circa 15 naar 13–13,5%, zonder negatieve effecten op de groeiprestaties. Onder huidige marktomstandigheden leidt dit echter naar verwachting tot meer dan 10% hogere voerkosten. Het is op dit moment onduidelijk of de verbetering van de stikstofefficiëntie en de afname van het NH_3-emissiepotentieel lineair blijven verlopen wanneer het RE-gehalte van het voer verder daalt tot onder circa 15%.

Voorwaarde voor verlaging van het RE-gehalte is dat wordt voldaan aan de aminozuurbehoefte van het varken. Deze behoefte wordt momenteel beschreven met het concept van het 'ideale eiwit', waarin de verhouding tussen essentiële aminozuren (EAZ) wordt vastgelegd voor optimale groeiprestaties. Dit profiel is echter voornamelijk gebaseerd op studies met voeders die vaak meer dan 15% RE bevatten. Er zijn duidelijke aanwijzingen dat het ideale profiel verandert bij lagere RE-gehalten. Daarnaast moet rekening worden gehouden met de voorziening van niet-essentiële aminozuren (NEAZ), omdat essentiële aminozuren nodig kunnen zijn als substraat voor de vorming van NEAZ in het dier. Het optimale aminozuurprofiel hangt bovendien af van het productiedoel: maximale stikstofefficiëntie, minimale TAN-uitscheiding of optimale prestaties onder suboptimale gezondheids- of houderij omstandigheden kunnen andere eisen stellen dan maximale groei.

Het voeren van eiwitarme voeders brengt risico's met zich mee op een te lage voorziening van essentiële aminozuren, wat ongewenst gedrag zoals oor- en staartbijten kan veroorzaken. Verhoging van specifieke aminozuurgehalten in het voer kan dit mogelijk verminderen, maar verandert tegelijkertijd de verhoudingen binnen het ideale eiwitprofiel en vraagt nader onderzoek. Positief is dat eiwitarme voeders de

darmgezondheid kunnen ondersteunen doordat eiwitfermentatie in de dikke darm wordt beperkt, waardoor negatieve effecten van fermentatiemetabolieten afnemen. Bij voeders die groeiprestaties behouden, kan verlaging van het RE-gehalte echter ook leiden tot minder inzet van reststromen uit de agrogrondstoffen verwerkende, voedings- en energiesector, waardoor stimulering van circulaire voerconcepten deels kan worden tegengewerkt.
Het potentieel om stikstofuitscheiding verder te verlagen via aanpassing van zeugen- en biggenvoeders lijkt beperkter. Introductie van tweefasen voeding bij drachtige zeugen kan de stikstofefficiëntie verbeteren. Omdat zeugen gedurende een deel van hun cyclus individueel worden gevoerd, lijkt toepassing van individuele precisievoeding haalbaar en kansrijk. Verdere optimalisatie van aminozuur- en RE-gehalten in voeders voor lacterende zeugen en biggen tot 25 kg kan mogelijk verdere verlaging opleveren, maar vraagt voorzichtigheid vanwege risico's voor prestaties en gezondheid.
Voeders kunnen ook worden aangepast door meer fermenteerbare vezels op te nemen, waardoor stikstofuitscheiding verschuift van urine naar feces. Hoewel dit effectief kan zijn, gaat het mogelijk gepaard met lagere stikstofefficiëntie en verminderde groeiprestaties. Daardoor lijkt dit geen zeer effectieve methode om NH_3-emissie substantieel te reduceren. Toevoeging van specifieke organische zuren of urease remmers aan voer kan NH_3-emissie verminderen door beperking van vervluchtiging. Hoewel het kwantitatieve effect waarschijnlijk beperkt is, lijkt dit additief te werken met andere maatregelen die stikstofefficiëntie verbeteren. Toevoeging van enzymen zoals proteasen, fytasen en carbohydrasen kan de eiwitverteerbaarheid enigszins verbeteren en daarmee de stikstofefficiëntie verhogen. Omdat dergelijke enzymen deels al worden toegepast, lijkt het aanvullende reductiepotentieel beperkt.
Er lijkt aanzienlijke ruimte aanwezig om de efficiëntie van stikstofbenutting bij vleesvarkens te verbeteren en daarmee de stikstofuitscheiding substantieel te verlagen. Dit vraagt echter meer inzicht in de metabole (post-absorptieve) benutting van aminozuren, onder praktische bedrijfsomstandigheden. Hiervoor is aanvullend onderzoek nodig, zowel onder gecontroleerde als praktijkomstandigheden.
Een andere mogelijkheid om de stikstofefficiëntie te verbeteren is het houden van beren in plaats van borgen, aangezien beren eiwit efficiënter benutten. Deze mogelijkheid wordt echter beperkt door risico op berengeur, mogelijke exportbelemmeringen naar bepaalde landen en grotere uitdagingen in de bedrijfsvoering.
Ten slotte lijkt er aanzienlijke potentie te bestaan om de variatie in stikstofbenutting in de tijd en tussen dieren te verkleinen via meerfasen voeding en precisievoeding op hok- of individueel dierniveau. Vooral precisievoeding op individueel of groepsniveau lijkt veelbelovend. Een nadeel is dat hiervoor aanzienlijke investeringen op bedrijfsniveau nodig kunnen zijn en dat verdere ontwikkeling nodig is voordat grootschalige toepassing in de praktijk mogelijk wordt.
Het potentieel van de verschillende opties om de stikstofefficiëntie te verbeteren en stikstofuitscheiding en NH_3-emissie te verlagen is samengevat in onderstaande tabel.

Samenstelling van het voer, voerstrategieën en managementmaatregelen, en hun mogelijke effecten op de stikstofefficiëntie (N-efficiëntie) en stikstofuitscheiding bij varkens.

Actie	Effect op N-efficiëntie (0/+ /++/+++)	Opmerkingen
Samenstelling van het voer		
Verlaging van het ruw eiwitgehalte (CP) van het voer	++	• Het CP-gehalte kan verder worden verlaagd zonder de groei van varkens te schaden, mits limiterende essentiële aminozuren beschikbaar zijn als additief. • De eerste zes limiterende aminozuren worden al gebruikt en hebben geleid tot een sterke verlaging van het CP-gehalte. Nieuw geregistreerde vrije aminozuren maken verdere verlaging mogelijk, maar verhogen de voerkosten.
Herdefiniëren van ideaal eiwit	++/+++	• Ideaal eiwit wordt momenteel vooral gedefinieerd op basis van lysine. • Het concept moet worden herzien rekening houdend met productiedoel, leeftijd, diercategorie en omstandigheden. • Een hogere voorziening van specifieke aminozuren kan onder suboptimale omstandigheden de N-efficiëntie verbeteren. • Meer inzicht in de benutting van aminozuren is nodig om N-uitscheiding verder te verlagen.
Verlagen van pH door toevoeging van benzoëzuur	+	• Wordt al op sommige bedrijven toegepast. Hogere doseringen kunnen effectief zijn, maar huidige niveaus zijn mogelijk te laag om ammoniakemissie sterk te reduceren.
N uitscheiding verschuiven van urine naar feces door hoge vezelniveaus	0/+	• Kan worden bereikt door meer fermenteerbare vezels. • Vermindert urinair TAN, maar kan de verteerbaarheid van eiwit en dierprestaties nadelig beïnvloeden.
Gebruik van enzymen als diervoederadditief	0/+	• Sommige enzymen, zoals fytase, verbeteren de eiwitverteerbaarheid licht. • Proteasen kunnen eveneens een beperkte positieve invloed hebben op de N-efficiëntie.

Actie	Effect op N-efficiëntie (0/+/++/+++)	Opmerkingen
Voerstrategieën		
Meerfasen voeding (> 3 fasen)	+	• Relatief eenvoudig, maar met een bescheiden effect ten opzichte van een driefasen systeem als referentie. Afhankelijk van het huidige voersysteem op het bedrijf kan een investering in voederinfrastructuur noodzakelijk zijn. • Wanneer momenteel een één- of tweefasen systeem wordt toegepast, kan een verbetering worden gerealiseerd door het aantal fasen te verhogen tot ten minste drie.
Precisievoeding	+/++	• Precisievoedering is een zeer veelbelovende methode om de N-efficiëntie te verbeteren. Er kunnen twee niveaus van toepassing worden onderscheiden: het houden van varkens in relatief kleine homogene groepen of individuele precisievoedering. • In het eerste geval worden varkens met een vergelijkbaar lichaamsgewicht, groeiprestatie en/of geslacht samengevoegd (en hebben daardoor meer vergelijkbare eiwit- en aminozuurbehoeften) en krijgen zij een ander voer dan andere groepen dieren. Wanneer de nutriëntenbehoefte binnen een groep weinig varieert, kan de voeding beter aansluiten bij de individuele behoefte, wat de N-efficiëntie verhoogt. • Individuele precisievoedering is de ultieme manier om de N-efficiëntie te verbeteren en de aanvoer van eiwit en aminozuren optimaal af te stemmen op de behoefte van het dier. Dit is eenvoudiger bij individueel gevoerde lacterende zeugen dan bij vleesvarkens in groepshuisvesting. Op basis van individuele gegevens (zoals lichaamsgewicht, voeropname, gezondheidsindicatoren en andere genotype- en fenotypekenmerken) wordt een op maat samengesteld rantsoen verstrekt aan elk individueel dier. • Deze methode wordt momenteel onderzocht, maar aanvullend onderzoek is nodig om bijvoorbeeld de dagelijkse nutriëntenbehoefte per dier nauwkeurig te kunnen voorspellen op basis van eenvoudig meetbare kenmerken. • Toepassing van individuele precisievoedering op praktijkbedrijven vraagt aanzienlijke investeringen (individuele voerstations, automatische weegsystemen, sensoren en software).

Actie	Effect op N-efficiëntie (0/+/++/+++)	Opmerkingen
Managementstrategie		
Verbetering van de voederefficiëntie	+/++	• Alle managementmaatregelen die de voederconversie (VC) of voederefficiëntie verbeteren, kunnen in principe bijdragen aan een hogere N-efficiëntie. Voorbeelden zijn: - Verbetering van gezondheidsmanagement en gezondheidsstatus van de dieren. - Gebruik van genetische lijnen met een hogere eiwitaanzet capaciteit. - Verbetering van de leefomgeving van de varkens (luchtkwaliteit, temperatuur). - Verbetering van dierenwelzijn en vermindering van sociale stress.
Beren houden	+/++	• Effectief om de voer- en stikstofefficiëntie te verbeteren. Mogelijk beperkt toepasbaar voor bedrijven die produceren voor de export markt. In de praktijk leidt het houden van beren tot meer uitdagingen dan het houden van borgen.
Scheiding van geslachten op hokniveau	+	• Effectief omdat beren en gelten verschillende nutriënten- en aminozuurbehoeften hebben en daardoor een verschillende N-efficiëntie vertonen. Bij gebruik meer voeders zijn investeringen in voederinfrastructuur nodig.

Summary

Nitrogen (N) emission is an important source of environmental pollution in the Netherlands, as its deposition into the environment deteriorates biodiversity and health-status of vulnerable nature-areas. Actions must be taken to reduce N-emission and deposition. Ammonia (NH_3) is an important source of N-emission, with animal production as a main source. Therefore, within the agricultural sector, further initiatives have been taken aiming to further reduce NH_3-emission. For pig production, adaptation of diet composition and application of precision feeding concepts may contribute to the reduction of N-excretion and NH_3-emission. A first possibility is to further reduce the crude protein (CP) and N content (as CP = N * 6.25) of diets for various categories of pigs (sows with piglets and growing pigs). The 'Planbureau voor de Leefomgeving' (PBL, 2020), estimated that a further reduction of the CP content of diets for pigs could result in an annual reduction of the NH_3-emission of 1.2 – 2.4 kton. However, reducing the dietary CP content is associated with risks and limitations, such as negative effects on animal performance and health. Moreover, it may raise feed costs. Therefore, it seems more effective to focus on improving the N-efficiency of pigs, as this takes other factors contributing to N-excretion into consideration. In the present report, the current literature was reviewed on correlations between dietary CP reduction of pig diets, N-excretion, and NH_3-emission, as well as to the reduction-potential of changes in the composition of diets for pigs (nutrient composition, ingredient composition, and the use of specific feed additives) and their combination. Attention has also been given to the possible negative effects of these modifications on animal performance, and animal health and welfare, and on production costs of piglets and pig meat.

Literature shows that a strong relationship exists between the dietary CP level, N-efficiency, N-excretion, and potential NH_3-emission from manure. Per percent dietary CP reduction, N-excretion can be lowered by about 8-10%. As this coincides with an improvement of N-efficiency, the reduction of urinary-N (TAN) excretion is relatively higher. This is relevant, as TAN is the substrate for NH_3 formation in manure. In controlled studies in research, on average 28% of TAN in manure was shown to be emitted as NH_3. However, in practice this value will largely vary, as it is affected by manure management practices, animal housing, animal genetics, health status, hygiene at the farm, dietary ingredient, nutrient composition, and feeding strategy.

For growing pigs (25-125 kg body weight) it appears possible to reduce the dietary CP level, weighted for feed intake in different growing phases, from about 15 to 13-13.5%, without negatively affecting growth performance, although, under current market conditions, it will raise feeding costs over 10%. It is currently unclear whether the improvement of N-efficiency and the reduction of NH_3-emission potential from manure decreases in a linear manner beyond decreasing the dietary level further to below 15% CP values. A prerequisite for the dietary CP content-reduction is that the pig's requirement for amino acids (AA) is covered by the dietary supply. The requirement is currently defined by the composition of "ideal protein", a concept that defines the ratio among essential AA (EAA) for "optimal" growth performance. The profile is, however, defined in studies using diets often containing more than 15% CP. There are clear indications that at lower CP levels the ideal profile changes. Also, the supply of non-essential AA (NEAA) need to be considered, as EAA may become limiting as substrate for formation of NEAA in the pig. The profile depends also on the target of pig production; it may be different to maximise N-efficiency, to minimise TAN excretion, or to enhance performance of pigs kept under suboptimal health or husbandry conditions, compared with scenarios where the goal is to maximise growth performance.

Feeding low protein diets is associated with risks of undersupply of EAA relative to the pig's requirements which could induce undesired behaviour, like ear- and tail-biting. Raising the level of specific AA in the diet could alleviate this behaviour. It affects, consequently, the ratio between AA of ideal protein but this requires further investigation. On the positive side, a low protein diet may enhance gut health, as it limits protein fermentation in the hindgut of pigs, reducing the risks of negative effects of protein fermentation metabolites in the gut. For pig diet compositions that sustain growth performance, reducing dietary CP content may result in a lower inclusion of by-products of food and energy production, thus may counteract the stimulation of more circular feeding concepts.

The potential to reduce N-excretion from the pig sector by a further reduction of the dietary CP contents of sow and piglet diets seems more limited. Introducing a two-phase feeding system for gestating sows may improve N-efficiency. As sows are fed individually during a part of their cycle, individual precision feeding

may be achievable, which has potential to improve N-efficiency and reduce N-excretion. Although further optimisation of AA and CP contents of diets for lactating sows and piglets till 25 kg may lower CP levels further, this requires caution as production performance or animal health may be put at risk.
Diets can be modified by including higher levels of fermentable fibre, to shift excretion of N from urine to faeces. Although this seems effective, it may coincide with a lower N-efficiency, and possibly with lower growth performance. The result does not seem an effective method to reduce NH_3-emission to a significant extent. Supplementation of diets with specific organic acids or urease inhibitors may be effective to reduce NH_3-emission by inhibiting volatilisation. Although their contribution to reduction of NH_3-emission will probably be modest to small from the quantitative perspective, the effect will likely be additive to other measures that improve N-efficiency. Dietary supplementation with specific enzymes, as proteases, phytases, and carbohydrases, may enhance protein digestibility and improve N-efficiency to a small extent. As they are, in part, already used at present, their additional potential to further reduce N-excretion seems limited.
There seems ample space to improve the efficiency of N-utilisation of growing pigs, allowing a considerable reduction of N-excretion. This requires, however, more insight in the metabolic (post-absorptive) utilisation of AA, also taking into account practical on-farm conditions. For the latter, more research is required in controlled and practical conditions to gain further understanding of the factors involved and the window of opportunity to increase N-efficiency of pigs grown under practical conditions. Another option to improve N-efficiency is to raise boars, rather than barrows as boars use protein more efficiently than barrows. However, the possibility may be limited due to the risk of the occurrence of boar taint, which may be problematic for the export of pork to some countries, and more difficult farming practices to raise boars.
Finally, there seems a considerable potential to reduce variation in N-utilisation in time and between animals, by introducing a multi-phase feeding system providing nutrients matching the nutrient requirements at different ages and feeding systems focussed at precision feeding at pen or individual animal level, respectively. Especially application of precision feeding concepts at individual or group/pen level seem promising in this respect. Disadvantage is that it may require a large investment at the farm, and that such a system still require further development before they can be applied in practice.
The potential of the different options to improve N-efficiency and to reduce N-excretion and NH_3-emission is summarised in the table below.

Summary table. Diet composition, feeding and management strategies, and their possible effects on N-efficiency and N-excretion in pigs.

Action	Effect on N-efficiency (0/+/++/+++)	Remarks
Diet composition		
Reduction of CP content of the diet	++	• Dietary CP contents can be further reduced without impairing growth performance of pigs. This requires, however, the availability of potential limiting essential AA (EAA) in free form as feed additive. At present, all EAA, with the exception of phenylalanine, are registered as nutritional additives in the EU. • The first six limiting AA in pig diets (lysine, methionine, threonine, tryptophan, valine, and isoleucine) are being used in practical diets for pigs, which resulted in a strong reduction of the dietary CP content over the years. The more recently registered free AA allow a continuation of this practice. At present prices, however, this will result in a significant increase in costs of feeds and feeding costs.
Re-defining ideal protein	++/+++	• At present, ideal protein is defined for EAA only using the requirement for lysine as reference. However, the ratio between EAA is determined in experiments using higher dietary CP levels and is probably different at lower CP contents. At a low dietary CP level NEAA may become limiting, which is currently not considered. Also, factors like the pig's health status and sanitary conditions in the pig house affect this ratio. Therefore, the ideal protein concept needs to be redefined, considering the following aspects: • Objective of production (e.g., maximal growth performance, maximal N-efficiency, minimal NH_3-emssion, sustaining pig health). For each of these objectives, the AA composition of ideal protein may be different. • Definition of ideal protein using low CP diets. This should include NEAA and must be defined for different ages (or BW) of the animals, and animal categories (sows, growing pigs). • Increased supply of specific AA relative to the currently supposed AA requirements may counteract the reduced N-efficiency of pigs under suboptimal conditions (health, sanitary state of housing). Thus, under such conditions the AA composition of ideal protein is different. Although this may not be relevant for all pig farms, the impact on N-efficiency can be relatively large. • A low dietary CP level with increased risk for suboptimal dietary supply of EAA relative to the requirement may induce unwanted behaviour of pigs, such as tail biting. This can probably be corrected by dietary supplementation of specific AA, thus by adapting the AA composition of ideal protein. • To optimise the AA composition of ideal protein for the different farm and animal conditions, more quantitative insight in post-absorptive utilisation of AA is required. It permits to reduce dietary CP content to a minimum, consequently reduce N-excretion and improve N-efficiency without compromising animal performance and animal health and well-being. It helps to customise protein nutrition of pigs under different conditions.
Reducing pH by dietary inclusion of benzoic acid as a feed additive	+	• Is already applied on some farms, but not widely. At a relatively high dose it might be effective, but currently applied dose levels may be too low for reducing urinary pH and reduction of ammonia emission.

Action	Effect on N-efficiency (0/+/++/+++)	Remarks
"Re-directing" N from urine to faeces by inclusion of a high dietary fibre levels	0/+	• Can be realised by a higher inclusion level of ingredients rich in fermentable fibre. • Effective to reduce urinary TAN excretion. However, it may reduce faecal CP digestibility and, depending on the level, reduce animal performance, which may counteract the positive effect with regard to ammonia emission.
Use of enzymes as feed additives	0/+	• Some specific enzymes, for example phytase, degrade anti-nutritional factors and subsequently improve protein digestibility slightly. The use of phytase is already widely applied to increase P-digestibility, thus offers little room for additional further improvement of N-efficacy. • Proteases may improve digestibility of dietary protein slightly, with a potential small effect on N-efficiency. Development of next generation proteases is a long-term process to be taken up by enzyme producers. • Application of targeted mixtures of fibre degrading enzymes (carbohydrases) may unlock fibre-protein matrices in the diet, rendering more protein available for enzymatic digestion in the pig's intestine. Such a development is a long-term process and involves major efforts of feed enzyme producers.
Acids as feed additives to improve growth performance	0	• Use of specific acids as feed additives may enhance growth performance and, subsequently, N-efficiency. They are, however, already applied in (primarily piglet) diets. In other diets they are less effective, and relatively expensive. The window of opportunity is small.
Urease inhibition in manure by feed additives	0	• May delay, but not reduce, NH_3-emission from manure, depending on the manure management strategy. Highly variable results are obtained in research. Effective doses of inhibitors may be very high; most effective seem specific chemical compounds which are presently not approved for use in animal nutrition (in the EU).
Feeding strategies		
Multiphase feeding (> 3 phases)	+	• Relatively easy, but with a modest effect as compared to a three-phase feeding system as reference. Depending on the current feeding system at the farm, investment in feeding infrastructure may be required. • If a one- or two-phase feeding system is currently applied, improvements can be made when increasing the number of phases to at least three.

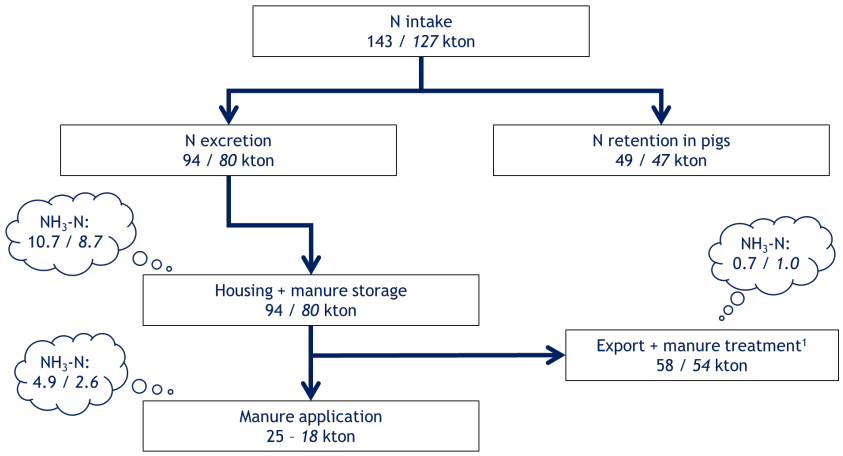
Action	Effect on N-efficiency (0/+/++/+++)	Remarks
Precision feeding	+/++	• Precision feeding is a very promising method to improve N-efficiency. Two levels of implementation can be distinguished: Keeping pigs in relatively small homogeneous groups of animals or individual precision feeding. • In the first case, pigs of similar BW, growth performance, and/or sex are grouped together (and have more similar protein and AA requirements) and are fed a different diet compared to other groups of animals. If, within a group, the animal's nutrient requirements vary little, they can be fed close to their individual requirements, which improves the N-efficiency. • Individual precision feeding is the ultimate way to improve N-efficiency and match protein and AA supply with their requirements for optimal performance. This is easier for lactating sows which are fed individually compared to growing pigs in group housing systems. Based on individual data of pigs (such as BW, feed intake (amount and pattern), health indicators, other genotypic and phenotypic information) a customised diet is presented to each individual animal. • This method is being explored in research at present, but requires additional research, e.g., to estimate the specific amounts of nutrients required per pig per day based on easily measurable parameters. • Application of individual precision feeding systems on farm requires a large investment (individual feeding stations, continuous weighing scales, sensors, and software).
Management strategy		
Improvement of feed efficiency	+/++	• All management strategies which improve feed conversion ratio (FCR) or feed efficiency could principally contribute to a higher N-efficiency. These could include: - Improvement of health management and health status of pigs on a farm - Use of improved genotype of pigs with higher protein deposition capacity - Improvement of the environment of pigs (air quality, temperature) • Improvement of animal welfare and reduction of social stress
No castration of boars	+/++	• Effective to improve feed- and N-efficiency. Possible limited acceptation for farms who rely on export of their meat. In practice, raising boars may be harder than raising barrows.
Separation of sexes at pen level	+	• Effective as sexes of pigs have different nutrient and AA requirements and N-efficiency. If an increased number of diets is required, an investment in feeding infrastructure at the farm may be necessary but can be combined with multiphase feeding.

List of abbreviations:

AA	Amino acid(s)
ADG	Average daily gain
BA	Benzoic acid
BW	Body weight
CH_4	Methane
CP	Crude protein (= N * 6.25)
dEB	dietary Electrolyte Balance
DDGS	Distillers Dried Grains with Solubles
EAA	Essential amino acid(s)
FCR	Feed conversion ratio (kg feed/kg BW gain)
kton	kiloton; 1000 tons; 1 million kg
LVVN	Ministry of Agriculture, Fisheries, Food Security, and Nature
N	Nitrogen
NEAA	Non-essential amino acid(s)
NH_3	Ammonia
NH_4^+	Ammonium ion
NO_x	Nitrogen oxides
NPN	Non-protein nitrogen
NSP	Non-Starch Polysaccharides
PBL	Planbureau voor de Leefomgeving [Netherlands Environmental Assessment Agency]
RSM	Rapeseed meal
SBM	Soybean meal
SID	Standardised ileal digestibility
TAN	Total ammoniacal nitrogen
TN	Total nitrogen
YSE	*Yucca schidigera* extracts

1 Introduction

Nitrogen emission is an important source of environmental pollution in the Netherlands, as its deposition into the environment deteriorates biodiversity and health-status of vulnerable nature-areas. There are two main types of nitrogenous compounds emitted, nitrogen oxides (NO_x) and ammonia (NH_3). Transportation and agriculture, especially animal production, are the most important sectors contributing to N-emission, respectively (PBL, 2025). Animal production causes 51% of the total NH_3-deposition, or 74% when considering deposition only caused by domestic (Dutch) emission (CLO, 2025).
To reduce NH_3-emission and deposition on nature-areas, actions must be taken. Therefore, the Dutch government and the industry and agriculture sectors develop strategies. Within the agricultural sector, projects have been started or are being developed aiming to reduce NH_3-emission. Measures to be taken can be, for example, technical modifications of animal barns (e.g., the use of air scrubbers), manure management, reduction of the protein (and N) content of diets for pigs, a reduction in the production volume (allowance of less animals in the sector), or combinations of such measures. For pig production, modification of the diets including further reduction of the dietary protein content and application of precision feeding concepts may contribute to the reduction of N-excretion and related NH_3-emission by the pig sector.
One of the measures possible is the reduction of the dietary-N content, i.e., the crude protein (CP; N-content * 6.25) content of diets for different categories of pigs (sows with piglets and growing pigs). The 'Planbureau voor de Leefomgeving' (PBL, 2020), estimated that a reduction of the CP content of diets for pigs in the Netherlands could result in an annual reduction of the NH_3-emission of 1.2 – 2.4 kton. However, reducing the dietary CP content comes with risks or limitations, such as effects on animal performance and health, and may considerably raise costs of feed. Therefore, a more general focus on measures to improve N-efficiency at farm level, rather than the sole focus on reduction of dietary CP content, could be more effective, as, in part, it implies consideration of aforementioned risk factors. In the present report, we investigate current knowledge on the correlations between dietary CP reduction and NH_3-emission, the reduction-potential of separate optional changes in diet composition (nutrient composition, use of specific ingredients and/or feed additives) and their combination, and possible negative effects of these modifications on animal performance, production costs of piglets and meat, and animal welfare and health.



[1]It should be noted that part of treated manure (e.g. separation of slurry in a solid and a liquid fraction, mineral-concentrate production, or fermentation of manure) is finally also applied as fertilizer on soils.

Figure 1 *The total flow of N and NH_3-emission related to pig production in the Netherlands. Values mentioned in kton N for 2019 (first value) and 2024 (second value), respectively. Besides emission as NH_3, about 0.3-0.4 kton N is estimated to be emitted as NO_x-species. Data adapted from CBS (2020, 2025), Cals et al. (2024), and Van Bruggen et al. (2024).*

Emission of NH_3 takes place at different places and moments of the farming process. Most emission is observed from animal housing, followed by manure application in the field. For pig production in NL, the N-flow and ammonia emission is depicted in Figure 1 for 2019 and 2024. In 2024, the total NH_3-emission from pig farming was about 25% lower than in 2019.

First, some background information and the research questions asked by the Ministry of LVVN will be presented.

1.1 Background and context

The excretion and emission of N from animal production in the Netherlands has to be reduced, to lower its subsequent deposition in the environment. It was estimated that a reduction of the CP contents of pig diets could contribute to an annual NH_3-emission reduction of 1.2 to 2.4 kton in the Netherlands. These values were calculated by applying "short and long-term targets" for the CP level in pig diets, as defined by the Ministry of LVVN (PBL, 2020). These CP levels are interpreted as short term (by 2025) and long term (by 2030) targets, respectively. They are indicated in Table 1, as well as the mean CP content of pig diets as used in the Dutch practice in 2024 (CBS, 2025).

Table 1 *Targets for dietary CP content in pig diets (g/kg[1)]; PBL, 2020) and realised values in 2024.*

Animal category	LNV 2019, reference	Reference KEV, 2019[2)]	Realised 2024[3)]	Short term target[4)]	Long term target[5)]
Sows and piglets	150	151.5	147.8	145	135
Growing pigs	157	156.5	148.8	145	130

1) Calculated as N content * 6.25

2) Realised in 2017 (PBL, 2020)

3) CBS (2025); For the calculation, the total feed intake for "Sows and piglets" was estimated based on an assumed sow-to-piglet feed consumption ratio of 1.29, where sow feed intake included both the gestation and lactation period, and piglet feed intake covered the period from weaning to 25 kg body weight (BW).

4) Around 2025

5) Around 2030

It was concluded by the PBL (2020) that a reduction in dietary CP-content to the short-term target could be technically realised. However, it would be difficult to reach the long-term targets given the assumed potential negative effects on animal performance, health, and welfare, and higher feed costs, affecting the economic profitability of the sector. Also, it was unknown whether all required essential amino acids (EAA) would be available in free (crystalline) form. These are required to formulate low protein diets with a proper amino acid (AA) profile aligned with the requirement for EAA by pigs, necessary for such CP-reductions (PBL, 2020). Table 1 shows that the defined short-term target for lower-CP diets is approached in 2024, but not fully realised yet, also because more of the required free AA became available for application in practical diets over the last years. It was recommended by PBL to investigate the possible disadvantageous effect of low-CP diets on animal performance, health, and welfare, and feed costs (PBL, 2020). In the current report, a low-CP diet is defined as a diet that has an overall (weighted mean) protein content lower than 150 g/kg for both, sows combined with their piglets until a BW of 25 kg, and for growing pigs from 25 kg to slaughter at 125 kg BW.

1.2 Problem, aim, and research questions

In the current report, we consider the pig sector in the Netherlands. Manure is the source of emitted NH_3. The potential for NH_3-emission from manure is expressed as total ammoniacal N (TAN), which is the sum of urea, its degradation product ammonium-ions, and dissolved NH_3 in manure. As little of the faecal-N is transformed into TAN, the main source is urine. The proportion of TAN in manure which is transformed into

and emitted as NH_3 depends on many factors. The TAN concentration is the major factor, but pH, temperature, buffer capacity, and electrical conductivity of the manure, the ratio between superficial area of the barn floor with the volume of excreted manure (Aarnink et al., 1993a), manure management, and the presence of air scrubbers, among others, affect the NH_3-emission. Pig nutrition affects only a part of these factors. Consequently, NH_3-emission cannot be expressed as a simple result of nutritional measures, although these can substantially affect the potential for this emission, mainly by reducing the production of (urinary) TAN. Improving N-efficiency is the most effective method to do so, as will be discussed. This means that we cannot directly compare potential reduction of N-excretion with the reduction objectives as indicated in the PBL-report (PBL, 2020), although we did consider that report for reference. Dietary CP reduction was the basis for the potential emission-reduction estimations by PBL (2020). In the present report a somewhat wider approach is taken. Improving N-efficiency implies a reduction of N-excretion, including TAN. It also takes zootechnical performance of the pigs into consideration. Compromising this performance strongly affects efficiency in a negative sense, reducing viability of the pig sector and raising N-excretion (per amount of meat produced) and N-output to the environment. No attention will be given to a possible effect of dietary measures on the emission of NO_x-compounds. These may be affected, but the contribution of pig manure is relatively small (Velthof et al., 2012; Cals et al., 2024), and little is known how it could be influenced by dietary measures (PBL, 2020).
The current desk-study aims to provide more insights into opportunities for improvement of the N-efficiency of pig production by dietary adaptation and feeding strategies, as well as their possible disadvantages.
The following three research questions are the basis for the present study:

1. Which correlations between dietary CP-reduction and NH_3-emission are already known?
2. What is the reduction-potential of individual dietary adaptations, and their combination, as compared to the PBL-estimation (PBL, 2020)?
3. What are possible negative effects of further reducing the dietary protein content on animal performance, production costs, and animal welfare and health?

The research questions are investigated and answered as follows:

Ad 1. A concise review is given on present scientific knowledge concerning the relationship between dietary composition, N-excretion, and NH_3-emission. The latter may be reduced by reduction of N-excretion or by measures to reduce its volatilisation from manure (slurry). The TAN-excretion is discussed as part of the total N-excretion. Also, the relation with other sustainability characteristics, notably of circularity and food production, have been considered.
Ad 2. The potential reduction of N-emission by dietary measures was estimated to be 1.2-2.4 kton annually by the PBL (2020), based on a number of principles for the short and the longer term, respectively. The basal question is whether the assumed dietary CP-reduction can be practically realised. Although the current study may not give a definitive answer to this question, first steps can be taken. Firstly, the relationship between the reference dietary CP-content and N-efficiency is described for growing pigs and for sows with piglets. The required N-efficiency to realise the short- and long-term reduction objectives is estimated. Secondly, for growing pigs the consequences of dietary CP-reduction on feedstuff demands are calculated by feed-optimalisations (least-costs calculations). This includes the availability of free AA as nutritional feed additives and the consequences for using more by-products in circular production systems. The possibility to include excretion of TAN in this approach is also described.
Ad 3. Possible disadvantages of dietary CP-reduction to improve N-efficiency are also described, based on scientific literature. Here, we focus on animal performances and health. The economic consequences of dietary measures are mentioned, but are only indicative, as they are strongly defined by market- and (individual) farm conditions.

2 Dietary measures to reduce nitrogen excretion

This chapter presents the relationship between diet composition, N-excretion, N-efficiency, and NH_3-emission. Firstly, the fate of N in the animal (dietary N-sources, digestion and metabolism of N) is described briefly. Aarnink and Verstegen (2007) suggested that three options are available to reduce NH_3-emission by nutritional means:

1. Reducing N excretion by lowering CP intake
2. Shifting N excretion from urea in urine to protein in faeces
3. Lowering the pH of manure by:
    a. lowering the pH of faeces
    b. lowering the pH of urine

The first point will be discussed in some depth. The urinary TAN fraction is strongly related to NH_3-emission and can be influenced by the other two points mentioned. These will be discussed, as well as some other possibilities to reduce the manure TAN fraction.

2.1 Sources of nitrogen, their digestion and absorption, and use in intermediate metabolism

Almost all N in pig diets is present in the form of protein in feed materials of plant and animal origin and, to a lesser extent, from free AA used to optimize the dietary AA balance. Proteins consist of combinations of AA. Only 20 AA are relevant as building blocks for proteins, although more exist and are found in the animal's body. In the present report, when discussing 'AA' we refer to these 20, unless indicated otherwise. With a few exceptions, the dietary protein content is calculated as the N-fraction multiplied by the factor 6.25 and is called "crude protein" (CP). This factor assumes that protein contains, on average, 16% N. However, this overestimates the real protein content. Calculated from the N-content of the individual AA, the actual conversion factor is generally lower (Boisen et al., 1987; Mariotti et al., 2008). This implies that supplying a diet with defined levels of AA, its N-content can be higher than expected based on using the standard conversion factor (6.25). Free AA supplemented to animal diets have higher N-conversion factors than protein-bound AA, thus have, on weight basis, a lower N-content.
The majority of protein is digested in the stomach and small intestine (jejunum and ileum) and resulting peptides (molecules containing 2-4 AA) and free AA are subsequently absorbed from the small intestine into the blood in the portal vein. In growing pigs, these AA and peptides are mainly used for the retention (deposition) of body protein in muscles and organs to sustain growth of the pig, and in reproductive sows for growth of foetuses and milk production. The efficacy of the utilisation of dietary AA for protein deposition depends highly on the dietary AA profile relative to the animal's AA requirements. Some AA cannot be synthesised within the pig's body, thus must be supplied with the diet (essential amino acids; EAA). Other AA are not necessarily supplied by the diet, as they can be (in part) synthesised within the pig (non-essential AA; NEAA). These NEAA may become available from the diet, or from breakdown of body protein (protein turnover), or from catabolising EAA to NEAA. There is a considerable turnover of protein in the different tissues, i.e., it is broken down and (re-)synthesised. As protein turnover also involves inevitable AA losses related to their oxidation in organs and tissues, these AA need replacement via their dietary supply. In addition, a small fraction of AA is used for numerous body processes including production of enzymes and hormones, and replacement of integument, generally referred to as maintenance processes. The efficiency of utilisation of absorbed AA (post-absorptive utilisation) largely depends on the dietary supply of AA and energy in relation to the requirements of the animal. Amino acids supplied above the ideal balance among AA, above the ratio relative to energy, or above the (genetic) capacity for protein retention of the animal are deaminated in the liver and other organs and tissues and excreted as urea in the urine. It is largely responsible for the NH_3-emission since urea is rapidly converted to NH_3 by the activity of urease in the faeces

when urine is in contact with faeces on the floor or in the manure pit. Ammonia can readily be emitted from urine and manure into the environment, but its actual emission depends on many factors, as indicated before. For example, a low pH of urine or manure drives the equilibrium between NH_3 and ammonium to ammonium dissolved in the fluid, thus reducing the emission.
Ileal undigested protein and endogenous protein enters the hindgut and can be used in microbial fermentation, generating bacterial protein and fermentation products including NH_3. Ammonia and urea can be exchanged between the pig's blood and hindgut, resulting in a net absorption of N into the blood or secretion into the hindgut. As a result, NH_3 produced in the hindgut is largely absorbed and excreted as urea in the urine. When an adequate amount of fermentable carbohydrates (fibre) is available as energy source for fermentation in the hindgut, more protein can be retained as microbial protein and excreted in the faeces. Both undigested dietary protein and microbial protein are less prawn to degradation and conversion to NH_3 in the manure and contribute far less to the NH_3 emission than urinary N excretion.
The flow of protein and N through the pig is schematically shown in Figure 2. The values mentioned are indicative at an individual pig level. Note that urinary TAN is the resultant of obligatory losses, resulting from protein turnover and use of AA for synthesis of molecules such as hormones and enzymes, and of AA imbalance and excess. Increasing N-efficiency is mostly the result of minimising these losses. Obligatory losses cannot be influenced by dietary measures. Amino acids in excess of requirement will be deaminated and catabolised to urea, thus are a source of TAN. They may be reduced by incorporating a lower level of CP in the diet, as long as the content of the limiting AA (the AA which restricts body protein retention and growth performance) is not lowered. Imbalances can be reduced by balancing the dietary AA composition, by selection of ingredients, supplementation with free AA, or a combination of these. Therefore, in pig nutrition, the "ideal protein" concept is used. Ideal protein means using protein with an AA profile which matches the EAA requirements of the target pig category for optimal performance (Van Milgen and Dourmad, 2015). As will be discussed in the present report, there are some limitations to the currently used ideal protein profiles. Their improvement is key to reduce urinary TAN losses.

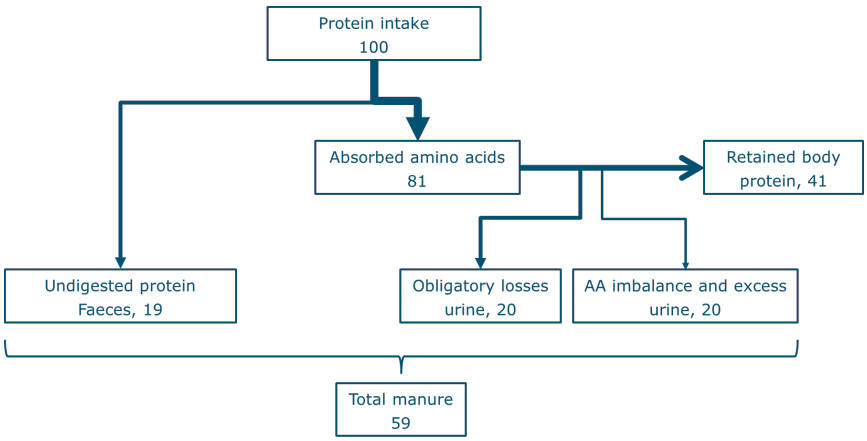


Figure 2 *Schematic flow of N from protein, amino acids, and their degradation products in the pig. Values are relative values (proportion of N-intake in %) at animal-level, for growing pigs. Based on Millet et al. (2018), Van der Peet-Schwering and Bikker (2018), and CBS (2025).*

In all feedstuffs, N is present not only in proteins, but also as non-protein N (NPN). This fraction, which is often considered to be small, includes free AA, NH_3, nucleic acids, urea, vitamins, and miscellaneous other compounds. Free AA as found in proteins, often considered as the main fraction of NPN, can readily be utilised by the animal. Some of the other NPN-components, e.g., vitamins, are useful for the animal, but others cannot be utilised. Together with the N-part of catabolised AA they are mostly metabolised to urea. The NPN-fraction is often small. For example, about 5% of the total N-content of soybean meal (SBM) is NPN and consists mainly out of free AA (Maubois and Lorient, 2016; Van Eys and Ruiz, 2021). Boisen et al. (1987) analysed an NPN fraction of 2.6% for SBM, but a value as high as 20% in grass meal. In experimental grower pig diets, Lenis et al. (1999) analysed an NPN fraction between 6 and 10% of total N.

Thus, depending on its composition, the amount of NPN in the diet may not be neglectable. The levels are, however, variable, among and within sources, due to factors like environmental conditions (climate, fertilisation), cultivar, and sample treatment (drying conditions, age at harvest) (Wilson, 1987; FAO, 2019). The NPN-fraction is higher in young, green plant material than in matured seeds. For the most relevant feedstuffs used in pig diets, the NPN-fraction seems quite constant. Its level is hard to reduce and is an inevitable consequence of using nature-derived feedstuffs. Therefore, despite its potentially large effect on TAN, it is not specifically discussed in the present report.
In summary, pigs require AA, which are building blocks of protein, for their life-processes (maintenance) and for production (growth of muscles (meat) or production of foetuses or milk). Most of the AA used for maintenance processes and of NPN, and AA consumed in excess or imbalance to the pig's AA requirements, will be catabolised and excreted as TAN via the urine. A part of this loss is, consequently, inevitable. Excretion of TAN can be reduced by preventing AA imbalances in the diet and preventing an excessive supply of AA via the diet. To match AA requirements of animals and dietary supply as good as possible, the concept of ideal protein was developed.

2.2 Relationship between N-excretion, N-efficiency, and N-emission

Nitrogen not being utilised by the pig ends up in faeces or urine. Faecal-N contributes little to the production of TAN (Aarnink et al., 1993b), which is the main substrate for NH_3 formation. Absorbed N which is not deposited in product (meat, foetus, milk), as well as most of the N utilised for maintenance purposes, is mainly catabolised in the body into urea which is excreted via the urine. Therefore, we define N-efficiency in the present report as:

N-efficiency = N retention / N intake

= (N-intake - N excreted) / N intake

= (N-intake - faecal-N - urinary-N) / N-intake

Consequently, to reduce the amount of TAN, N-efficiency must be increased, or the amount of excreted N must be shifted from urine to faeces. The latter will be discussed in paragraph 2.5).

In a meta-analysis, Cappelaere et al. (2021a) clearly showed that a direct relationship between N-efficiency, TAN, and NH_3-emmission exists. This analysis was aimed to determine the effect of a reduction of dietary CP-level for growing pigs on N-excretion and on NH_3-emission. The dietary AA-composition in the used experiments were balanced for pig's requirements, thus a reduction of the CP-level increased AA utilisation, reduced N-excretion, and, consequently, increased N-efficiency. As the fraction of ingested digestible N that is not retained in the body is excreted in urine, increasing N-efficiency in post-absorptive metabolism linearly decreases the amount of TAN (Figure 3).

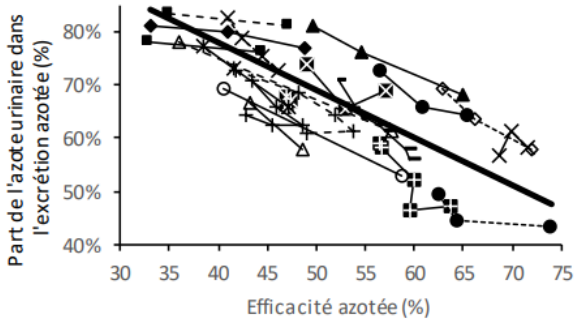


Figure 3 *Nitrogen excretion in urine as a proportion of total nitrogen excretion in relation to the efficiency of nitrogen utilisation by growing pigs as observed in individual studies considered in a meta-analysis; the black solid line represents the mean relationship over studies (Cappelaere et al., 2021a).*

Importantly, the authors reported a strong linear relationship between TAN and NH_3 emission (Figure 4), with 28% of TAN emitted as NH_3. There are, however, many factors besides the urinary TAN concentration that affect NH_3-emission, as pH, temperature, buffer capacity, and electrical conductivity of the manure, the ratio between superficial area of the barn floor with the volume of excreted manure, and the presence of air scrubbers. Under practical conditions, these aspects will likely result in a large variation of realised NH_3 emission. Nevertheless, N-efficiency appears to be a good predictor of TAN. Its improvement will result in a lower N-excretion and a reduction of NH_3 emission.

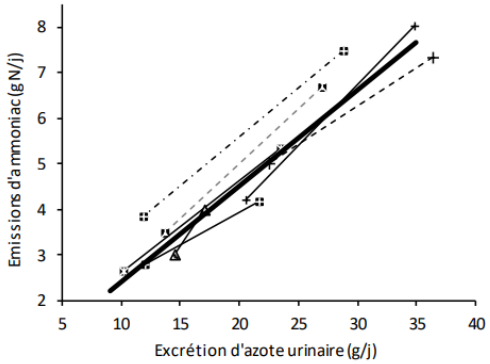


Figure 4 *Ammonia emission in farm buildings (g/animal/d) as a function of urinary nitrogen excretion (g/animal/d) in growing pigs as observed in individual studies considered in a meta-analysis; the black solid line represents the mean relationship over studies (Cappelaere et al., 2021a).*

2.3 Improving N-efficiency in pigs

There are many technologies or practices that may improve N-utilisation by pigs. Navales et al. (2025) mention dietary measures and feeding practices, for example reducing dietary CP level together with AA-balancing, use of feed additives as enzymes and acidifiers, precision feeding, split-sex feeding, and feed processing. Genetics, environment, and animal health status are mentioned as examples of other possibilities. A part of these possibilities can be considered as the pig farm's management. Factors like animal housing, genetics, and hygiene all influence N-excretion. They cannot be influenced by dietary measures. However, the different factors may interact, making it more complex to affect N-efficiency, and finally NH_3-emission, consistently. All these factors, together with the farmer's expertise, define animal performance. This includes pig production (as growth, number of piglets), feed intake, and feed efficiency (the amount of feed required for this production). Improving this efficiency reduces N-excretion per amount of product produced. However, the highest feed efficiency is not necessarily realised at the lowest dietary CP-level.
We will not focus on the impact of farm management on NH_3-emission, other than measures on feeding strategies (Chapter 3). The impact of growth performance will be discussed briefly but dietary CP reduction at some length, as this was mentioned as a solution by the PBL (2020), and further balancing of the ideal protein AA profile.

2.3.1 The impact of growth performance

Reduction of the dietary CP content is a logical measure to reduce N-input at the source, allowing subsequent reduction of N and TAN excretion and NH_3-emission. However, its realisation is multi-facetted and not straight forward, as indicated above. Improving N-efficiency is more related to urinary TAN excretion, than a reduction of the CP content as such.
Nitrogen efficiency can be improved in different ways. Improving feed efficiency (or feed conversion ratio (FCR): kg feed / kg body weight gain) is an effective method. In an experiment with partly individually and partly group-housed crossbreed pigs, Shirali et al. (2012) measured that pigs growing from 60 to 140 kg BW excreted 173 g N per pig less per 0.1-unit reduction of the FCR. Feed efficiency is affected by many factors. Dietary aspects include ingredient choice, nutrient levels and digestibility, and balance between nutrients. A proper combination of feed ingredients with high digestibility and adequate AA pattern, supplemented with

free AA to optimise the AA pattern relative to the requirements of the pigs is indispensable to realise a high feed efficiency.

2.3.2 The impact of digestibility

Digestible protein is the part of dietary protein which is absorbed from the intestine. Non-digested CP appears in faeces. Thus, if the intake of digestible CP is unchanged, but digestibility is higher, the dietary CP level can be lowered. If the subsequent utilisation of the digested protein is unchanged, a similar amount of N will be excreted in urine. Thus, to obtain the same level of utilisable AA, elevating CP digestibility allows to decrease the dietary CP level, reduces N-excretion, improves N-efficiency, but does not reduce TAN.
The other way around is also true. Faeces do not only contain non-digested feed protein, but also bacterial protein, mainly formed in the pig's large intestine. For their growth, bacteria may use urea. There is excretion of urea into, and absorption from the large intestine. If a part of this urea can be bound by bacteria, thus end up as faecal-N, TAN may be reduced. Thus, there is a switch from urinary to faecal N. The latter is not (directly) volatilised as NH_3 thus this may reduce N-emission. This option is discussed in paragraph 2.4.
Digestibility of nutrients, including CP and AA, is the resultant of an interaction between the animal and the feed ingredient. It is affected by factors such as animal's age and physiological status, and diet composition and ingredient characteristics, including the levels of protein and fibre and how they interact. A large variation exists in digestibility between feedstuffs. For example, the (total tract) protein digestibility of SBM is 87%, while that of an alternative protein source, rapeseed meal (RSM), is 74%. For the animal even more relevant is the ileal protein digestibility (standardised for feed-intake related endogenous losses), which is 92 and 74%, for the former ingredients respectively (CVB, 2023a). The result is that the dietary CP-level can be lower when using SBM instead of RSM as one of the main protein sources, without effect on the nutritional value in terms of supply of protein and amino acids. Such differences in ingredient use can have a direct impact on N-efficiency, without affecting TAN excretion in a quantitative way, assuming that pigs are fed to their (CP/AA) requirements.
The former can be illustrated using the following example. Consider two identical theoretical diets that differ only in protein (N) digestibility. The first diet has an ileal and total tract protein digestibility of 85% and 90%, respectively, whereas the second diet has digestibility values of 68% and 72%, respectively (i.e., both 20% lower on a relative basis). To provide the same amount of digestible CP and AA, the dietary CP content of the second diet must therefore be approximately 25% higher. As a consequence, N-efficiency is reduced by 20% when the low-digestibility diet is used, and faecal N excretion increases substantially (the exact increase depends on the difference in faecal protein digestibility between diets). However, because post-absorptive utilisation of digested CP is assumed to be identical, urinary TAN excretion remains unchanged in absolute terms. Expressed relative to N intake, urinary TAN excretion is 20% lower for the low-digestibility diet. Alternatively, if dietary CP content was maintained at the level of the highly digestible diet, pigs would need to consume approximately 25% more feed to meet their CP and AA requirements.
It is often considered that all digested AA are available for the animal's metabolic utilisation. This is, however, not always correct. Available AA can be used by pigs for their maintenance or protein deposition. Batterham (1992) and Officer et al. (1997) considered that digestibility does not reflect AA availability, at least not for lysine, methionine, threonine, and tryptophan, which they contributed to an effect of heat-treatment. For lysine an analytical method has been developed to correct for this deviation, the "reactive lysine" method. Applying results obtained with this method for heat-treated ingredients resulted in a better estimate for availability (Rutherfurd et al., 1997). To maximise N-efficiency, this aspect must be considered, as absorbed but unavailable AA will be catabolised into urea. Another point was raised by Levesque et al. (2011), who measured a higher threonine utilisation by sows than expected based on ileal digestibility data, which are obtained in growing pigs. They contributed this to a greater capacity of sows to digest and absorb nutrients from feed ingredients than growing pigs. Formulating sow diets using ileal digestibility coefficients derived from growing pigs may lead to an overestimation of available protein and amino acids, thereby decreasing nitrogen efficiency.
Dietary protein digestibility by a pig can be influenced by different measures. The first and foremost, is the choice of ingredients. See the example of SBM and RSM above. The choice for specific ingredients is determined by their nutrient composition, their digestibility, and their costs, besides specific characteristics as the appearance of anti-nutritional factors. Anti-nutritional factors, as trypsin inhibitors and phytate, often reduce protein digestibility. Their effect can be reduced by, e.g., heat-treatment or dietary supplementation

with enzymes as phytase (which degrades phytate). Such treatments are commonly used at present, thus offer little space for further improvement of CP digestibility. The development of other enzymes, as proteases that digest (otherwise not-digested) proteins, or (mixtures of) specific carbohydrases that unlock proteins from the fibrous matrix in some ingredients, may slightly improve protein digestibility. This is, however, a long-term opportunity. Dietary supplementation with specific acids, as formic or benzoic acid, may improve performance but also N-digestibility (Eckel et al, 1992; Bühler et al., 2006; Guggenbuhl et al., 2007). This is already applied in a part of pig feeds, but their use might be extended. However, the space to improve protein digestibility using these additives seems limited.
Ingredients having a high CP digestibility improve N-efficiency. Less N is excreted with faeces, but, assuming post-absorptive utilisation is not affected, it will not affect TAN excretion to a large extent, as this is mainly influenced by this utilisation (Figure 2). Conversely, ingredients having a low CP digestibility may result in a higher protein fermentation in the large intestine. The resulting higher NH_3-concentration and appearance of other end products of protein fermentation impair the intestinal barrier function, thus deteriorates intestinal health of pigs (Noorman et al., 2025a). Also, most of the NH_3 produced is absorbed and excreted as urea.
In summary, a lower CP digestibility results in a higher excretion of N in faeces. Faeces deliver less TAN than N excreted in urine. However, N-efficiency is also lower. To maintain animal performance, a higher dietary CP level or higher feed intake is required. This negates the possible reduction of NH_3-emission potential and makes pig production more expensive. Also, it may induce protein fermentation in the large intestine, which shifts N from faeces to urine and affects pig's intestinal health negatively. Inclusion of high-digestible CP ingredients improve N-efficiency, but, assuming no change of post-absorptive utilisation, it affects TAN-excretion little.

2.3.3 Reducing dietary protein level

Aarnink et al. (1993b) estimated by model calculations a 9% reduction of ammonium nitrogen content in manure when dietary CP is reduced by 10 g/kg. This was confirmed by Canh et al. (1998a), comparing three levels of dietary protein (165, 145, and 125 g/kg) in growing pigs. Each 10 g/kg reduction in crude protein content of the diet reduced the manure-ammonium content by a mean of 10% and NH_3 emission by 10 to 12.5%. The higher reduction of NH_3 emission was explained by a lower pH of the manure when dietary CP content was reduced.
A reduction of dietary CP-content is a logical way to reduce N-excretion, as it is a measure at the source: what does not come in, does not go out. However, it is only realistically feasible when it does not deteriorate animal performance and health. This was investigated in a large number of studies. Kies et al. (1992) fed diets containing 18, 15, or 12% CP in the grower period (25-60 kg), and 16, 13, or 10% in the finisher period (60-95 kg) to individually housed and fed pigs. The diets were balanced using (then commercially available) crystalline lysine, methionine, threonine, and tryptophan. Efficiency of N-utilisation increased with decreasing dietary CP-content, from 51 to 55 and 62% in the grower period, and from 53 to 61 and 65% in the finisher period, resulting in about 8% decreased total N-excretion per percent dietary CP reduction. Ammonia excretion was not measured. Animal performance was not significantly affected in the grower period, but in the finisher period the lowest CP-level resulted in a lower growth performance (about 6% lower average daily gain (ADG) and 3% higher FCR, relative to the highest protein diet), while the intermediate diet did not differ from the high-CP treatment. Although not significant, carcass muscle percentage was about 1% lower at the low-CP treatment as compared to the other treatments. In a fourth dietary treatment, with protein levels of 15 and 13% in the grower and finisher periods, a part of the protein was supplied as gelatine, which imbalanced the dietary AA profile apart from the four EAA mentioned. It resulted in a similar performance as the low-protein group, suggesting that AA other than these four were limiting. As expected, N-excretion was similar to the intermediate protein group, indicating it was determined by the protein-level.
A similar experiment was performed by Tuitoek et al. (1997). They tested three levels of CP, 16,14, and 12% in grower diets and 14, 12, and 10% CP in finisher feeds (formulated levels), and balanced the diet by supplementation of free AA to an assumed ideal protein. Performance was not significantly affected, with the exception of the lowest CP-treatment in the finisher period. They concluded that dietary CP can be reduced to about 13% in both grower and finisher diets of pigs, as long as free AA are added to match an ideal protein.
Since then, numerous studies have demonstrated the reduction in N-excretion and/or NH_3-emission by this approach, reviewed by, among others, Webb et al. (2014), Cappelaere et al. (2021a,b), and De Almeida et

al. (2024). Webb et al. (2014) reviewed six studies under U.K.-like conditions, in which the effect of a dietary CP-reduction on NH_3-emission was evaluated with dietary CP content ranging from 240 to 120 g/kg, without loss of growth performance of the pigs. On average, for each 10 g CP reduction per kg diet, N excretion was lowered by 8% of (range 7–10%) and NH_3-emission by 8% (range 2–10%). Cappelaere et al. (2021a) included 27 studies in a meta-analysis and reported a reduction of N excretion and NH_3 emission by 8% and 10%, respectively, per 10 g/kg reduction of the dietary CP content. Moreover, this study demonstrated a much larger reduction of N-excretion in urine than in faeces: 10 and 3%, respectively (Figure 5). The effect on NH_3 emission is presented in Figure 6. Of relevance for practice, this figure shows no difference between individual or group-housed pigs. In this type of N-balance experiments, animals were often housed individually. These results are in line with Sajeev et al. (2018), reporting a reduction of TAN excretion of 8% and NH_3 emission of 11% per 10 g/kg reduction in dietary CP-content. As a consequence, the proportion of N excreted as urea is reduced by about 2.5 percentage points per 10 g/kg CP reduction.

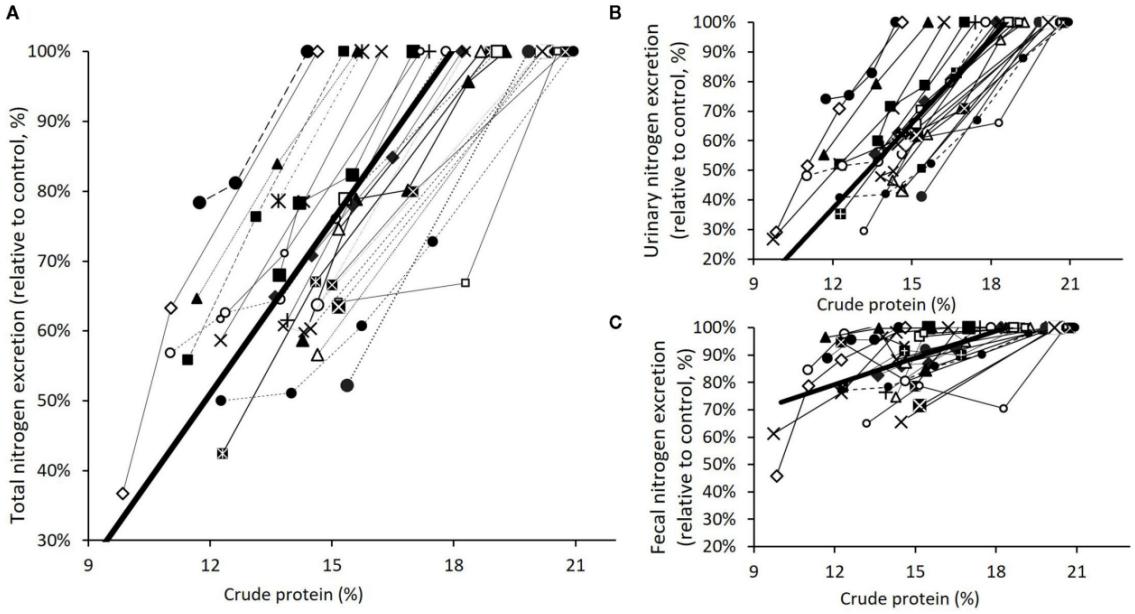


Figure 5 *Meta-analysis of the effect of dietary crude protein reduction on nitrogen excretion in pigs: total excretion (A), urinary excretion (B) and faecal excretion (C) as observed in individual studies considered in a meta-analysis; the black solid line represents the mean relationship over studies (Cappelaere et al., 2021b).*

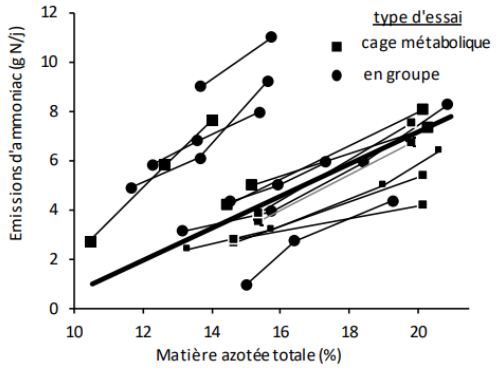


Figure 6 *Meta-analysis of the effect of dietary crude protein reduction on NH_3 emission in pigs individually housed in metabolism cages or in groups as observed in individual studies considered in a meta-analysis; the black solid line represents the mean relationship over studies (Cappelaere et al., 2021a).*

Most of these studies included diets containing between 12 and 20% CP and reported that pig performance was not affected at lower CP-content, if diets contained a properly balanced AA-profile by supplementation with free AA. Nonetheless, Cappelaere et al. (2024) suggested that a diminishing response might be observed at low dietary CP content, i.e., 15.0 and 13.8% in the grower (28-48 kg BW) and finisher (48-80 kg BW) periods, respectively. In their study such an effect seems mediated by an increase in daily feed intake of low protein diets. This effect would be absent in nutrient balance studies in which pigs are fed according to a fixed feeding scheme. This requires attention in future research. Different authors found that performance degraded when the CP-level was lowered by about 4%-units as compared to the positive control applied, despite diets were at least balanced for lysine, methionine, threonine, and tryptophan. Especially for piglets (<20 kg BW) large effects were found, up to 34 and 26% worse ADG and FCR, respectively (Nyachoti et al., 2006; Gloaguen et al., 2014). For grower pigs (20 – 50 kg BW), reducing CP-level from 18 to 13% deteriorated ADG and FCR with about 8 and 9%, respectively (Powell et al., 2011; Roux et al., 2011), and in finisher pigs (75-95 kg BW) a CP-reduction from 15 to 10% resulted in a worse ADG (about 17%) and FCR (about 13%, mean values of 2 treatments; Zhang et al., 2016). Their conclusions are also relevant given the actual dietary protein contents in Dutch diets for pigs, which is, weighted over the whole growth period, below 15% (Table 1).

A review by De Almeida et al. (2024) confirmed these results. Lowering dietary CP levels often resulted in a deterioration of growth performances, unless diets were properly balanced by supplementation of free AA. This would allow a CP-reduction of 2-5%-units, which could be interpreted as an overall reduction to about 15% CP. However, they stress there is an important difference between growth phases (piglet, grower, and finisher phases). Piglets are subjected to stress factors, such as weaning, the transition from milk to solid feed, and adaptation to different facilities and group-members, while their immune system is still underdeveloped. The latter results in a relatively high protein requirement, with a specific AA composition. Also, the relatively large body protein synthesis in young animals results in a high protein demand to be supplied via the diet, while at the same time their feed intake capacity is relatively limited. In experiments, the effect of CP-content reduction on growth performance of piglets was variable, because of the factors mentioned, but also due to the effect of using different crossbreds, sexes, and housing and environmental conditions, apart from the dietary protein interventions. However, without supplementation of free AA, growth performance reduces at a CP level below 15 to 17%. With supplementation of free AA, a lower CP-level could be realised without affecting performance (De Almeida et al., 2024). For example, reducing the CP-level from 17.6 to 15.6 and to 13.5%, but with supplementation of 9 different free AA's, Gloaguen et al. (2014) observed no reduction of growth performance, but performance reduced at about 12% CP in the diet. Interestingly, dietary supplementation with glutamic acid, an AA considered non-essential, restored performance. In an accompanying balance experiment, decreasing CP-level from 19.7 to 16.8, 14.0, or 12.7%, they measured 29% lower N-excretion at the 16.8%-diet, compared to the 19.7%-diet, due to a higher N-utilisation efficiency. However, ADG and FCR degraded linearly, decreasing N-retention, which resulted in no further improvement of N-efficiency. Millet et al. (2018) showed in an experiment using six levels of CP (14-19%) and two of standardised ileal digestible (SID) lysine (10 or 11 g/kg feed) that growth performance decreased at a CP level below 17 or 16% at the lower and higher lysine level, respectively. The highest performance was not realised at the diet showing the highest N-efficiency. They suggested that at low levels, CP itself could be limiting for performance, rather than lysine and the other EAA. Thus, NEAA became limiting. They hypothesised that dietary NEAA may be more efficiently used than NEAA synthesized by the animal via transamination of AA.

With progressing age/weight mentioned factors gradually lose impact, so in the finisher phase a reduction of the dietary CP-level, down to about 12% CP, would be feasible without affecting pig performance (De Almeida et al., 2024). Zhao et al. (2019) studied lower protein contents, with their control diets containing 17.5, 16.0, 14.5, and 13.0% CP, for the phases 25-50, 50-75, 75-100, and 100-125 kg BW, respectively. With balancing of all EAA, 2 or 4%-units CP reduction did not deteriorate performance or slaughter characteristic and meat quality. Nitrogen utilisation was higher at the low CP-treatment, and excretion decreased (about 10% per 10 g CP/kg diet). However, not balancing with all EAA resulted in up to a 5% lower ADG and 10% higher FCR.

In most studies mentioned, low CP diets were supplemented with a number of free AA, to maintain animal performances. At present, in Dutch practice up to six free AA (lysine, methionine, threonine, tryptophan, valine, and, for piglet diets, isoleucine) are regularly used. Dietary CP contents can be lowered to a level where the next AA becomes limiting. If it is possible to supply the next limiting AA in a free form, it might be possible to reduce the CP contents even further, without deteriorating pig performance. Given that there are

ten EAA, the availability of the remaining four in free form could allow a further reduction in CP until all EAA become limiting, provided that NEAA do not become limiting. In the EU, presently nine of the ten EAA are registered as nutritional feed additives (EC, 2025). Their application allows further reduction of dietary CP contents, but at present they are relatively expensive for use in commercial diets, and their use may increase the feed costs and affect economics of pig farming. The potential to reduce dietary CP contents by free AA other than the first six mentioned above, and the effect on feed costs, will be further discussed in section 4.3.

In summary, this review concludes that the dietary CP-level can be reduced to a level below 15% for growing pigs without degrading growth performance, if the AA-profile is properly balanced. This results in a higher N-efficiency and, consequently, in lower N-excretion. The minimum concentrations in the diet, at which this reduction does not affect performance negatively, differ for the different age-groups and animal categories. The minimal CP level achievable is, however, unclear from literature. Based on a meta-analysis and applying a broken-stick model, Rocha et al. (2022) considered the minimum CP-level of AA-balanced diets which does not compromise performance (ADG and FCR) is 18.4, 16.2, and 11.5% for nursery, growing, and finishing pigs, respectively.

2.3.4 Further reducing dietary protein level – how far can we go?

The findings discussed in the previous section raises the question: to which level could dietary CP be reduced, without affecting growth performance of pigs negatively. This question is investigated in the present section, by means of some theoretical calculations.

Millet et al. (2018) calculated the N-efficiency of pigs using data from Belgian pig-production practice. For growing pigs, from weaning to slaughter (at 8 and 110 kg BW, respectively), they estimated an N-efficiency of pigs of 46%, and for sows (+ piglets until weaning) of 24%. The combined N-efficiency for sows and their progeny till slaughter weight was calculated at 43%. Applying the same methodology using data of Van der Peet-Schwering and Bikker (2018) and the CVB (2023b), values for N-efficiency of pigs are calculated at 43% (from weaning till slaughter; mean of three sexes), at 22% (sows and their litters till weaning), and at 41% for sows and their offspring until slaughter. Further details on the calculations are given in Appendix 1. These values are based on data from individual pigs. The differences between the calculations of Millet et al. (2018) and those presented here are primarily explained by the different assumed slaughter weights (110 vs. 125 kg BW) and, potentially, by differences in pig genotype. It is well established that with increasing age and BW, N-efficiency in pigs decreases.

In a next step, using growth performance data of pigs as given by the CVB (2023b), we estimated the theoretical relationship between N-efficiency of pigs and the N-excretion for three sexes of animals, boars, barrows, and gilts (25-125 kg BW). Assuming an overall average dietary level of 15% CP, thus weighted for the three phases (start, growing, and finishing phase), N-utilisation was calculated at 44, 39, and 41% for the respective sexes, coinciding with a total N-excretion (via faeces and urine) of 3.2, 3.9, and 3.7 kg N/animal, respectively. In section 3.1 it will be examined further whether these differences between the sexes can be used advantageously to reduce N-excretion from pig production.

Besides the aforementioned calculations, a factorial approach was taken to estimate the relationship between dietary protein requirements, N-efficiency, and related N-excretion. This approach includes that CP-requirements for maintenance and for body protein deposition (growth) are calculated separately and summed to obtain a total dietary protein requirement over the entire production period. This results in an estimation for a minimum dietary CP-level required for realisation of an assumed growth performance over the production period. Growth performance data were taken as before (CVB, 2023b) to calculate body protein retention of each of three animal sexes in the respective production periods. Data on the protein requirement for maintenance purposes, i.e., for skin and hair losses, inevitable N-losses related to body protein turnover, and basal intestinal protein losses, were taken from Van Milgen et al. (2008) and NRC (2012). The basal assumptions for these calculations are further given in Appendix 2. Protein utilisation efficiency for maintenance is relatively constant, whereas the efficiency of N utilisation for body protein deposition (the main component of growth) varies considerably. Because non-utilised N is excreted largely as TAN, this factor has a major impact on N excretion. Accounting for variation in utilisation efficiency yielded mean dietary CP requirements for each of the three sexes and enabled estimation of N-efficiency, N-excretion, and their relationship throughout the production period (25–125 kg BW), as shown in Figure 7.

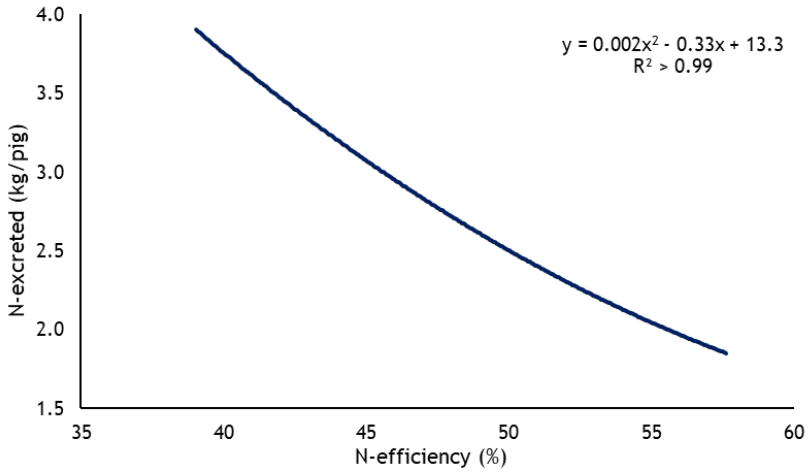


Figure 7 *The relationship between the overall N-efficiency and N-excretion in pigs (25-125 kg BW). The N-efficiency values are based on calculations for the three sexes of pigs, varying the values of post-absorptive N-efficiency for body protein deposition from 60 to 90%. Details on the calculations are provided in Appendix 2.*

Figure 7 shows clearly that improving N-efficiency in pigs reduces N-excretion. The value for N-efficiency can be linked to post-absorptive (metabolic) N-efficiency of body protein deposition. According to the calculations presented here, this value is estimated at about 64% for present-day boars and somewhat lower for barrows and gilts. The NRC (2012), however, indicates a value of about 74%, although not providing details of the background of this value. Assuming that the growth performance of pigs would not be changed and if this value could be improved from 64 to 74%, the mean dietary CP-content could be reduced by 16 g/kg, and N-excretion by about 18% compared to the reference scenario. Results of these model calculations are presented in Table 2. For barrows and gilts, similar shifts were observed as for boars.

Table 2 *Calculations on the effect of changing the post-absorptive (metabolic) efficiency of N-utilisation for body protein deposition on required dietary protein level, N-efficiency, and N-excretion of growing boars (25 – 125 kg BW).*[1]

Metabolic N-efficiency for protein deposition (%)	Required dietary CP-level (g/kg)	N-efficiency (%)	N-excreted (kg)
60	159	41.5	3.53
64 (current)	150	43.9	3.21
70	140	47.2	2.81
73.5 (NRC, 2012)	134	49.1	2.60
80	125	52.5	2.27
90	114	57.6	1.84

[1]The dietary CP-level mentioned is an overall value for the entire growth trajectory, thus weighted for consumption of starter, grower, and finisher diets.

It is important to note that metabolic efficiency of ileal digestible protein (N) for body protein (N) deposition is both genetically determined and influenced by optimisation of dietary CP and AA supply relative to the AA requirements of growing pigs. The genetic component of body protein deposition is strong: Verschuren et al. (2021) estimated the heritability at 0.21-0.27 and a review (Kasper, 2024) mentioned that a value as high as 0.54 has been reported. The theoretical efficiency values of 80 and 90% (Table 2) are only included for reference, as they are unlikely to be achievable in practical conditions. Further, these calculations assume a similar ileal protein digestibility for diets of each of the different growth phases and a constant body composition in terms of proportion of protein in body mass at different body weights of these pigs. These assumptions all influence the results of these model calculations, but they require more in-depth study for refinement. Such a theoretical approach can be used to estimate an "absolute minimal" dietary CP level

which would allow the realisation of a given growth performance, with minimal N-excretion and, subsequently, low NH_3-emission potential. Although such minimal values are unlikely to be realised in practice of pig farming, they can serve as an objective when developing new feeding strategies targeting maximum N-efficiency and low N-excretion.
Thus, there seems to be potential to further improve N-efficiency of growing pigs and consequently reduce the dietary CP level and N-excretion, if the post-absorptive (metabolic) N-efficiency can be improved. If latter value can be raised to the level suggested by the NRC (2012), N-excretion may be reduced by about 18% as compared to the current situation.

2.3.5 Sows and piglets

So far, we mainly discussed dietary measures and N-efficiency in relation to growing pigs. As Millet et al. (2018) showed for the Belgian conditions, and our calculations confirm that in Dutch conditions, sows (with piglets up to weaning but simply called 'sows' here) use N considerably less efficient than growing pigs (25-125 kg BW). Although there may be some opportunities to slightly improve N-efficiency of sows as will be shown in the section 3.3, it will not be discussed in great depth for reasons outlined below.
Of all pig feed, about 67% is for growing pigs (25-125 kg BW), 13% for piglets (weaning to 25 kg BW), 3% for rearing sows, and 17% for sows (CBS, 2025). Any improvement in N-efficiency of growing pigs is most influential for total N-excretion in Dutch pig farms. Piglets utilise N generally very efficient with a value of about 60%, calculated according to the methods applied in section 2.3.4. This value might be improved further, following a similar approach as mentioned for growing pigs. However, it should be noted that especially shortly after weaning, these piglets are prone to health disturbances, and targeting optimal nutrient supply and preventing any nutrient deficiency in these young animals is key.
Considering the N-efficiency values calculated in section 2.3.4, 43% for growing pigs from weaning till slaughter and 22% for sows and their litters till weaning resulted in a combined value of 41%. The lower value for sows carries less weight due to the high number of piglets per sow. Although improvement of N-efficiency of sows is feasible by optimising the dietary AA balance, this is hampered by the limited availability of information about the ideal AA composition of CP for sows as compared to growing pigs. Generation of more information on this aspect is required. Generally, however, responses of dietary interventions on sow performance (number of cycles and number of piglets raised per cycle and their BW gain) are more variable than effects on growth performance in growing pigs. A possibility to improve N-efficiency of sows is to introduce two feeding phases for gestating sows (phase feeding is discussed in section 3.2). About 65% of the sow feed is consumed during gestation. In the first 2/3 part of the gestation period, dietary protein is mainly used in the body for maintenance purposes, as maternal, uterine, and foetal growth is still low (Dourmad et al., 2008). In the last third of the gestation period, however, CP requirements increase due to the faster growth of the foetuses. Low dietary CP concentrations fulfil the sow's protein requirement in the first part of gestation. As it is presently common practice to feed just a single diet during the entire gestation period there is a relatively high protein supply (N-excess) in the first part of gestation, as it is formulated to cover the protein and AA requirements over the last part of the gestation period. Although the dietary CP content of gestation diets is usually low, introducing a second gestation diet may offer an opportunity to improve N-efficiency of sows. In lactating sows, however, on the one hand, care has to be taken to reduce the CP contents, as protein requirement of sows for milk production is high. Hampering maximum milk production of the sow may affect growth and health of the piglets in the litter, as briefly discussed in section 3.3. On the other hand, lactating sows are usually fed individually, opening options to feed them according to precision feeding principles (section 3.3), which has a large potential to improve N-efficiency.

2.3.6 Effect on other factors

can have other (positive and negative) effects which must be considered. According to De Almeida et al. (2024) positive effects include a (slightly) improved energy utilisation, reduced (post-weaning) diarrhoea, improved health, and an increased intramuscular fat content. An example of a negative effect is related to the effect on animal harmful behaviour. Van der Meer et al. (2017) observed an increase of tail-biting behaviour by growing pigs fed a low CP, slightly AA limiting diet. The effects could be limited, but not avoided, by dietary supplementation of three EAA (methionine, threonine, and tryptophan). Recently, Minussi et al. (2023) showed that such behaviour could be avoided by dietary supplementation of eight EAA to a diet with a (weighted) CP-level of about 13.0%. Although differences in experimental objectives and design may

be interfering factors, from these studies it appears clearly that low CP diets, with increased risk of AA limitation or deficiency, can induce unwanted behaviours, which can be alleviated by supplementation of a targeted mixture of EAA.
To supplement low-CP diets with free AA to match the pig's requirements, it is essential that all essential AA are available as nutritional feed additives. As mentioned before, nearly all EAA are registered as feed additives at present in European Union Register of Feed Additives (EC, 2025). They are, however, relatively expensive and may increase feed costs. This will be explored in section 4.3. Yet another negative aspect is that increasing N-efficiency will result in incorporation of high-quality-high CP ingredients (ingredients with a high CP-content, a high protein digestibility, and a balanced AA-profile) into feed. This may hamper using of by-products, e.g., originating from processing of crops. Use of such ingredients in animal diets is important when moving towards animal production systems with even more attention for sustainability and circularity of production chains.

2.4 Dietary measures

2.4.1 Improving N-utilisation by optimising the AA-profile

From the foregoing it is clear that N-emission can effectively be reduced by improving the pig's N-efficiency, allowing a lower dietary CP content, while maintaining animal performance, health, and product (meat) characteristics. Regarding the nutritional aspect, it requires optimising the post-absorptive AA profile, to maximise their metabolic utilisation in organs and body tissues. The first aspect, changing digestibility of dietary protein, will be discussed in section 2.5. Matching dietary AA supply with the animal's AA requirements improves N-utilisation. The dietary AA profile can be optimised, for example via dietary supplementation of specific free EAA. This results in a lower requirement for dietary CP, as will be discussed in section 4.3. Minimal N-excretion can be achieved by maximisation of N-efficiency. It requires further balancing of the dietary supply of AA with the animal's AA requirement.
Theoretically, supplying ideal protein results in maximal utilisation of AA: exactly the right amount of a specific AA is supplied via the diet at the right moment in time at each location (tissue) of the pig's body to be incorporated in any of the specific proteins synthesised in the tissue. As Van Milgen and Dourmad (2015) indicated, however, AA-requirements are not constant, thus the AA composition of ideal protein is not a constant 'book-value'. Consequently, published ideal protein AA profiles for pigs vary considerably (e.g., Boisen et al., 2000; Van Milgen and Dourmad, 2015). A potential limitation of currently applied ideal protein profiles is that they are usually derived using diets containing >15% CP. The optimal AA profile might differ when further reducing the dietary CP level.
Maximisation of N-efficiency requires a very good understanding of the dietary CP and AA supply potential, and of the animal's AA requirements. The nutritional value of many feedstuffs, including the AA composition and their (standardised ileal) digestibility, is rather well established, although variation on both characteristics exists. Much is known about the animal's AA requirement, but this aspect needs further refinement. Ideal protein profiles are available and used satisfactorily, but they are limited to EAA and not primarily aimed at maximising N-utilisation. Elevating N-utilisation requires improved knowledge on the metabolism of AA in the pig. A serious limitation is that current AA-requirement values were usually defined using diets with, compared to current standards, moderately medium to high CP levels. In part, this is related to the design of such experiments, as, to estimate the requirement of one AA, the other AA needs to be supplied at a non-limiting level. For example, Van der Peet-Schwering et al. (2020a) performed an experiment to validate new CVB-recommendations for SID lysine levels in growing pig diets. The overall (weighted) CP level in the study was 17.5-18.5%, about 5%-units higher than the indicated long-term target of 13% for Dutch pig diets as mentioned by the PLB (2020; Table 1). The dietary CP level may affect the order of limitation of individual AA and thus the composition of ideal protein. Therefore, optimal dietary AA ratios to maximise AA and N-efficiency must be also investigated with diets with relatively low CP levels, i.e., at levels at or below the ones mentioned as long-term target for the dietary protein level for pigs by PLB (PLB, 2020; Table 1).
The ideal protein concept is generally used in feed formulation for the past decades. It allowed a large improvement of N-efficiency and, related, allowed a reduction of the dietary CP content over the years (Table 1). This resulted in lower N-excretion per pig over time. Further improvement of N-efficiency, necessary to realise the long-term targets in dietary protein content (Table 1), requires further optimisation of the ideal

protein concept. This is a multi-facetted issue. Animal characteristics such as sex, genetic potential for protein deposition (lean growth), and actual growth performance in a certain environment may affect the AA composition of the ideal protein profile. Also, throughout the growing period this profile seems to be dynamic, as suggested by Zhang et al. (2013). These authors hypothesised also that the ratio between EAA relative to lysine may be different when diets contain a (very) low CP-level compared to normal or high CP diet. They observed considerable differences, but this aspect has been hardly investigated. Therefore, studies to measure AA requirements using (very) low dietary CP contents are needed. Similarly, under low dietary CP conditions, knowledge is lacking on the impact of the dietary EAA/NEAA ratio and on differences in absorption kinetics of individual AA from the digestive tract on the optimal AA profile for a given objective, e.g., maximal N-efficiency. Finally, the effects of specific AA or mixtures of AA on animal health and behaviour in different environmental conditions (e.g. sanitary and temperature conditions), may affect the ideal protein profile as well.

At present, the ideal protein profile considers balancing the ratio among individual EAA relative to lysine. Together with the requirement for the first limiting AA, usually lysine, this defines the dietary AA levels. However, when pigs fed low protein diets ingest the exact amounts of EAA required for optimal growth performance, probably by including extensively free AA, the amount of NEAA may become limiting. In classical feeds, with CP-levels >15%, this is usually not the case. Therefore, NEAA are not included in the ideal protein composition. However, in low CP diets, there may be an insufficient supply, or an insufficient amount of EAA available in the pig's metabolism to synthesise adequate amounts of NEAA. At present, an implicit assumption is that sufficient amounts of NEAA can be synthesised by the animal itself from other AA or precursors, which may not be the case when feeding low CP diets. Consequently, NEAA can become limiting. This may affect animal's performance and/or health status negatively, as some of these NEAA perform essential functions in metabolism, and even result in a higher N-excretion. The dietary NEAA supply may even be more important if they are more efficiently used in metabolism than AA synthesized by transamination in other metabolic pathways, as hypothesised by Millet et al. (2018). However, Lenis et al. (1999) did not observe such a lower efficiency when the dietary EAA:NEAA ratio was as high as 70:30. When the EAA:NEAA ratio is high, the efficiency of utilisation of EAA is lower (Heger et al, 1998).

For these reasons, to maximise N-efficiency, dietary NEAA supply needs to be taken into consideration, besides that of EAA (Heger et al., 1998; Boisen et al., 2000), and it has been suggested to consider this in feed formulation (Wu, 2014; Millet et al., 2018). To realise this, a new ideal protein profile must be defined. This requires a better knowledge of requirement of all 20 AA, thus including NEAA (Wu et al., 2013), their digestibility and metabolic utilisation, and their requirement for maintenance purposes and for body protein deposition. The ratio between the dietary amounts of (digestible) EAA and NEAA to maximise N-efficiency was found to be about 50:50 by Wang and Fuller (1989) and Lenis et al. (1999). The latter noted that at lower dietary CP-levels the ideal ratio, as well as its relevance, increased. Heger et al. (1998) and Boisen et al. (2000) argued that expressing the EAA-requirement is preferably expressed relative to the total dietary N-content (TN), rather than in relation to NEAA. This implies that mentioned values are slightly lower, about 47% for EAA:TN, as TN comprises NPN. The highest N-retention was measured by Heger et al. (1998) at an EAA:TN ratio of 48% (or lower) when growing pigs were fed at a constant EAA-N level, but the highest N-efficiency they observed at a ratio of about 65%. They attributed this to a 'sparing effect' on the utilisation of EAA. Similarly, Camiré et al. (2023) concluded that the ratio EAA-N:TN affects the ideal protein composition. Dietary CP level (N-intake) and age (body weight) affected N-utilisation and the ideal EAA-N:TN ratio, besides the ratio between individual EAA.

In summary, reducing CP levels to or below those indicated as long-term targets (Table 1; PBL, 2020) to reduce N-emission does not seem possible without affecting performance negatively, unless a dietary AA-balance and supply is realised to cover pig's AA requirements for the production objective as closely as possible. This can be achieved by supplementation of the diets with free AA. However, to support N-efficiency maximally and to minimise N-excretion, current ideal protein concept must be extended to include NEAA as well. The dietary AA balance varies with N-intake and BW, and depends on, among others, animal genetics and the animal's health status. Also, it is affected by the production objective (e.g., high N-efficiency, or supporting health status of animals). Ideal protein must be defined considering such factors. Possible limitations to this approach are discussed in section 4.1.

2.4.2 N-excretion as microbial protein

Use of diets with ingredients with a relatively low protein digestibility at faecal level results in a higher amount of N excreted in faeces. Faeces contain much less TAN than urine, as most N is present in organic form. During storage of manure some mineralisation may occur, but the process involved is slow (Velthof et al., 2012; Van Boxmeer et al., 2024). This is in contrast with urinary TAN; the breakdown of urea in urine to ammonium (NH_4^+) and carbon dioxide starts immediately after contact with faeces. For this, the action of enzyme urease, produced by the faecal microbiome is required. Within 24 h, all urea in manure may be converted into NH_4^+ (Van Boxmeer et al., 2024). Separation of faeces and urine slows the rate of the conversion process down but does not completely prevent it, as urease-producing bacteria are also present on the floor and walls of pens in which pigs are housed. This was confirmed by Aarnink et al. (1997), who showed that less fouling of the barn floor resulted in a lower NH_3-emission.
Another method to direct excess of N to faeces, rather than to urine, is to incorporate N in the large intestine, originating from ileal digesta and from flux of urea into the intestine, into bacterial protein by stimulating bacterial fermentation (Bakker et al., 1998). Bacterial biomass is finally excreted via the faeces. Bakker et al. (1996) observed a net appearance of N in the large intestine with reduced N-excretion in urine when raw potato starch was included to the diet to stimulate microbial fermentation. Several other studies reported a reduction in N excretion in the urine with increasing dietary fermentable fibre content. Kreuzer and Machmüller (1993) found that inclusion of 10 to 22% fermentable substrate in pig diets reduced urinary N-excretion from 39 to 35% of daily N intake. Canh et al. (1997) found a decrease in the urinary to faecal-N ratio from 3.8 to 1.2, with increasing the dietary non-starch polysaccharide (NSP) content from 14 to 31%, while apparent faecal N digestibility decreased from 85 to 75%. Lynch et al. (2007) reported a decrease in the urinary to faecal-N ratio from 5.1 to 3.9 and from 4.4 to 3.2, with inclusion of 12.5% chicory inulin in diets with 20 and 14% CP, respectively. Zervas and Zijlstra (2002) observed a reduction in the urinary N-excretion as proportion of total N-excretion of approximately 20% by inclusion of 15% soybean hulls or 20% sugar beet pulp. Combining different studies, Jongbloed (2001) found a clear curvilinear decrease in urinary to faecal-N ratio with increasing dietary NSP content (Figure 8). It seems possible to shift N-excretion from urine to faeces by inducing fermentation in the large intestine by incorporation of fibrous materials, which reduces the amount of TAN. This may coincide, however, with lowering of N-digestibility. For example, by inclusion of 7.5 or 15% barley-fibre to a barley-SBM-based grower pig diet, Partanen et al. (2007) measured significant lower ileal and total tract N-digestibilities. Increasing the fermentable substrate content in the diet from 10 to 22%, Kreuzer and Machmüller (1993) observed a reduction of N-retention from 41 to 38% (relative to N-intake) and of ADG from 630 to 570 g, while FCR increased from 3.09 to 3.36. Lynch et al (2007) also found a lower N-retention at a higher dietary NSP-level, but results were variable, as Canh et al. (1997) and Zervas and Zijlstra (2002) even found a higher N-retention. The latter authors tested the NSP-inclusion at two dietary CP levels. They concluded that a reduction of dietary CP reduced urinary-N excretion, that fermentable fibre shifted N-excretion from urine to faeces, and that these effects are additive.

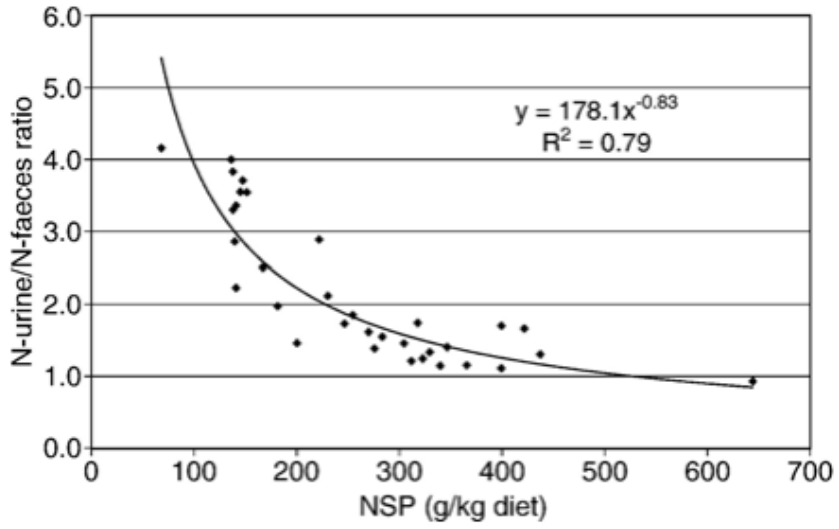


Figure 8 *Relationship between NSP content of the diet and the urinary-N/faecal-N ratio (Jongbloed, 2001).*

In an experiment by Ngoc et al. (2021), inclusion of 25% maize-DDGS, brewer's grains, or coconut cake as fibre sources decreased NH_3-emission from manure with approximately 5, 21, and 25%, respectively (mean values 20-70 kg BW), as compared to a low-fibre control diet. However, ADG decreased with 1, 10, and 12%, and FCR increased with 2, 11, and 11%, respectively, while methane (CH_4) emission from manure was significantly higher, especially for the coconut cake treatment (84 and 37% in the grower (20-40 kg BW) and finisher (40-70 kg BW) period, respectively). Similarly, Lashkari et al. (2025) observed higher CH_4 emission when diets were fortified with different types of fibre for piglets, growing pigs, and gestating and lactating sows. In that study NH_3-emission was not measured. Finally, higher dietary fibre levels may reduce NH_3-concentrations and other products of protein fermentation in the animal's digestive tract, which is, in some studies, associated with improved barrier function of the gut, supporting animal health (Noorman et al., 2025b). This aspect requires further investigation.
In summary, elevating the level of dietary fibre may shift a part of the N-excretion from urine to faeces, reducing TAN and subsequent NH_3-emission. This fits well with increasing the use of plant derived by-products from the food industry, which often contain higher fibre levels. On the downside, it may result in a higher emission of CH_4, a lower faecal CP digestibility, and, depending on the feed formula, reduced animal performance.

2.4.3 Reduction of ammonia formation, urease inhibition

Nitrogen in urine of pigs is mainly present as urea. Urea is converted to TAN by urease, an enzyme produced by many bacterial species. Although faecal bacteria are most active in this respect, faecal contact is not strictly required to initiate urea degradation by urease. The enzyme already appears in urine during urination, and upon contact of the urine with the pen floor or soil, although in lower concentrations and amounts (Aarnink et al., 1997; Vaddella et al., 2010). Interestingly, the urease activity in faeces appears animal-species dependent: it is more than 2-fold higher in faeces from pigs than from beef cattle (Dai and Karring, 2014). Inhibition of urease reduces the conversion of urea to NH_3, thus may effectively reduce NH_3-emission from manure. Numerous compounds that could act as urease-inhibitors are known, both chemical molecules (currently not approved as feed additives in the EU) and natural products, such as garlic-extract and flavonoids. Although not aimed at application in animal feeds, Matczuk and Siczek (2021) reviewed that chemical inhibitors are up to 75% more effective than allicin, an active molecule in garlic-extract. The most effective concentration of allicin to reduce urease activity was 5% relative to the urea concentration on a weight basis. Such a ratio between inhibitor and substrate in urine cannot be obtained by feeding of a garlic extract to pigs.
In animal feeding, dietary application of *Yucca schidigera* extracts (YSE) as a urease inhibitor is promoted. Reported experimental results do, however, not show clear reductions of NH_3-emission in pigs. For example, Colina et al. (2001) observed that YSE reduced NH_3-emission by 22% in a pilot experiment, but 7% in their larger follow-up experiment. On the contrary, Panetta et al. (2006) did not find an effect of YSE in the diet on NH_3-emission in pigs. Interestingly, Kemme et al. (1993) showed that dietary YSE affected the rate of NH_3-emission from pig manure, which was highest when YSE was supplied at 6-fold the recommended dose. After less than one day, differences between treatments disappeared, thus YSE application did not have an advantage anymore over the control treatment. These authors suggested that the effect of YSE would rather be due to binding of NH_3 than to urease inhibition. Based on an extensive literature review, Veraart et al. (2022) concluded it is unlikely that dietary YSE supplementation reduces NH_3-emission substantially (>20%) from livestock environments, although some studies indicate a potential for a limited reduction.

2.4.4 Reduction of ammonia volatilisation

A method to reduce NH_3-emission from manure is to increase its acidity (reduce its pH). It has a two-sided effect: it reduces the activity of urease, and it shifts the chemical balance between ammonium-ions (NH_4^+) and NH_3 in the solution towards ammonium, thus releasing less gaseous NH_3. The relationship between pH and temperature on NH_3-emission is shown in Figure 9.

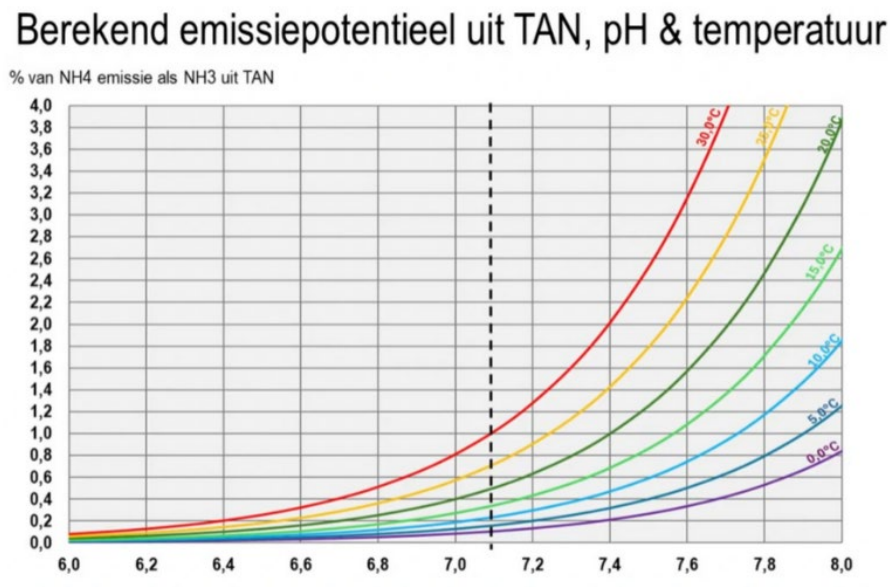


Figure 9 *The effect of pH and temperature on NH_3-emission potential from manure-TAN. Calculated with a model by VanHoof, cited by De Heij (2025). Actual emission rate depends, also, on factors such as air speed and surface area of the manure (Van der Zee, 2025).*

One way to realise manure acidification is by increasing the dietary fibre content. During fermentation of organic matter from the diet in the pig's large intestine or in the manure pit, short-chain fatty acids (acetic acid, propionic acid, and butyric acid) are produced. In slurry from pigs fed a diet containing 30% sugar beet pulp, Canh et al. (1998) measured a nearly 1-unit lower pH than in slurry from pigs receiving a grain-based diet. The concentration of short-chain fatty acids was 80% higher in manure, the urinary-TAN content was 37% lower, and more faeces and less urine was produced. Similar results were obtained by Jarret et al. (2012). They observed that increasing crude fibre level from 29 to 49 g/kg diet increased the faeces to urine weight ratio, decreased slurry pH from 9.2 to 8.7, and reduced NH_3-emission from slurry over a 16-days period with 31%. Alternatively, fibrous materials are directly added to slurry in the manure pit as substrate for microbial fermentation. Such an intervention is, however, beyond the scope of current study.
Another approach to reduce urinary pH is by dietary supplementation of benzoic acid (BA). Benzoic acid is metabolised in the liver to hippuric acid, by conjugation with glycine, an NEAA, which is excreted with urine. Other organic acids included as feed additive in the diet are, after absorption in the digestive tract, metabolised by the animal and are not excreted as acids. Dietary supplementation of up to 2% BA resulted in a linear urinary-pH reduction from 7.2 to 5.4 (Kluge et al., 2010) or from 8.5 to 6.0 (Murphy et al., 2011). Other studies also found significant reductions of pH of the urine by including BA in the diet (Bühler et al., 2006; Gräber et al., 2012; Humphrey et al., 2022). Of these, Murphy et al. (2011) and Humphrey et al. (2022) demonstrated that a lower pH coincided with a reduction of NH_3-emission from manure. Canh et al. (1998) suggested that NH_3-emission and pH are linearly related and that 1-unit lower pH would reduce NH_3-emission with 67%. Despite a large number of studies confirming these effects, the EFSA (2015) noted that an effect on urinary pH alone is of little practical or biological relevance. The currently typical supplementation of 0.3 – 0.5% of BA to pig diets would result in only a limited reduction of NH_3-emission. An alternative would be to acidify slurry in the manure pit (e.g., Overmeyer et al., 2021; Puente-Rodriguez et al., 2022), but this is beyond scope of current study
Canh et al. (1998) also investigated the effect of reduction of the dietary electrolyte balance (dEB; dietary (Na + K – Cl)). Over an array of salts, they measured that lowering the dEB from 320 to 100 mEq/kg dry matter reduced the pH with about 0.3-unit and NH_3-emission by about 10%. The dietary dEB level, however, can be varied to a limited extent as it may affect animal's health and performance. Although a wide variation exists in literature on the optimal dEB level for pigs, for growth performance it was suggested to be between 200 and 500 mEq/kg diet (Dersjant-Li et al., 2001) or reported to be 250 mEq/kg (NRC, 2012). Therefore, there seem to be limited opportunities in practice to affect slurry pH via manipulation of the dEB.

In summary, it is possible to reduce NH_3-emission by acidifying manure via dietary measures. Of these measures, dietary supplementation with BA seems most effective. However, a large effect would require a higher inclusion level than presently common in practice, due to the costs of this acid.

3 Feeding strategies

In Chapter 2 we discussed the possible impact of dietary measures to improve N-efficiency which may reduce NH_3-emission. As mentioned in section 2.3, many other factors, which we summarised as pig farm's management, affect the actual emission from pig barns as well. Application of different feeding strategies will be discussed in the present chapter. Under feeding strategy, we consider methods on how targeted diets are supplied to targeted (groups of) pigs. Three main possibilities will be discussed: strategies related to pen allocation of animals (e.g., separation of sexes), multiphase feeding, and precision feeding. Other management factors are outside the scope of present study.

3.1 Separation of sexes

In section 2.3.4, calculations were made on the impact of dietary measures on N-efficiency. It was shown that N-efficiency in the growing period varied between the different sexes (i.e., boars, barrows, and gilts). This is the result of slight differences in rate and composition of retained body mass. Consequently, requirements for nutrients vary between the sexes.
Currently, in practice pigs are grown in groups of separated or mixed sexes. Based on the calculations shown in section 2.3.4, boars use protein more efficiently than barrows and gilts (Table 3). To allow a better growth performance, boars have a higher protein-requirement, and thus their diets should contain a higher level of CP than that of barrows and gilts. This may be counter-intuitive: boars can only fully realise their growth potential by feeding them diets containing higher CP levels than required for barrows and gilts. Their higher N-efficiency of results, nevertheless, in a lower N-excretion. Feeding the same diet for barrows and gilts results in an oversupply of dietary protein, and to a higher N-excretion, mainly via urine.

Table 3 *Nitrogen-efficiency and excretion of boars, barrows, and gilts (25-125 kg BW) at present-day performance (CVB, 2023b) and assuming diets fed are equal in CP-level for the sexes. Results of model calculations.*

	Boars	**Barrows**	**Gilts**
Dietary CP-level (g/kg)	150	150	150
N-efficiency (%)	43.9	39.0	40.4
N-excreted (kg)	3.21	3.91	3.71

These calculations allow some (theoretical) scenario analyses. In Table 4 results are given assuming that the N-efficiency of barrows and gilts could be raised to the same level as that of boars. Such higher efficiency would allow feeding of diets containing lower CP-levels and would result in a similar N-excretion for barrows and gilts as for boars over the entire production period.

Table 4 *Dietary CP-levels and N-excretion of boars, barrows, and gilts (25-125 kg BW) at present-day performance (CVB, 2023b), theoretically assuming N-efficiency to be equal for the sexes. Results of model calculations.*

	Boars	**Barrows**	**Gilts**
N-efficiency (%)	43.9	43.9	43.9
Dietary CP-level (g/kg)	150	133	138
N-excreted (kg)	3.21	3.20	3.21

These results suggest that keeping and feeding the sexes separately may allow a reduction of N-excretion by about 15%, if N-efficiency of barrows and gilts could be improved to the level of boars. Van der Peet-Schwering et al. (1999) indicated that N-excretion may be reduced by about 1.5% by separating barrows and gilts and feed barrows restrictedly. For boars, which were not considered in that study, the difference will be larger. Although separation of the sexes can easily be realised in practice, feeding different diets may be difficult, as it not only requires supply of different diets but also a more advanced feed supply infrastructure on farm.
The results suggest that, from the perspective of improving N-efficiency and reducing N-excretion, boars should not be castrated. This may conflict, however, with the interests for export of pig meat by the Dutch pig sector, as occurrence of boar-taint in meat of pigs is not accepted in many countries. Also, boars may show a more aggressive behaviour and are more difficult to keep than barrows (Van der Peet-Schwering, 2011).

3.2 Multiphase feeding

The nutrient requirements of pigs are not constant during their life. For growing pigs, therefore, the system of phase-feeding has been developed. At present, it is most common to apply a three-phase feeding program, with a starter phase (25 – 50 kg BW), a grower phase (50 – 80 kg), and a finisher phase (80 kg – slaughter; weights mentioned are indicative). Diets are defined to contain nutrient levels (energy, CP, AA, and minerals) matching the nutrient requirements of animals in the specific growth phase, while minimising oversupply. Figure 10 shows the principle for dietary protein. Often, at the start of a phase, many animals will receive less protein and AA than required as the CP level is usually not set to cover requirements of all animals at that particular moment. These animals will, consequently, not grow according to their full genetic potential. For example, this will be the case for 50% of the pigs if the diet is formulated to cover the mean requirement of the pigs for protein and EAA at that point (e.g., 25 kg BW). Usually, underfeeding is limited by formulating diets that cover requirements of most animals at that point. The largest part of the growing period, however, the diet contains a CP level leading to a supply that exceeds the animal's requirement for protein and EAA.

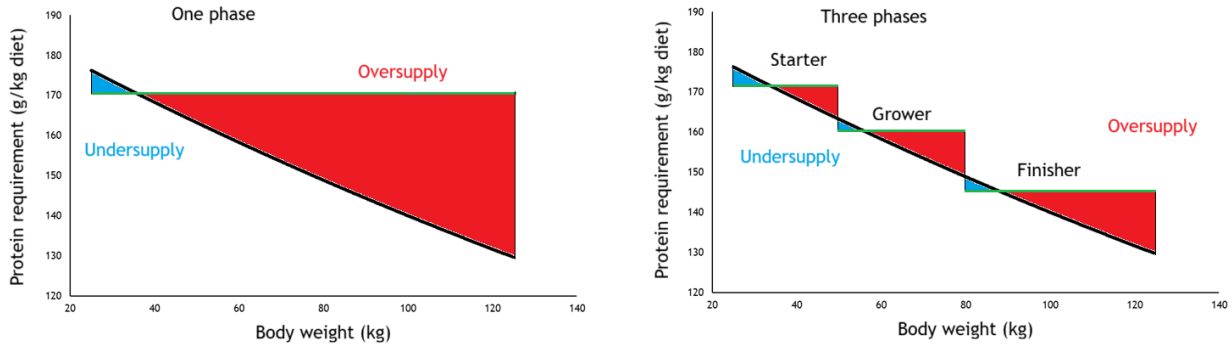


Figure 10 *The principle of phase feeding. The requirement for protein per kg diet decreases with increasing BW. On the left, one-phase feeding is shown; just a single diet is fed over the entire growth period (25-125 kg BW). The right figure shows a three-phase feeding scheme.*

By dividing the growth trajectory (25-125 kg BW) in separate phases, animals are fed closer to their protein requirements (Figure 10), resulting in improved N-efficiency, lower oversupply, and, subsequently, lower N-excretion. By increasing the number of phases, the gap between N supply and requirement can be reduced further. Lenis and Jongbloed (1999) reviewed that N-excretion reduced by about 6% per additional feeding phase. However, they also noted that in some studies phase feeding reduced animal performance (e.g., Bourdon et al., 1995; Van der Peet-Schwering et al. 1996). Bradford and Gous (1991), on the contrary, reported an improvement of feed efficiency when using up to five phases. They did, however, not find similar results in a replication of the study using three phases. In that study N-excretion was not measured. The latter was done by O'Connell et al. (2005), comparing a five-phase with a one phase feeding scheme. The diets in the separate phases were formulated to contain different levels of digestible lysine (high – medium – low). Compared to the one-phase feeding scheme, they did neither observe a difference in performance nor

a reduction of N-excretion when using high lysine diets. At the medium lysine range, growth performance was not affected, but N-excretion was 13% lower. When using low lysine diets, N-excretion was reduced by 25%, but growth performance was compromised. They suggested that a part of the lower performance in the first part of the experiment, due to undersupply of protein to a part of the pigs, was made up for by compensatory growth. This was also suggested by Menegat et al. (2020), who found that two-, three-, or four-phase feeding improved performance, depending on the dietary lysine level. They did not measure N-excretion. In a three-phase feeding system, N-excretion was found to be 1.5% lower as compared to using a two-phase system, as measured recently in a N-balance study by Sobatka and Drazbo (2025). However, N-retention was significantly lower in the three-phase system. These studies indicate clearly that phase-feeding requires precise setting of the dietary nutrient levels and can reduce N-excretion in pigs without compromising performance. As a three-phase system is commonly applied, a significant part of potential increase in N-efficiency is already materialised in practice compared to using a single diet over the entire production period.

Although increasing the number of phases may allow to reduce the N-excretion in theory, there is a practical limitation. It is not feasible to ensure a perfect coverage of animal's protein requirements, given the continuous change of nutrient requirements during the growth phase and the differences between animals. With increasing the number of phases, the individual variation in protein requirement between pigs may become larger than the differences in protein levels of the diets in the separate phases, which could nullify possible advantageous effects. Also, a larger number of phases requires not only the production of more types of feed, which decreases feed production efficiency, but also an adaptation of the feeding system and infrastructure at the farm which may require a large investment. Therefore, multiphase feeding has been developed, where the diet composition is adapted in regular intervals, e.g., weekly, or even daily. The multiphase feeding system makes advantage of the changing nutrient requirement of pigs during the growth period (25-125 kg BW): a relatively high protein requirement and low energy requirement in the early part of this period, and the inverse for the latter part. Therefore, two diets are produced with a high and low protein to energy ratio, respectively. By mixing these diets in appropriate ratios, a 'sliding scale' of dietary protein level can be made. By changing the diet-mix of two diets weekly, Henry and Dourmad (1993) estimated that N-excretion could be reduced by 10% in boars and 20% in castrated males, as compared to a two-phase feeding system. Similarly, Van der Peet-Schwering et al. (1996) measured a reduced N-excretion of about 12% at a multiphase-feeding scheme, as compared to two-phase feeding. Pomar et al. (2014) found a similar reduction, comparing a daily-mixed individual multiphase feeding system with a three-phase system. Weight gain of the multiphase fed animals was higher in their experiment, which was related with a higher body fat deposition. They predicted that feed costs would be 1% lower when using multiphase feeding.

In all these cases, the diet composition is aimed to match the nutrient requirements of animals in a specific group. Phase feeding accommodates the reduction of the pig's nutrient requirements over time. A multiphase feeding program can be realised in practice if mixing of diets is possible at the farm. This is the case, for instance, at farms applying liquid feeding systems, often with application of liquid or moist by-products, and on farms with a computerised dry feeding system that allows mixing different components. Otherwise, it may be necessary to invest in adaptation of the feeding system to make multiphase feeding possible.

In summary, multiphase feeding may contribute to an improvement of N-efficiency. However, as compared to the presently most common three-phase system, the impact of adding one or two phases will likely be limited. Use of a multiphase feeding system by mixing two or more diets probably has a larger effect, provided that a loss in performance due to underfeeding of some of the pigs can be minimised.

3.3 Precision feeding

So-far, we have discussed pig performance and requirements within the husbandry-setting as is common practice today: animals are kept in groups in barns, rooms, or pens and fed according to the assumed mean requirements of animals in a room. Diet composition is the same for all animals in the group. This results in overfeeding nutrients to a part of the animals and underfeeding to another part.

Phase feeding considers the change in relative nutrient requirements of pigs over time, but does not correct for between-animal variation. Not all pigs consume the same amount of feed, grow at the same rate, have the same body composition in terms of protein and fat deposited, or possess a similar health status. Also, animals vary in their metabolic efficiency to utilise nutrients, including AA, which is in part genetically determined. Taking this individual variation into account would allow to feed the pigs even closer to their

nutrient requirements, thus improve their N-efficiency. Feeding pigs in small groups, but ideally at an individual level, with regular (weekly or, preferably, daily) adaptation of the diet composition, is called "precision feeding". This recently received much attention in research.

Precision feeding is an aspect of "precision livestock farming", which is defined by Wathes et al. (2005) as the management of livestock farming using the principles and technology of process engineering. This definition suggests it is a highly technological approach. As precision feeding aims to feed the individual pig as closely as possible to their nutritional requirements, the diet must be adjusted frequently, preferably daily, in amount and composition. Thereto, three types of activities are necessary: data must be collected, the data must be processed, and the (feeding) system must be controlled (Pomar and Remus, 2019). Data to be collected, at the individual level, are foremost those of feed intake and BW gain. This implies that animals must be fed individually, that the amount of feed consumed is measured, and that pigs are weighed regularly, ideally daily. This is technologically demanding: the system requires automated individual feeders and weighing equipment. These systems are available in some research facilities but currently uncommon in practical pig farms. The data collected must be processed to compare it with the farm's production objectives, and to take subsequent actions. Actions may be adaptation of the amount of feed supplied in case pigs are not fed ad libitum, and/or of the diet composition. The data processing involves mathematical modelling. Mathematical models are used to calculate the nutrient requirements for the next meal or day, given a defined feed intake and growth performance, based on the measured inputs and expected chemical composition of the BW gain (content of moisture, protein, fat, and minerals). These requirements and the expected body composition have to be defined per case, e.g., for the genetic line of animals at that farm. This results in target values for each pig, for feed intake (amount and composition) and BW-gain. Finally, the system must be controlled: the targeted amount of feed with a specific nutrient composition must be offered to the individual animal for which it has been formulated (Pomar and Remus, 2019).
Precision feeding appeared a very effective tool to reduce N-excretion in different experiments. For example, in growing pigs (30-118 kg) Andretta et al. (2016) measured an N-efficiency of 53% for precision-fed animals, as compared to 45% for three-phase fed pigs. This coincided with a reduction of N-excretion of over 25%, while performance and N-retention were not affected. In other studies by this research-group, precision feeding reduced N-excretion between 12 and 22%, as compared to three-phase feeding (Pomar et al., 2014; Andretta et al., 2014).

The objective of precision feeding is to eliminate a part of the variation between pigs as attempted in a study by Misiura et al. (2021). Based on data from an experiment on 32 pigs, they simulated growing pigs (35-120 kg BW) in a two-phase and a precision feeding system. Values for an average pig or for a heterogenous group of pigs were calculated. For the average pig, precision feeding resulted in a 7% lower N-excretion, but for the heterogenous group this was 15%. Improvement of 'real-time' (i.e., daily) AA requirements and protein deposition estimations are investigated as they are essential to improve precision feeding models further (Hauschild et al., 2020; Remus et al., 2020a,b).
Precision feeding has also been evaluated in gestating and lactating sows. In gestating sows, feeding a mixture of two feeds, Gaillard and Dourmad (2022) found a reduction of N-excretion of 18% as compared to the control treatment (sows fed one diet), without any loss of reproductive performance. In a comparable design, Cloutier et al. (2024) compared precision feeding with standard feeding of gestating sows over three cycles. They observed no differences in performance. No information on N-excretion was presented, but CP-intake was about 9, 16, and 20% lower in the first through third cycle at precision feeding. In lactating sows, Spinler et al. (2025) investigated the effect of precision feeding on sow performance. Compared to the control treatment (feeding a single diet) performance was similar, except litter growth rate tended to be slightly lower. This was attributed to a low intake of lysine via the diet by a part of the sows. Litter growth was similar to the control for sows consuming the intended amount of lysine. The effect on N-excretion was not measured in the experiment. Although the results suggest that precision feeding is also possible in lactating sows, these animals appear sensitive for differences in their nutrient supply relative to their nutrient requirement, emphasising the necessity of a strict control their daily feed intake.
In most of the experiments on precision feeding mentioned, the daily dietary allowance was calculated on the basis of SID lysine intake. The other AA were supplied in a fixed ratio, according to an ideal protein profile, and their intake reduces at the same rate as that of lysine. As the relative lysine requirement is high for protein deposition and low for maintenance, as compared to a number of the other AA, this may result in an undersupply of these other AA. This may restrict the pig's maximal AA-utilisation and performance. The ideal

protein ratios, defined under phase feeding conditions, might then not be "ideal" under precision feeding conditions anymore. This is, indeed, the case, as has been shown for methionine and threonine in the starter period (25-50 kg BW) and for threonine in the late finisher period (110-135 kg BW; Remus et al., 2019a,b, 2020a). These authors discussed that the estimation of AA requirements should be improved for applications in the precision feeding system for growing pigs (Remus et al., 2020b). The ideal ratio between AA should not only be defined for this feeding system but should probably be estimated dynamically using a mathematical model, as mentioned. This allows also to define the specific target objective: e.g., maximum nutrient utilisation efficiency, maximum growth rate, or maximum lean deposition. Each of these targets results in different AA requirements and, likely, also in different ideal protein with a targeted AA composition. The precision-feeding system can be extended beyond measurement of feed intake and body weight. For example, by including data on the environment such as room temperature, and pig's health-status and behaviour. Animal's body temperature and sounds they make, like coughing, are both important indicators of health-problems. Sensors for measurement of these and other variables have been evaluated (e.g., Ferrari et al., 2008). Animal behaviour can be captured by cameras and activity sensors. These data can be used to further improve nutrient supply to the animals, as health-issues may result in a higher requirement of specific AA (section 4.1). Early detection of illnesses allows dietary enrichment of these AA, which may reinforce the animal's immunological reactions and shorten the period of sub-optimal health. As N-efficiency in episodes of disease deteriorate severely, it helps to improve overall N-efficiency and reduce N-excretion. Further detailing on the former is beyond the scope of present report, but it is an important development which received attention in research, both for growing pigs as for sows (e.g., Gaillard et al., 2020, 2021), and which should be integrated in further research on precision feeding.

In summary, precision feeding seems a promising way to improve N-efficiency and reduce N-excretion. In growing pigs and in gestating sows N-excretion could be reduced by 10-20%, or even more, largely dependent on the experimental contrast evaluated and composition of the diets involved in the study. It is, however, technology demanding. Specific equipment is required, as individual feeders and, ideally, weighing equipment and possibly other sensors. The large amount of data must be processed continuously, and proper mathematical models must be available to compare the measured values with the targets and propose corrections if necessary. Accurate knowledge on nutrient requirements as well as of the nutritional value of feedstuffs and diet formulation are essential. Such systems are under investigation, but they should be further developed for large-scale application in practice. The large investments required must be compensated by lower costs of feed and environmental benefits.

4 Limitations to dietary measures and feeding strategies

In the chapters on dietary measures and feeding strategies, several possibilities have been discussed to improve N-efficiency and, subsequently, reduce N-emission. Some limitations were indicated, such as a current lack of sufficient knowledge, or necessary investments in feeding infrastructure at the farm. In the present chapter, some of the limitations will be further discussed.

4.1 Dietary measures

Efficiency of N-utilisation can be improved by optimising the dietary AA-ratio according to the ideal protein concept, allowing a reduction of dietary CP-levels, and of N-excretion and emission. There are, however, a number of potentially limiting factors to this approach.

An aspect of relevance in application of the ideal protein concept is that of timing, or AA-kinetics. Rérat (1993) indicated: "The absorption kinetics [of AA from the digestive tract] seem to be a rather important factor in the temporal distribution of free AA in body tissues and may be at the origin of transitory imbalances. As a result of these imbalances, the metabolic utilization of AA may be depressed, leading to higher levels of circulating urea fluxes and a lower nutritive value. This puts focus on the attention which should be paid to research on the 'time factor' in the relationships between digestive and metabolic utilization of nutrients." When reducing dietary CP-levels, the AA-levels are balanced by supplementation of free AA. These are rapidly absorbed after entering the small intestine, contrary to AA from protein, which must be hydrolysed before being absorbed in the gut. Kinetics of AA absorption are, thus, different. Dietary free AA are absorbed fast, which may induce a higher degree of their oxidation, contrary to AA derived from dietary protein, which are released in the digestive tract in lower quantities over a longer period of time. As protein deposition is a continuous process, this may result in an AA-imbalance. This difference in absorption kinetics resulted in a lower N-efficiency when feeding diets with a (relatively) high level of free AA (Batterham and Bayley, 1989).

Covering AA requirements by inclusion of free AA in the diet was, indeed, shown to result in lower weight gain and N-utilisation in different studies. Eugenio et al. (2022), suggested that "… the bioavailability of AA provided in free form by the diet may not be the same as that coming from intact proteins." In practical feed formulation the aspect of absorption-kinetics received little attention. When the ratio intact protein : free AA diminishes with decreasing CP-levels and increasing free AA supply, this aspect will gain relevance. Possibly animals can adapt to rapidly available AA in the diet (Nolles et al., 2009). In rats, they measured a higher post-prandial AA-oxidation in animals fed a diet containing AA only in a free form, as compared to animals receiving AA as intact protein, after 5 but not after 26 days, which was related to slowing-down of the AA-absorption rate from the gut of the free AA-diet. Whether such adaptation exists in pigs as well is, to our knowledge, not studied. If this is the case, such adaptation period is likely longer for pigs than for rats.

Batterham (1974) and Boyd et al. (2024) suggested that free AA are not as efficiently utilised in post-absorptive metabolism as those derived from intact protein. AA-utilization by piglets could deteriorate when more than 35% of the dietary AA is supplied in a free form (Officer et al., 1997). This disadvantage could be attributed to the imbalance of available AA, due to the fast rate of AA absorption, but is contradictory to work of Monchi and Rérat (1993). In rats, they observed a higher BW gain of animals fed a whey-protein hydrolysate mainly containing small peptides (< 5 AA), than animals fed a free AA mixture (with nearly the same AA-pattern). Amino acid absorption from the small intestine was, however, faster in animals fed peptides, which agrees with work of Adibi and Morse (1977) in humans.

The health status of pigs and the sanitary condition of their housing affect performance considerably (Figure 11, from Le Floc'h et al., 2018). Infectious and inflammatory diseases may induce protein loss, growth retardation, and increased nitrogen excretion. A reduced intake of feed demands a higher dietary CP-level to supply the same amount of dietary protein and AA to the animal, apart from the high requirement of some specific AA for the synthesis of inflammatory and immune proteins and other compounds important for body defence functions. Also, efficiency of AA-utilisation may be impaired, because they, provided by diet or muscle protein catabolism, are used by the liver for gluconeogenesis and acute-phase protein synthesis,

rather than for body protein deposition (Le Floc'h et al., 2004). This shift in utilisation affects the required AA-profile directly, as protein composition of defence-proteins deviates strongly from that of muscle or milk. Especially the requirement for tryptophan, glutamine, cysteine, and arginine is higher. A higher N-excretion was measured in pigs after a non-pathogenic health challenge as compared to healthy animals, and an elevated requirement for tryptophan, methionine, tyrosine, and valine was suggested (Kampman-Van de Hoek, 2015).

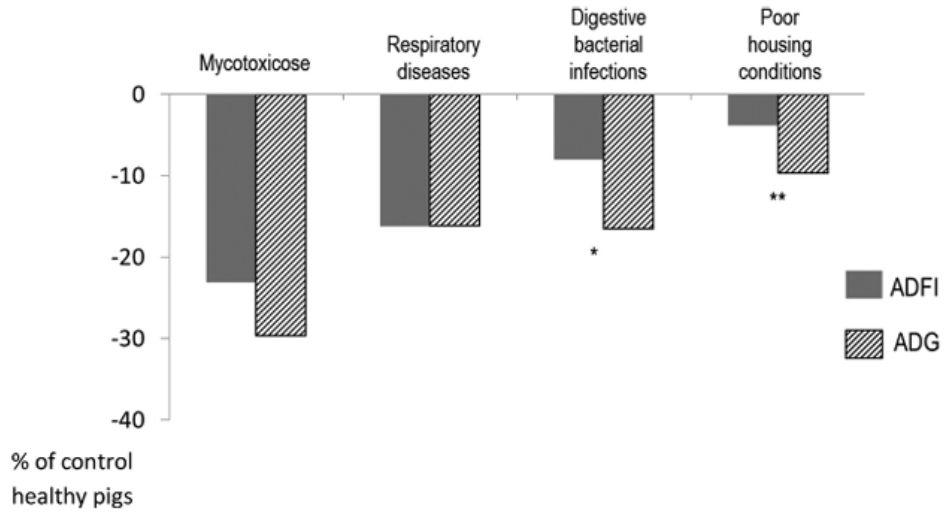


Figure 11 *Impacts of health disturbances on average daily feed intake (ADFI) and average daily gain (ADG) in % of the value for control healthy pigs (from Le Floc'h et al., 2018, after Pastorelli et al., 2012).*

Not only clinical disease or challenge raises the requirement of (specific) AA. Animal's husbandry environment plays a role as well. The effect of low sanitary conditions has been investigated, and is induced by, among others, not-cleaning and disinfecting of the room, insertion of fresh manure from an external farm, and/or abstention of vaccinations (e.g., Le Floc'h et al., 2009; Van der Meer et al., 2016). Noorman et al. (2023) measured a 9%-units lower total tract N-digestibility for pigs kept under poor sanitary conditions, as compared to those kept under good conditions. In the experiment of Le Floc'h et al. (2009) performance of piglets (8-25 kg BW) was worse under low sanitary conditions, which could largely be compensated by a higher level of dietary tryptophan. Van der Meer (2017) showed that AA requirements were increased under low sanitary conditions. She measured that a combination of extra added methionine, threonine, and tryptophan could partly restore the difference in pig performance with those raised under high sanitary conditions. Under low sanitary conditions, N-efficiency was reduced from about 62 to 53%, although the difference was smaller for restricted-fed animals.
In an experiment by Van der Peet-Schwering et al. (2020b) with pigs (20-125 kg BW) kept under low sanitary conditions, ADG was 4.5 and FCR 1% worse than pigs kept under high sanitary conditions. An extra supplementation of a mixture of AA improved performance of both groups of animals, but to a larger extent of those kept under low-sanitary conditions. They noted that the balance with the requirements for energy needs to be considered as well. Similar results were obtained in a comparable experiment with piglets (8-25 kg BW; Van der Peet-Schwering et al., 2021). In this case, however, no clear interaction with extra energy supply was observed, and results differed slightly between two farms. By modifying the dietary EAA composition and energy level, reduction of growth performance of pigs kept under low sanitary conditions and/or sub-optimal health condition can, at least in part, be compensated (Le Floc'h et al., 2012). As this will improve the N-utilisation, it reduces N-excretion. However, the optimum diet composition for pigs in such condition requires further research. Together, these results show that N-efficiency of pigs kept under poor housing conditions, or that are in a suboptimal health condition, is deteriorated. Dietary supplementation with specific AA may support animal's immune system and correct performance and N-efficiency in part.
Van der Meer et al. (2017) showed that a reduction of the dietary CP content from about 17 to 14% in the starter period, and from about 15 to 12.5% in the grower and finisher periods resulted in increased damaging behaviour of pigs, as tail and ear biting, impacting their welfare negatively. Dietary supplementation of some specific EAA counteracted this effect, but only in part. Minussi et al. (2023) compared behaviour of pigs receiving diets with a normal or a low CP-level (about 3%-units lower), and the

low-CP level enriched with free AA (to the level of the normal CP-diet). No differences were observed in the prevalence of ear biting, but at the low-CP diet, there was more and more severe tail biting than at the other treatments. Thus, a low dietary CP level may cause damaging behaviour of pigs, which can be corrected by supplementation of AA. The optimal composition of the mixture of AA to be supplemented needs to be studied further, as in the first mentioned study the correction of performance was only realised partly.
A potential disadvantage of focussing on the reduction of N-excretion is that it potentially diminishes the inclusion of certain feed ingredients, which may hamper sustainability and circularity of pig production. For example, more regional sourced ingredients or by-products of the food industry which may (partly) replace SBM (a high-quality protein source) often have a lower protein digestibility and/or less favourable AA-pattern to suit the pig's AA requirements. Thus, diets including such ingredients may require a higher CP-level or higher free AA supplementation. Another potential disadvantage of using more by-products is that they may contain anti-nutritional factors. Most feedstuffs contain such factors, but they are well-controlled by proper treatments, as heat-treatments or application of enzymes (section 2.3.2.). However, if new ingredients are introduced, or being applied at higher levels, this aspect needs attention, as they may decrease CP digestibility and increase N-excretion.
To summarise, there may be limitations in the supplementation of the diet with free AA, if their digestion kinetics induce an imbalance at the post-absorptive level. As this may hamper the optimisation of the ideal protein profile, this needs to be considered in research. The improvement of N-efficiency may also be impaired by health status and housing conditions of the animals. This may be corrected in part by an adaptation of the diets following a modified ideal protein profile considering changes in AA requirements under such conditions. The result may be that N-efficiency of pigs under such conditions is lower than that of "ideally kept" pigs (healthy and kept under very good sanitary and climate conditions) but will be higher than in case no adjustments on the diets would be made. An important risk of feeding low CP diets may be the undesired negative effect on damaging behaviour of pigs. This may also be partly corrected by adapting the dietary AA profile.

4.2 Feeding strategies

Separation of sexes may contribute to a considerable reduction of N-excretion. Ideally, boars are not castrated, as their N-efficiency is much higher than that of barrows. Implementation in practice, however, may be difficult. Intact boars may produce boar taint, which is unwanted and may be hampering exportation of meat to some countries. Apart from this argument, materialising the potential lower N-excretion by separation of the sexes would require feeding of different diets. This would not only require the production of different feeds, but also of different feeding systems at the farm. This includes the availability of more silos and extension of feeding lines which likely requires a substantial investment. To evaluate the potential of such measures, these aspects need to be evaluated in more depth.
The same limitation is true for multiphase feeding. Currently, three-phase feeding per group of pigs is most common in the Netherlands. Extending this to more phases would require a high investment at the farm, while the N-efficiency improvement of additional phases diminishes. Multiphase feeding by mixing diets may also require some investment, as they must be mixed.
Precision feeding is promising to reduce N-excretion more impactful. The concept has been proven effective in a research setting. However, to realise it in practice requires considerable additional work. Mathematical models need to be developed or adapted to estimate individual animal's requirement on a daily basis and correct the amount and composition of the diet if required. They must be able to process large data, as measurements of feed supply or feed intake, feeding behaviour, and BW. Data on AA requirements of pigs for this type of feeding need to be more dynamic. At the farm level a large investment is required and, although this may be offset by lower feed costs, farmers need to be interested in this technology, and such investments must be affordable and worthwhile for them. The technology requires proper development of hard- and software and further economic evaluation. Application also requires further technological developments, including development of sensors, image technologies, and weighing equipment, and more precise information on the dynamics of nutrient and AA requirements of pigs (Banhazi et al., 2012).

4.3 Realisation in practice, including some economical aspects

An important factor not yet discussed is the N-efficiency of pigs as observed in practice as compared to those observed in research settings. The analysis presented in section 2.3.4 resulted in an estimated N-efficiency of 43% for growing pigs (weaning - 125 kg BW), and of 41% for the combination of sows and their progeny till slaughter weight. This calculation used performance data as common in Dutch practice. Millet et al. (2018) reported that an N-efficiency of 54% was obtained in an experiment with group-fed boars in a three-phase feeding system, using practical diets. Andretta et al. (2016) reached up to 57% in individually fed pigs in a precision feeding setting. It is not uncommon to observe such large differences between results obtained in research facilities and at practical farms. For example, using similar pig genetics, energy efficiency of pig was 8% higher in research facilities than in practice (Gaines et al., 2012). Likely, this is the result of differences in housing, environment, hygiene status, and control of feeding. As mentioned in section 4.1, for example, deteriorating sanitary conditions in an experimental setting reduced N-efficiency and growth performance of growing pigs (Van der Meer et al., 2017; Van der Peet-Schwering et al., 2020b). A similar loss of efficiency is to be expected when animals are in a suboptimal health condition. These factors are, usually, more controlled in research settings than in practical farms. The standard of research facilities is unlikely to be realised in practice, as it is labour and time-intensive, thus expensive. However, it indicates there is opportunity for N-efficiency improvement in pigs. The negative effect of suboptimal conditions on performance may be alleviated by the supply of tailored diets.

It is important to get a better understanding of the relationship of realised N-efficiency at a pig farm with conditions such as hygiene and health status at that farm. There is a large deviation between farms in practice (Sollberger et al., 2013) and even between experimental farms (Van der Peet-Schwering et al., 2020a). Field research similarly to the "Koe en Eiwit" program https://koeeneiwit.nl/, although with a different objective, will enlarge our knowledge on the magnitude of such differences and their possible causes. Reducing variation in N-efficiency among farms will contribute to improvement of overall N-efficiency of the sector.

Separation of sexes during the growing phase may improve N-efficiency. Although this separation is not complicated at itself, to materialise the advantage it may be necessary to feed different diets and to invest in separate feeding systems. The advantage of the sex-separation needs to be worthwhile to regain this investment. Boars have a much higher N-efficiency than barrows. However, boars are more difficult to keep than barrows and may show a more aggressive behaviour (Van der Peet-Schwering, 2011). Also, boar meat may be less appreciated given the potential of boar taint, which may be less appreciated by consumers and be problematic for exportation of meat to some countries. In western France, in 2023, boar taint appeared prevalent in about 1.5% of boars (Conan et al., 2024). Malodorous boars were, on average, heavier, older, and fatter than non-malodorous boars, which may be cues to reduce this unwanted odour.

The application of precision feeding seems a very promising development to improve N-efficiency of pigs. Ideally, feed is offered to individual pigs, although applying the technology to smaller, more homogeneous groups of pigs may show an advantage as well, and might be easier to realise in practice at a short term. The technology and systems required are still under development, and research into aspects like the ideal AA composition of the diets is required. A disadvantage is that the investment necessary, for example in sensors and software, will be considerable. Although feeding costs will be lower, it is presently unclear whether this suffices to regain the investment. Also, it is uncertain whether farmers are interested and willing to invest in high-technology farming.

On part of the pig farms in the Netherlands, diets are formulated and composed on farm. This holds especially for farms using liquid or moist ingredients and having a liquid feeding system. On these farms it may be possible to adjust diet composition for certain subgroups (pens) of pigs. This could principally be done on a daily basis and offers a practical possibility to realise some of the advantages that phase and precision feeding offer. For individual feeding, individual feeders are required as well as validated estimations of nutrient and AA requirements in time. The use of moist and liquid by-products is part of circular feeding concepts, thus should not be discouraged by changes of feeding systems related to precision feeding concepts.

As indicated in sections 2.3.3. and 2.3.6, all EAA with the exception of phenylalanine are presently registered as a feed additive in the EU. Their availability permits a further reduction of the dietary CP contents, beyond the reduction which has already been realised by inclusion of the first five limiting EAA, lysine, methionine, threonine, tryptophan, and valine, which are available in a free form for a longer period. Free AA are, however, relatively expensive feed ingredients, which is especially the case for the more recently available

products, such as leucine and isoleucine. When reducing the dietary CP contents, supplementation with free AA is necessary, to cover the animal's dietary AA requirements for potentially limiting AA, resulting in a feed costs increase. To get some insight into this aspect, a number of feed formulation calculations have been made. Details are presented in Appendix 3. For growing pigs (25–125 kg BW) it appears possible to reduce the dietary CP content with about 20 g/kg diet, as compared to the diet with unrestricted CP contents (the "optimal" least costs diet for the given animals). Per gram CP-reduction per kg diet, the feed costs rise with about € 1 per ton of feed. Weighted for feed intake during the separate phases, as calculated in section 2.3.4, this would mean an increase of feed costs per pig of more than 10%, from € 52.85 to € 58.36. See Appendix 3 for details. The effect of this dietary CP reduction on N-efficiency and N-excretion was calculated using the model described in section 2.3.4 for growing boars (25-125 kg BW). Reducing the dietary CP content with 20 g/kg improved N-efficiency from 43 to 51%, and N-excretion decreased from 3.3 to 2.4 kg, or about 26%. This decrease was more pronounced for urinary N-excretion (TAN), which decreased from 2.0 to 1.4 kg N/pig, or 32%. Faecal N-excretion was reduced with 17%. Details are shown in Appendix 4. The reduction of the CP content coincided with a reduction of byproducts included in the diet, which goes against stimulation of using more circular diets. At the lower CP level, about 10% less of ingredients like RSM and cookies-mix was included in the diet.

In summary, there is often a large discrepancy between the N-efficiency of growing pigs realised in a research setting and in practice. Closing this gap has a large potential to reduce N-excretion of the pig sector. This requires more insight into the factors determining this gap. The potential to reduce dietary CP contents by continuing current practice, i.e., dietary supplementation with the next limiting AA, is considerable, but will raise costs of pig production significantly. As indicated before, a more precise estimation of the AA composition of ideal protein allows an improved supply relative to the animal's requirement, which may limit the additional feed costs.

5 Conclusions

This study was conducted to review the potential of dietary CP reduction and other measures to improve N-efficiency and reduce NH_3-emisison. The following can be concluded about the relationship between CP reduction in diets for growing-finishing pigs, N-efficiency in pigs and potential NH_3-emission from manure:

- A strong relation exists between the reduction of dietary protein level, increase in efficiency of N-utilisation in post-absorptive metabolism, reduction in N-excretion, and potential NH_3-emission from manure.
- Dietary CP reduction is one of the methods to effectively improve N-efficiency in pigs, under the condition that the requirements for essential amino acids are still covered by the dietary supply.
- Per percent dietary CP reduction, N-excretion can be lowered by about 8-10%. As N-efficiency improves in that condition, the reduction of urinary-N (TAN) excretion is relatively higher.
- In research settings, on average 28% of TAN in manure is emitted as NH_3. This value will vary largely in practice and is affected by manure management practices, animal housing, animal genetics, health status, hygiene at the farm, dietary ingredient and nutrient composition, and feeding strategy.
- The use of N-efficiency as criterion rather than the sole focus on CP-reduction allows a wider range of diet and management measures to be implemented to reduce the environmental impact of N-excretion.

TAN excretion as primary source of ammonia formation and emission in the pig sector, can be reduced via changing diet composition and feeding strategies as also suggested by PBL (2020). We conclude that:

- For growing pigs (25-125 kg BW) the effect of improving N-efficiency by dietary CP reduction is linear, at least till an overall (weighted) dietary CP level of 150 g/kg. The (weighted) CP level in feed for growing-finishing pigs in the current Dutch practice has been reduced over the previous years, approaching the short-term target suggested by PBL in 2020. Provided that the diets are adequately balanced for all essential AA, it is assumed that the growth performance of pigs has not been affected negatively.
- Improving feed efficiency (feed conversion ratio) in pig production effectively increases N-efficiency and reduces N-excretion. It can be affected by, among others, farming management, pig genetics, health status and diet composition.
- Model calculations estimated that, given the current performance of growing pigs, the dietary CP level could potentially be reduced further to around 130–135 g/kg. This estimation assumes that the AA composition of the "ideal protein", that is the ratio of essential amino acids required for optimal body protein deposition and growth, accurately reflects the pig's actual AA requirements. However, it remains to be proven whether lowering dietary CP below 150 g/kg (weighted value) down to 130–135 g/kg continues to linearly increase N-efficiency and linearly reduce the NH_3 emission potential from manure.
- The ideal AA profile in the diet may be different when dietary CP level is low, as compared to the profile derived in studies using diets with higher dietary CP levels (typically with weighted CP levels well above 150 g/kg). Non-essential AA should be incorporated in the ideal protein profile as well. This requires further investigation as pigs should be allowed to synthesize sufficient non-essential AA from precursors to be able to reach maximum protein deposition capacity.
- Dietary modifications to reduce NH_3-emission by inhibiting volatilisation, e.g., by application of specific acids or urease inhibitors, may be effective. Their effect on NH_3-emission will, likely, be additive to the effect of N-efficiency improvement as pointed out above in relation to dietary CP reduction. However, quantitatively, their contribution will likely be modest to small.
- Shifting excretion of N from urine to faeces by increasing the level of fermentable fibre in the diet is possible, thereby reducing TAN excretion. However, overall N-efficiency might be reduced due to negative effects of fibre on protein digestion. This does not seem an effective method to substantially reduce NH_3-emission.

Possible negative effects of these dietary modifications on animal growth performance, production costs, and animal welfare and health are:

- Reducing the dietary CP level below 150 g/kg will raise feeding costs significantly. As an indication, at present-day prices, we calculated that a reduction of the dietary CP content with 1 g/kg will raise feed costs by about € 1/ton of feed. A reduction of the dietary CP content of 20 g/kg will increase feeding costs of a growing pig (25-125 kg BW) by more than 10%.
- Feeding a low protein diet is associated with both potential positive and negative effects on health and welfare of pigs. It may induce undesired behaviour, such as tail-biting, in case the diet is limiting in one or more essential amino acids. Supplementation with targeted mixtures of AA is promising to counteract these negative effects but require further study. Feeding low protein diet limits protein fermentation in the digestive tract and reduces the risks of negative effects of protein fermentation metabolites in the gut.
- A reduction of the dietary CP contents lowers the inclusion level of by-products in the diet and goes against stimulating concepts of feeding pigs circular diets.

Other conclusions and options to further improve N-efficiency and consequently reduce N-excretion and NH_3-emission in the pig sector:

- At present, the average N-efficiency of a growing pig (25-125 kg BW) in the Netherlands is about 43%. There appears to be potential to improve the efficiency to about 50% or higher by both reducing dietary CP content and better matching the dietary AA supply with the actual AA requirements of pigs on a farm.
- The N-efficiency of sows (with piglets to weaning) can potentially be improved according to similar concepts as in growing pigs, e.g., by CP-reduction and optimisation of the AA profile. Potentially, there is some scope for improvement in the gestation period of sows, by introducing a second feeding phase and related diet. Moreover, sows are generally individually fed, at least a part of the time, over multiple reproductive cycles, aspects of precision feeding can be implemented, including the use of earlier performance data.
- At present, often a rather fixed AA profile ("ideal protein" concept) is used for all categories of pigs to formulate diets and to cover the essential AA requirements of pigs. However:
    - The AA requirements depend on the objective of production. Currently, it is based on maximising pig's growth performance, but objectives could also be maximising N-efficiency or minimising TAN excretion.
    - At low dietary CP levels, non-essential AA may become limiting. Therefore, they need to be included in the ideal protein profile.
    - AA requirements are different for animals kept under sub-optimal sanitary and/or health conditions.
    - AA requirements may be different when defined in a precision feeding system as compared to a group phase-feeding system, as the ratio between requirements for maintenance and for protein deposition may vary at an individual pig level.
    - AA requirements evolve with age, meaning that they are different for sows than for growing pigs and for piglets (up to 25 kg BW).
- Using high protein ingredients with a high CP-digestibility improves N-efficiency but does not necessarily lead to a lower TAN excretion. Conversely, ingredients with a lower CP-digestibility may reduce N-efficiency, induce risks to reduce pig performance and intestinal health, and may lead to a higher TAN excretion.
- Protein digestibility may be increased by application of specific enzymes, as proteases, phytases, and carbohydrases as feed additives. As such enzymes are already applied in part nowadays, their potential contribution to further limitation of N-excretion seems limited.
- To maximise N-efficiency, male pigs should not be castrated. Possibly, this option is limited due to the possible occurrence of boar taint, which is potentially problematic for export of meat to particular countries. Also, at the farm boars may be more difficult to keep than barrows.
- Increasing the number of feeding phases reduces the period of mismatch between dietary protein supply and AA requirements. The potential improvement of N-efficiency above three phases, as currently standard practice, is, however, limited. Multi-phase feeding, by mixing two or more diets, may be of interest, provided that a reduction in performance due to underfeeding of part of the pigs is minimised, but might require investments in feeding infrastructure at the farm.

- Precision feeding at animal level is principally a very promising concept, which may improve N-efficiency and reduce N-excretion considerably. Possibly, more precisely feeding small, more homogenous groups of pigs, rather than individual animals, may be an intermediate option, as individual feeding requires large investments at the farm. Precision feeding at animal level requires further research and development of new systems before they can be implemented in practice.

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Appendix 1 N-efficiency sows (+ piglets) and grower-finisher pigs

The N-efficiency was calculated according to the method of Millet et al. (2018). See this publication for details on calculations.

A: Sows (+ piglets until weaning)

Sow and piglet phase	Millet et al.	NL-data	Comments for NL-data[1]
Days lactation (d/y)	67	67	2.35 cycles/y; 28.3 d lactation/cycle (CBS)
Days gestation / non-productive (d/y)	298	298	
N piglets (per sow * y)	27	31.5	CBS
Weaning weight piglets (kg)		7.5	CBS
Starting weight G-F period (kg)		25.5	CBS
Feed intake lactation (kg/d)	6.9	6.9	Van der Peet and Bikker (2019)[2]
Feed intake gestation/non-productive period (kg/d)	2.7	2.9	Van der Peet and Bikker (2019)[3]
Creep feed intake (total period, kg/piglet)	0.275	0.8	CBS
Dietary CP-content (g/kg)			
Lactation	160	136	Overall value sows + rearing sows + creep feed, weighted for number of
Gestation / non-productive	130		animals (CBS)
Creep feed	170	195	Costermans et al. (2020)
N-intake sow (kg/y)	28.6	28.9	From daily feed intake + dietary CP-
N-intake piglets (kg/y)	0.2	0.8	content
N-content weaner piglet (kg)	0.2	0.18	N-content at weaning: 24 g/kg (CBS)
BW gain sow (kg/y)	48	34	CBS
N-retained in sow (kg)	1.4	0.9	N content sow gain: 25.2 g/kg (CBS)
N-retained in piglets (kg)	5.4	5.7	
N-efficiency sow (%)	23.5	22.0	N-retained (sow + piglets) / N-intake (sow + piglets) * 100

[1]: Where "CBS" is indicated, it concerns 2024-values (CBS, 2025).

[2]: Assumed: parity 3, with correction for higher litter weight. Dietary energy content 9.3 MJ NE/kg.

[3]: Assumed: parity 3, with recovery. Dietary energy content 8.7 MJ NE/kg.

B: Growing pigs (weaning – 125 kg BW)

	Millet et al.	NL-data[2]			Comments for NL-data[1]
		Boars	Gilts	Barrows	
Age at start G-F period (d)		76			CBS
Feed intake weaning - start G-F period (kg/piglet)		29.2			CBS
N-content piglet at start G-F period (kg)		0.64			N-content gain weaning - start G-F period: 25.8 g/kg (CBS)
Slaughter weight (kg)	110	125			CBS
N-content slaughter pig (g/kg)		25			CBS
FCR					
Piglet[3]	1.7	1.62			CBS
Starter	2.1	1.98	2.09	2.11	Based on CVB (2023b)[4]
Grower	2.6	2.23	2.45	2.40	
Finisher	3.3	2.68	3.15	2.96	
G-F		2.37	2.67	2.58	
Dietary CP-content (g/kg)					
Piglet	174	165			CBS
Starter	159	162			Estimated values[5]
Grower	146	154			
Finisher	138	143			
G-F		149			CBS
N content pig (kg)	3.1	3.1			110 or 125 kg BW
N-intake pig (kg)					
Piglet	0.8	0.8			
Starter	1.1	1.3	1.3	1.3	
Grower	1.5	1.6	1.8	1.8	
Finisher	2.9	2.8	3.2	3.1	
G-F	6.3	5.6	6.3	6.1	Millet et al.: 8-110 kg
N-efficiency pig (25.5-125 kg) (%)		44	39	41	
N-efficiency growing pig (8-110 kg /7.5-125 kg)	46	46	41	43	
N-efficiency sow + her offspring					
N-intake (kg/y)	199	231	254	247	
N-retention (kg/y)	85	99	99	99	
N-efficiency	43	43	39	40	

[1]: Where "CBS" is indicated, it concerns 2024-values (CBS, 2025).

[2]: Where no values are indicated for barrows and gilts, these are equal to that of boars

[3]: Pig's weight ranges (kg BW) for the separate phases according to Millet et al. (2018) and, between parenthesis, NL-data: 'Piglet' 8-25 (7.5-25.5), 'Starter' 25-45 (25.5-50), 'Grower' 45-70 (50-80), 'Finisher' 70-110 (80-125), 'G-F' 25-110 (25.5-125). Phases for the Dutch situation were defined according to CBS (2025) and Van der Peet-Schwering and Bikker (2018).

[4]: Assuming diets containing 9.68 MJ NE/kg. Data were (linearly) interpolated at day-level and extrapolated to 125 kg BW.

[5]: The values agree with overall G-F value (CBS) after weighting of feed intake in the separate phases.

Appendix 2 Data used in the calculation of N-efficiency in growing pigs and sows with piglets using a factorial approach

For further details see also paragrafsectiph 2.3.4.
Growing pigs (25-125 kg BW):

- Pig weight and energy intake: CVB, 2023b, Table 22. Values are linearly interpolated per day up to 113 days of age and extrapolated to a BW of 125 kg.
- Slaughter weight: 125 kg (CBS, 2025)
- Three feeding phases: starter (25-50 kg BW), grower (50-80 kg BW), and finisher (80-125 kg BW).
- Energy value of growing pig diets: 9.68 MJ NE/kg (starter, grower, and finisher diets)
- (Where relevant) Dietary protein level: 162, 154, and 143 g CP/kg (for starter, grower, and finisher diets, respectively; estimation based on CBS, 2025)
- Standardised ileal digestibility (SID) of CP: 85, 83, and 81% (for starter, grower, and finisher diets, respectively; arbitrary values)
- Protein losses with skin and hair: 0.1044 g CP/kg^0.75·day (Van Milgen et al., 2008)
- Basal protein turnover losses: 0.3611 g CP/kg^0.75·day (Van Milgen et al., 2008)
- Basal intestinal losses: 14.05 g CP/kg dry matter intake (NRC, 2012)
- Efficiency of CP utilisation for maintenance: 0.85 (NRC, 2012)
- (Where relevant) Efficiency of CP utilisation for protein retention: 0.735 (NRC, 2012)
- Mean protein content in BW gain growing pigs: 156.3 g/kg (Royer and Bikker, 2025)

Sows and piglets:

- Number of birth cycles: 2.35/sow·year (based on CBS, 2025)
- Length of lactation: 28.3 days/cycle (CBS, 2025)
- Number of piglets weaned: 31.5/sow·year (CBS, 2025)
- Birthweight: 1.4 kg/piglet
- Average daily gain to weaning: 0.22 kg/piglet·day
- Weaning weight: 7.5 kg/piglet (CBS, 2025)
- Weight at start growing period: 25.5 kg/piglet (CBS, 2025)
- Age at start growing period: 76.0 days (CBS, 2025)
- Energy value sow diets: 8.71 and 9.33 MJ NE/kg (gestation and lactation, respectively)
- Energy requirement sow gestation: 7.36 MJ NE/kg (parity 3 with recovery; Van der Peet-Schwering and Bikker, 2019)
- Energy requirement sow: 64.75 MJ NE/kg (parity 3 with correction for higher litter growth; Van der Peet-Schwering en Bikker, 2019)
- Creep feed intake: 0.8 kg/piglet (CBS, 2025)
- BW gain sow: 14.5 kg/cycle (CBS, 2025)
- N content BW-gain: 24.0 and 25.2 g N/kg (piglet and sow, respectively; CBS, 2025)

Appendix 3 The effect of dietary CP reduction on diet costs

As is common in practice, least costs feed compositions were formulated using linear programming. We used the solver add-in of Excel for these calculations. Diets were calculated for the starter (25-50 kg BW), grower (50-80 kg BW), and finisher (80-125 kg BW) phases. Nutritional requirements were taken for boars, as given by CVB (2023b). For AA, these include only minimum requirements for EAA, thus no minimum inclusion levels were assigned to NEAA or CP. The raw material matrix of the CVB table (CVB, 2023a) was used, with additional values for ingredients such as phytase from a commercial supplier. Raw material constraints were as in common practice. Their costs were taken from different sources (August 2025 prices). Costs of free AA other than lysine, methionine, threonine, tryptophan, and valine, were estimated from quotations on the internet. Because different sources of information were used, the resulting cost price of diets should only be considered as indicative.

For each of the three diets, a first calculation was made without limiting the CP level, which results in a "optimal" least costs diet composition, given the nutritional and raw material constraints indicated above. Then, the maximal CP level was reduced in steps of 5 or 10 g/kg diet, down to a level where the formulation program did not provide a practically realistic composition anymore. A not-realistic diet composition is defined as a composition which gives a feasible solution in the least-costs calculations, but which includes, for example, ingredients uncommon in diets for the specific category of pigs, such as the inclusion of milk powder in a finisher diet. Most striking in this respect was the inclusion of free L-phenylalanine, an EAA, which is at present not registered as a feed additive in the EU. Through the realistic results a regression line was fitted relating dietary CP level and costs per ton of feed. The results for the starter diet are shown in Figure 12. Results for the grower and finisher diets provided a similar picture. Relevant results are shown in Table 5.

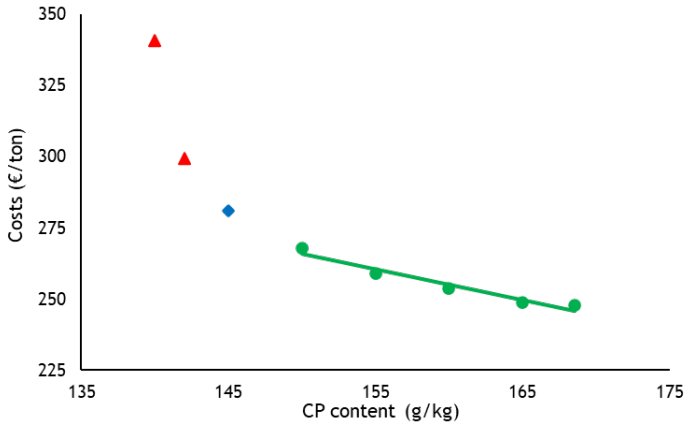


Figure 12 Results of least costs starter feed formulation for boars. First the dietary CP contents was unrestricted and then reduced in steps of 5 g/kg. The green dots indicate the resulting feed costs for which the calculated feed composition was realistic. A linear regression line (green line) was fitted through these values. The red triangles indicate outcomes where free L-phenylalanine was included in the diet, although it not yet available for use in animal feed. The blue dot indicates a composition where no free phenylalanine was included, but which does not appear realistic.

Table 5 *Results of the least costs formulations of diets for growing boars with decreasing CP content (25-125 kg BW). See text for basic principles.*

Diet	"Optimal" CP-contents (g/kg)	Minimal "realistic" CP-contents (g/kg)	Regression equation1
Starter	169	150	Y = 428 – 1.08 * X (R^2 = 0.95)
Grower	155	130	Y = 398 – 1.15 * X (R^2 = 0.96)
Finisher	143	120	Y = 344 – 0.91 * X (R^2 = 0.97)

[1]Where Y = feed costs (€/ton) and X = dietary CP contents (g/kg)

In relation to reduction of NH_3-emission, the dietary CP content was discussed by PBL (2020) as "overall" values, i.e. for the whole growth period (25-125 kg BW). To make the results as shown in Table 5 comparable, we weighted these results for the amounts of feed consumed by a boar in the respective phases (as calculated in paragraph 2.3.4): 49, 68, and 121 kg starter, grower, and finisher feed, respectively. The overall "optimal" dietary CP contents, thus without constraint for CP in the formulation, is 152 g/kg. The weighted costs are € 221.88 per ton diet. The lowest calculated overall "realistic" dietary CP content is 129 g/kg, which costs € 245.01 per ton diet. A dietary CP reduction of 1 g/kg increases the weighted feed costs by about € 1.02 per ton. Given the indicated amounts of feeds, reducing the dietary CP contents from 152 to 129 g/kg, the feed costs per pig rise from € 52.85 to € 58.36, or more than 10%. In other words, a dietary CP-reduction as proposed as a long-term target (PBL, 2020; Table 1) might be possible, but will increase feed costs, and reduce the economy of pig production, considerably. Of course, intermediate steps in reducing dietary CP could be considered. From Figure 12 it appears that the relationship between dietary CP-reduction and feed costs is linear, as long as the dietary ingredient composition remains "realistic". Please note that the values are indicative, and that there may be small differences in result when formulating diets for the other sexes (barrows and gilts).

Appendix 4 The effect of dietary CP reduction on N-excretion in pigs.

The effect of dietary CP reduction, as calculated in Appendix 3, on N-excretion was estimated for growing boars (25-125 kg BW) using the model as applied in paragraph 2.3.4. An intake of 49, 68, and 121 kg starter, grower, and finisher feed, respectively, was assumed, irrespective of the dietary CP content. The results are presented in Table 6.

Table 6 *Effect of dietary CP reduction of about 20 g/kg on N-efficiency and N-excretion for a growing pig (boar) (25-125 kg BW)[1].*

		"Optimal"	"Minimal"	Reduction (%)
CP content (g/kg)	Starter	169	150	
	Grower	155	130	
	Finisher	143	120	
	Total (weighted)	152	129	
CP digestibility (%)[2]		77.9	78.4	
N-intake (kg)	Digestible	4.51	3.85	
	Non-digestible	1.28	1.06	
	Total	5.79	4.92	
N-deposition (kg)		2.51	2.51	
N-excretion (kg)	Faeces	1.28	1.06	17
	Urine	1.99	1.35	32
	Total	3.27	2.41	26
N-efficiency (%)		43	51	

[1]The dietary CP contents presented are based on the "least costs calculations" (Appendix 3). The diet with the lowest CP content but still with a "realistic" ingredient composition is compared with the diet with an unrestricted ("optimal") CP level. The CP-content of the calculated diets are used to estimate N-efficiency and N-excretion using the model described in paragraph 2.3.4 and Appendix 2. The partitioning of excreted N into faeces and urine was based on the calculated faecal CP (N) digestibility values of the diets according to CVB data (2023a).
[2]Weighted for feed intake in the separate phases.

Reducing the dietary CP content with about 20 g/kg improved N-efficiency from 43 to 51%. This resulted in a reduction of N-excretion of about 26%. The decrease was more pronounced for urinary (TAN) than for faecal N-excretion: about 32 and 17%, respectively. Note that these values are indicative, based on model calculations with numerous assumptions that need to be verified and further detailed.

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