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Ley crop silage in diets to fattening pigs

- How does it affect pig performance, nitrogen utilization, health and behaviour?

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Cover: left picture: fresh silage mixed with commercial feed in a total mixed ration (TMR) before feeding. Right picture: happy, curious pigs fed silage.
(photo: Johanna Friman)

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Ley crops in diets to fattening pigs – How does it affect pig performance, nitrogen utilization, health and behaviour?

Abstract

There is an increasing interest to use silage as a feed ingredient to pigs. The aim of this thesis was to study the effect of using silage in the diet to fattening pigs and how feeding strategy influenced pig performance, behaviour, gut health and nitrogen utilization. Two studies were performed. Study I focused on 1) pig performance, 2) behaviour and gut health and 3) nitrogen utilization and study II focused on pig behaviour and time budgets. In study I, 128 fattening pigs (30-110 kg) were fed either a commercial control feed (control) or received silage in a pellet (Pellet-S) or in a total mixed ration (TMR) containing fresh, chopped silage (TMR-Ch) or fresh, intensively treated silage (TMR-Ex). In study II, 126 growing pigs (30-70 kg) received a commercial control feed (control) or silage in a pellet (Pell-S) or fresh in a TMR with chopped silage (TMR-S). In both studies, silage replaced 20% of the dietary crude protein content (g/kg).

The results in study I showed that pigs fed silage in general had a satisfying growth, but feeding fresh silage slightly reduced the daily weight gain. Pigs fed the pelleted silage had the highest daily weight gain and that feeding fresh silage slightly reduced the daily weight gain, however, pigs fed intensively treated silage performed similar to pigs fed the control diet. In study II, pigs fed TMR with fresh silage spent more and longer time performing foraging behaviours and were overall more active compared to pigs fed the pelleted silage and control diets. Feeding fresh silage reduced occurrences of gastric lesions in the gastric mucosa. Silage-based diets reduced the ammonia volatilization from the manure, which highlights the potential of using silage to reduce the environmental load from pig housing. The results support that silage is a suitable feed ingredient for fattening pigs, with potential to improve pig health and welfare.

Keywords: Finishing pigs, Silage, TMR, Dietary fibre, Weight gain, Carcass traits, Gastric lesions, Social interactions, Foraging behaviour

Vallfoder till slaktgrisar – Hur påverkar det grisarnas tillväxt, kväveutnyttjande, hälsa och beteende?

Sammanfattning

Det finns ett ökande intresse för att använda ensilage som fodermedel till grisar. Syftet med denna avhandling var att studera effekten av att använda ensilage i foderstaten till grisar och hur utfodringsstrategi påverkar grisarnas tillväxt, beteende, maghälsa och kväveutnyttjande. Två studier genomfördes. Studie I fokuserade på 1) tillväxt, 2) beteende och maghälsa och 3) kväveutnyttjande och studie II fokuserade på grisarnas beteende. I den första studien ingick 128 slaktgrisar (30-110 kg) som utfodrades antingen med ett kommersiellt foder (kontroll) eller åt ensilage i en pellet (Pellet-S) eller som fullfoder (TMR) innehållande färskt, hackat (TMR-Ch) eller intensivt bearbetat (TMR-Ex ensilage. I studie II fick 126 växande grisar (30-70 kg) antingen ett kommersiellt foder (kontroll) eller ensilage i en pellet (Pell-S) eller färskt som TMR med hackat ensilage (TMR-S). I båda studierna ersatte ensilage 20% av fodrets råproteininnehåll (g/kg).

Resultaten från studie I visade att grisar som fick ensilage generellt växte bra, men utfodring med färskt ensilage minskade den dagliga tillväxten något. Grisarna som utfodrats med pelleterat ensilage hade den högsta dagliga tillväxten, därtill växte grisarna som utfodrades med intensivt bearbetat ensilage lika bra som grisar som fick kontrollfoder. I studie II, tillbringade grisarna som fick TMR med färskt ensilage mer och längre tid med att utföra födosöksbeteenden och var överlag mer aktiva jämfört med grisar som utfodrats med pelleterat ensilage och kontrollfoder. Utfodring av färskt ensilage minskade förekomsten av magsår i magslemhinnan. Ensilage i foderstaten minskade ammoniakavgången från färsk gödsel, vilket belyser potentialen med att använda ensilage för att minska miljöbelastningen från grisstallen. Resultaten stödjer att ensilage är en lämplig foderingrediens för grisar, med potential att förbättra grisarnas hälsa och välfärd.

Nyckelord: Tillväxtgris, Ensilage, TMR, Kostfiber, Produktion, Slaktkroppsegenskaper, Magsår, Sociala interaktioner, Födosöksbeteende

Dedication

To my own pigs on our farm, that let me live out my ideas. I wish all pigs could be as spoiled as you.

To all metal rock, for keeping me afloat in my darkest moments.

I tur och retur hörs från flyttfågelstrecken
Vackert land vi bor i
Det hålls som predikan och tal till avecen
Vackert land vi bor i
Och vrålas i fyllan från Västerbrons räcken
Vackert land, vackert land
Vackert land vi bor i

Lillasyster (Original: Bo Kaspers Orkester)

What if my dreams don't become reality?
Is my life just a big mistake?
Will I be happy for the times I had
Or would I reconsider and recalculate?

Anders Fridén, Björn Gelotte, Niclas Engelin, Howard Benson (Wallflower, In Flames)

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Friman, J., Lundh, T., & Presto Åkerfeldt, M. (2020). Grass/clover silage for growing/finishing pigs - effect of silage pre-treatment and feeding strategy on growth performance and carcass traits. *Acta Agriculturae Scandinavica, Section A - Animal Science*, 70:3-4, 151-160.

II. Friman, J., Mjöfors, K., Salomon, E., & Presto Åkerfeldt, M. Feeding silage to fattening pigs - effects on nitrogen utilization and ammonia losses from fresh manure. (submitted to *Acta Agriculturae Scandinavica, Section A - Animal Science, 2022-12-07 (under revision*)

III. Friman, J., Verbeek, E., Sannö, A., & Presto Åkerfeldt, M. Inclusion of silage in diets to fattening pigs: effect on gastric ulcers and skin lesions. (submitted to *animal: The international journal of animal biosciences, 2023-04-12*)

IV. Friman, J., Verbeek, E., Fitske, L., & Presto Åkerfeldt, M. Feeding silage with different pre-treatment influences behaviour and time budgets in fattening pigs. (Manuscript)

Paper **I** is reproduced with the permission of the publishers.

Planning of the study with co-authors and conducted the experiment. Performed the statistical analysis and summarised the results. Responsible for writing and compiling the manuscript including correspondence with journal.

II. Planning of the study with co-authors and conducted the experiment. Performed the statistical analysis and summarised the results. Responsible for writing and compiling the manuscript including correspondence with journal.

III. Planning of the study with co-authors and conducted the experiment. Performed the statistical analysis and summarised the results. Responsible for writing and compiling the manuscript including correspondence with journal.

IV. Planning of the study with co-authors and conducted the experiment. Performed the statistical analysis and summarised the results. Responsible for writing and compiling the manuscript.

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Abbreviations

AAs	Amino acids
ADFI	Average daily feed intake
ADWG	Average daily weight gain
DF	Dietary fibre
DM	Dry matter
DMI	Dry matter intake
DWG	Daily weight gain
FCR	Feed conversion ratio
LW	Live weight
MJ	Mega joule
N	Nitrogen
NCR	Nitrogen conversion ratio
NDF	Neutral detergent fibre
NE	Net energy
NH_3	Ammonia nitrogen
NH_4-N	Ammonium nitrogen
NSP	Non-starch polysaccharides
PCR	Protein conversion ratio
TAN	Total ammonium nitrogen
TMR	Total mixed ration
TOT-N	Total nitrogen
SCFA	Short-chain fatty acids
SOC	Soil carbon
VFA	Volatile fatty acids
WSC	Water-soluble carbohydrates

1. Background

Swedish pig production is facing several challenges, with a high demand on the industry to reduce its climate footprint and become more environmentally sustainable. Consumers also demand more ethical animal production with high animal welfare standards. In addition, there is a global need to lower the use of imported feed sources and to find locally produced alternatives for feed for food-producing animals (van Zanten et al., 2014)

Pigs are highly explorative animals with an inherent need to explore their environment and search for feed (Stolba & Wood-Gush, 1989). In organic production, pigs shall have outdoor access, larger housing environments and *ad libitum* access to roughage, which is needed in order to meet the pigs' behavioural needs (EC, 2018). In some certification systems, the pigs also have access to pasture during summer periods (KRAV, 2023a). Organic production increases animal welfare standards but can have implications on the productivity of the pigs, as more energy is used for movement and maintenance (Stern & Andresen, 2003). Furthermore, finding high-quality organic feed ingredients can be challenging, which may lead to an increased need to import ingredients or may require overfeeding of protein to meet the pigs' requirement of amino acids. This could cause conflicts with the goals of sustainable production (IFOAM, 2014) as it might increase the climate impact per kg of meat.

Non-organic production is associated with pigs being raised in indoor housing and a greater opportunity to use feed ingredients to reach high growth rate and feed efficiency. This is positive from an environmental perspective as high growth rate and efficient feed conversion can lower the climate impact per kg of meat. From a welfare perspective, however, these intensive production systems can affect pig welfare negatively, mainly due to a limited opportunity for the pigs to perform exploratory behaviours.

Although it is required that Swedish pigs shall receive enrichment material such as straw (SJVFS, 2019), fattening pigs are still raised in confined environments with limited opportunity to perform foraging behaviour. With fewer opportunities to explore the environment, root and search for feed, pigs are likely to develop unwanted behaviours associated with negative welfare, such as tail biting, aggressive interactions or manipulation of housing equipment.

In organic pig production there is a demand to produce the majority of feed on the farm, a minimum of 20% for producers certified according to the EU regulation for organic production (EC, 2018) and 50% for those accredited by KRAV (KRAV, 2023b). It is also praxis to include perennial grass/clover leys to control pests and weeds in the crop rotation and to obtain nitrogen (N) through biological N fixation, though the use of some fertilizers and pesticides have been approved for organic production (The Rural Economy and Agricultural Societies, 2023).

Crop rotations which include perennial leys have several positive environmental effects, including increased carbon storage, soil health, biodiversity and reduced nutrient leaching (Manevski et al., 2018; Martin et al., 2020).

Previous experience and knowledge has shown that ley crops have the potential to be used as a feed resource to pigs (Wallenbeck et al., 2014; Wüstholz et al., 2017; Presto Åkerfeldt et al., 2018). It can also be useful as enrichment material and promote biodiversity in the crop production. This knowledge served as the starting point for the development of this thesis which includes the following thoughts and questions:

- What would be the most efficient method of inclusion for ley crops in the diets of pigs in order to increase their silage intake, without compromising on pig productivity?
- Will ley crops included in the feed ration still serve as an enrichment material for the pigs, promoting good health and possibilities for the pigs to express their behavioural needs?
- Could there also be an opportunity to find valid arguments for incorporating perennial leys in conventional pig farms, to both benefit crop production, but also be utilized as a feed resource and improve pig welfare in these systems?

2. Introduction

2.1 Swedish pig production

Today over 90% of Swedish pigs are raised indoors in conventional systems and only around 3% are produced organically, with access to outdoor areas and/or pastures (Swedish Board of Agriculture, 2021a). Of those 3%, the majority are raised in accordance with the regulations stated by KRAV.

In Sweden, the regulations covering organic animal production are based on either EU regulations (EC, 2018) or the local organization KRAV, which adheres to EU regulations but has also incorporated guidelines from IFOAM (IFOAM, 2014). KRAV's rules aim to cover aspects that are not included in the EU regulations and introduce additional guidelines, particularly in the area of animal welfare.

Pigs have a high motivation to root and search for feed. In a semi-natural environment, they spend around 75% of their time examining their surroundings, rooting and grazing (Stolba & Wood-Gush, 1989). Although we could not expect farm animals to behave just like their wild ancestors (Algers, 2008), they should have the opportunity to engage in the behaviours that are crucial for their welfare and that they are strongly driven to perform, which is stated in the Swedish Animal Welfare Legislation (2018:1192). Organic production aims to meet the behavioural needs of pigs by allowing outdoor access, larger housing environments and, in some cases, access to pasture (KRAV, 2023a). The pigs should have *ad libitum* access to roughage to give them the opportunity to root and forage (EC, 2018). From an animal welfare perspective, these systems are very positive, but they do have some challenges. Due to outdoor housing, organic pigs require more energy for locomotion and maintenance, and some health issues can arise (Stern &

Andresen 2003). There is also a challenge in finding viable protein sources for organic pigs with an adequate amino acid composition (Zollitsch, 2007). Together, these factors often result in a slower growth and reduced feed efficiency, which can result in a higher climate impact per kg produced meat compared to conventional produced pork (Halberg et al., 2010). Since the use of pure amino acids (AAs) is banned in organic production (EC, 2018) it is difficult to balance a diet for organic pigs that meets their nutritional requirements with respect to essential AAs (Wlcek & Zollitsch, 2004). One strategy for overcoming this challenge is feeding an excess amount of protein, which is a drawback considering environmental impact and resource efficiency (Wlcek & Zollitsch, 2004).

In conventional production, with indoor housing, pigs are more protected from disease and pathogens and the pig health status can be better monitored. In contrast to organic production, the use of AAs is permitted, and there is an opportunity to facilitate a vast variety of feed ingredients. These two aspects allow a flexibility when optimizing feed rations, allowing the pigs to reach a high daily weight gain and feed efficiency. This is positive from an environmental perspective as healthy and productive animals result in a lower climate impact per kg of meat produced.

The downside of these intensive systems is the welfare aspect. It is stated in the Swedish Animal Welfare Legislation (2018:1192) that production animals should be housed in a way that allows them to perform natural behaviours and, in order to meet the exploratory needs of the pigs, the EU regulations for organic production states:

> '[…] pigs must have permanent access to a sufficient quantity of material to enable proper investigation and manipulation activities, such as straw, hay, wood, sawdust, mushroom compost, peat or a mixture of such, which does not compromise the health of the animals.'

However, fattening pigs in Swedish conventional housing conditions, are often provided with bedding material once daily, but are still kept in confined pens. It can be questioned whether the daily provision of straw is enough to fulfil the need to root and perform exploratory behaviours. There is potential to improve the housing conditions for conventional fattening pigs and create a more satisfying environment, which would promote wellbeing.

2.2 Ley crop production

Ley crops is a broad definition of any grasses and legumes that can be included in a ley, such as timothy (*Phleum pratense*), meadow fescue (*Festuca pratensis*), perennial ryegrass (*Lolium perenne*), or red (*Trifolium pratense*) and white clover (*Trifolium repens*). A ley is defined by the Swedish Board of Agriculture (2023) as:

> '[…] crop on arable land originally sown with forage grass, forage legumes or a mixture of these.'

A major difference between conventional and organic crop production is that organic farms generally include a greater proportion of mixed clover/grass leys in the crop rotation, in order to obtain N inputs through biological fixation (IFOAM, 2021). The significance of incorporating rotational grass and legumes into crop rotations has gained attention in agricultural production due to the beneficial impacts in comparison to annual crops (Aronsson et al., 2007). These benefits include enhancing soil fertility, promoting biodiversity, and producing substantial amounts of biomass per hectare with reduced environmental consequences (Manevski et al., 2018; Martin et al. 2020). Ley is common in Swedish agriculture, and rotational grasslands with clover and other legumes are grown on a little over 40% of the Swedish arable land (Swedish Board of Agriculture, 2021b). However, only around 0.3% of this ley proportion is found on pig farms (Karlsson et al., 2022).

According to the KRAV standards, a minimum of 20% ley must be included in the crop rotation and should include legumes for N fixation (Krav, 2023b). There is also an aim towards high self-sufficiency, with a requirement that a minimum of 50% of the feed is produced on farm or in close cooperation with neighbouring farms (KRAV, 2023b). This is in contrast to conventional production, in which feedstuffs can be purchased to a greater extent. Nevertheless, many conventional pig producers still grow the majority of their own feed due to the economic benefits of home-grown feed. However, since pigs are fed mostly with cereals, crop rotations are characterized by the specialized, intensive production of predominantly cereal crops in monocultures. These systems are at a higher risk of nitrate leaching, and compacted and depleted soils, which, in turn, can damage soil fertility, biodiversity and crop yield (Brady et al., 2019)

Establishing mixed leys in these systems has the potential to provide several positive effects, such as the reduced risk of N leaching (Manevski et al., 2018; Martin et al., 2020). Leys also lower weed pressure in subsequent annual crops by impeding the emergence of annual weeds and counteracts the occurrence of plant diseases and pests (Tidåker et al., 2016; Martin et al., 2020). This creates positive conditions for the subsequent crop, providing good pre-crop value for cereals and allowing an increased crop yield (Tamm et al., 2016; Andersson et al., 2023). Due to its effect on weeds, there is a decreased need for herbicides in the long term, and the N fixation of the legumes reduces the requirement for mineral N fertilizers, which affects the energy use and climate footprint of the cultivation (Tidåker et al., 2016)

Rotational grasslands are known to capture and store carbon as soil organic carbon (SOC), which helps mitigate climate change (Prade et al., 2017; Henryson et al., 2022). In 2015, the United Nations Climate Change Conference (COP 21) in Paris launched the “4 per 1000” initiative, which aims to increase SOC in the top 40 cm of agricultural soils by 4‰ annually to mitigate the climate impact of greenhouse gas emissions. According to Henryson et al. (2022), SOC concentrations were measured at 2.4% on pig farms, compared to 3.0% on dairy farms. The study by Henryson et al. (2022) also found that pig farms (included in the study) had a ley proportion of 5%, while dairy farms had 67%. The largest observed annual increase of SOC reached a peak of 5‰, which exceeds the goal of 4‰. Even though the actual amount of SOC sequestered can differ greatly between farms, due to factors such as soil and climate conditions, as well as management practices (Bolinder et al., 2010). These results are interesting and promote an argument for incorporating more leys on pig farms.

Furthermore, the use of silage in a traditional pig diet was recently evaluated using a life cycle perspective. It was found that there was a reduction of the climate footprint of one kg of conventional pork when parts of the pigs feed ration were replaced with grass-clover silage (Zira et al., 2023). The reduction was concluded to be due to i) lower N application, resulting in reduced nitrous oxide emissions and lower emissions from mineral fertilizer production compared to grains; ii) reduced diesel usage; iii) higher yields from grass-clover ley compared to other fodder crops; and iv) precursor crop effects from the cultivation of grass-clover ley. The results from Zira et al. (2023) indicated promising results regarding the incorporation of perennial leys into a monoculture crop rotation and the potential for reducing the climate impact of pig production.

2.3 Roughage for pigs

In recent years, interest in using green biomass as a nutrient source for pigs has increased. This originates from the necessity to find new feed sources due to difficulties in finding high-quality feed ingredients, especially for organic pigs (Wlcek & Zollitsch, 2004). Using ley crops is interesting for many reasons, among these the fact that it is a source of nutrients that cannot be consumed by humans, but can be utilized by animals. In addition, it can be locally produced, which can reduce the reliance on import and transport of feed ingredients and has positive effects on crop production. From another perspective, roughage can promote the welfare of the pigs. There is a potential to increase the utilization of ley crops to improve pig production from several viewpoints. Roughage can consist of several different mixes of forage crops and it can be dried and stored and used as both hay or fermented and stored as silage.

2.3.1 Nutrient utilization

Dietary fibre (DF) includes a wide range of carbohydrates known as non-starch polysaccharides (NSP) that include pectins, cellulose, hemicelluloses, β-glucans and fructans (Bindelle et al., 2008). Some sources of DF are highly digestible for fattening pigs (e.g. sugar beet pulp or soybean hulls) while others are almost indigestible (e.g. wheat straw). The differences in digestibility are linked to the physico-chemical properties of DF (Noblet & Le Goff, 2001). Pigs' stomach and small intestine lack enzymes that can break down DF (Kass et al., 1980). Absorption of nutrients from DF is therefore minor in the small intestines and, instead, the DF is digested in the caecum and colon through microbial fermentation. The fermentation generates short chain fatty acids (SCFA) that can be absorbed and used for energy (Andersson & Lindberg, 1997). However, energy utilization from SCFA is limited in the pig and the fibre performs several physiological actions along the gastrointestinal tract (Dierick et al., 1989; Noblet & Le Goff, 2001; Bindelle et al., 2008). For example the binding of nutrients to the fibers that prevents nutrient absorption can have a negative impact on the nutrient digestibility (Andersson & Lindberg, 1997; Moeser & van Kempen, 2002). Moreover, fibre decreases the retention time in the small intestine, which reduces the exposure time of the diet to digestive enzymes, which also affects the absorption of nutrients (Bindelle et al., 2008; Hooda et al., 2011). A lower nutrient digestibility might thereby have a negative impact on the pigs' growth performance. Since the aim of pig production is, among other things, high feed efficiency and daily growth, the use of fibrous feedstuffs is therefore not desired (Carlson et al., 1999; Lindberg, 2014). However, pigs need a certain amount of fibre in their diet to maintain normal physiological function in the digestive tract (Wenk, 2001), and therefore grass meal or beet fiber is often used to optimize the fibre content (Nilsson, 2023). Furthermore, the pigs' ability to digest fibre depends on age and live weight (LW) (Noblet & Le Goff, 2001).

2.3.2 Nitrogen utilization

Increasing DF in the pig diet will shift the N excretion pattern from less urinary-N towards more faecal-N excretion. This is caused by the microbial fermentation in the hindgut. Undigested protein is being used for building up bacterial protein, which reduces the ammonia absorption in the hindgut and lowers the levels of blood urea (Bindelle et al., 2008; Lindberg, 2014). With more N being entrapped as microbial mass, urinary-N excretion is reduced and faecal-N output increases due an increased excretion of microbial-N (Bindelle et al,. 2008; Jha & Berrocoso, 2016). After urination, urea is rapidly converted to ammonia (NH_3) when mixed with the enzyme urease present in faeces (Galassi et al., 2010). In contrast with urea, N in feces is less rapidly degraded to NH_3, resulting in reduced NH3 volatilization (Noblet & Le Goff, 2001; Galassi et al., 2010). In addition, the production of volatile fatty acids (VFA) from the fermentation process lowers the pH in the hindgut and faeces, which is both beneficial for gut health and also contributes to the reduction of NH_3 volatilization in manure (Zervas & Zijlstra, 2002; Aarnink & Verstegen, 2007; Galassi et al., 2010)

2.3.3 Gut health

Gastric lesions are a recognized health and welfare problem in pig production (Robertson et al., 2002; Mößeler et al., 2014). Gastric lesions and ulcers mainly occur in the non-glandular region, the *pars oesophagea*, of the gastric mucosa. Gastric ulcers can reduce growth performance, cause pain, and indicate stress and deprived welfare (Ayles et al., 1996; Amory et al., 2006; Rutherford et al., 2018). High stress, barren environments, and finely ground or pelleted feed are some of the causal factors for the development of gastric ulcers (Amory et al., 2006; Mößeler et al., 2014; Holinger et al., 2018). However, fibrous feeds can slow down the passage rate in the stomach, reducing the fluidity of the stomach content, thereby protecting the *pars oesophagea* from erosion (Regina et al., 1999; Mößeler et al., 2014). Coarser grinding reduces the prevalence of gastric lesions (Regina et al., 1999; Nielsen & Ingvartsen, 2000; Mößeler et al., 2014) and adding straw to the diet, or housing pigs on straw beddings, can also reduce the occurrence of severe ulceration (Bolhuis et al., 2005; Herskin et al., 2016). In addition, it was discovered that the provision of grass silage is even more effective in reducing gastric ulceration than straw alone (Holinger et al., 2018).

The production of SCFA promotes a good gut health in several ways, e.g., by suppressing pathogenic bacteria and enhancing beneficial microbes, and increasing epithelial cell proliferation in the gastrointestinal tract (Montagne et al., 2003; Tan et al., 2021).

In addition, fibre affects the morphology of the microbiome in the gut (Lindberg, 2014; Li et al., 2021). Some studies indicates a connection between the gut microbiome and the brain through the gut-microbiota-brain axis (Foster et al., 2017; Wang et al., 2020; Kobek-Kjeldager et al., 2022), which can potentially influence pigs' behaviour, predominantly behaviours relating to stress and anxiety (Foster et al., 2017).

2.3.4 Pig performance and behaviour

Pigs exhibit a wide range of exploratory behaviours and are highly motivated to forage and manipulate substrates (Studnitz et al., 2007; Kallabis & Kaufmann, 2012). If the need to root, forage, and explore is limited, the pigs may redirect oral activities towards their interior and pen mates, which could lead to injuries and reduced welfare (Olsen, 2001; Studnitz et al., 2007; Kallabis & Kaufmann, 2012). Therefore, pigs should be provided with straw to enable foraging behaviour and reduce negative behaviours (SJVFS, 2019), Studies have also shown that pigs benefit from the provision of roughage in addition to the daily straw provision (Olsen, 2001; Presto Åkerfeldt et al., 2019). Negative oral behaviours and aggressive interactions towards pen mates were reduced when pigs were provided with silage (Olsen, 2001; Høøk Presto et al., 2009; Presto et al., 2013; Holinger et al., 2018). When pigs were given round bale silage with a long straw length in racks, or silage mixed with commercial feed and fed as a TMR, it positively affected the activity levels and social interactions of the pigs (Presto et al., 2013). However, pigs seem to sort out desirable parts of the silage when it has longer straw length. This generates a larger amount of residuals and consequently, the pigs do not consume the whole fed ration with reduced amounts of energy and lower daily weight gain as a result (Wallenbeck et al., 2014; Presto Åkerfeldt et al., 2019). When the commercial feed instead was mixed with chopped silage (1-3 cm) or silage processed in a bioextruder in order to receive a particle length (<0.5 cm) it was found to be successful considering the silage consumption and growth performance (Wüstholz et al., 2017; Presto Åkerfeldt et al., 2018).

Providing silage mixed with commercial feed as a pellet has also resulted in total consumption of the silage pellet and growth performance similar to pigs fed commercial compound feed (Wallenbeck et al., 2014). Feeding silage in a pellet is practical since it can be fed by the automatic feeding system. Moreover, the fibre content in the silage pellet might be beneficial as it could influence satiety and the behaviour of the pigs (Presto et al., 2013). However, pelleted silage does not provide any possibility to root and it has less value as an enrichment material.

In recent years, new techniques of bio refining have been developed to separate the protein from the fibre from fresh grass and silage, which enhances its accessibility for monogastric animals like pigs. A protein concentrate originating from green biomass has been produced, with favourable amino acid composition, high nutrient digestibility and it has been effectively utilized by pigs (Damborg et al., 2020; Ravindran et al., 2021; Stødkilde et al., 2021).

2.3.5 Practical implications

Due to practical issues, silage is often stored in round bales and given to the pigs either directly on the concrete outdoor area or provided in racks in the pen. As mentioned, this is beneficial from an enrichment perspective, but results in spillage and reduced energy intake, which negatively affects pig's weight gain. Moreover, it can be argued that the handling of the silage is a heavy task and is time consuming for the producer. Feeding silage as a pellet therefore seems like an efficient practice. However, this takes away the purpose of utilizing the silage as both enrichment and a nutrient source.

There is a lack of knowledge regarding practical and effective strategies to include the silage in the diet for pigs, and how it should be done in order to contribute with both enrichment and sufficient nutrition.

3. Aims

Silage has a well-known positive effect on pig welfare and plays an important role in a sustainable crop production system through its effect on various ecosystem services. Nevertheless, silage is not fully utilized within pig production, due to practical implications and that it is considered low feed value. Thus, the overall aim for this thesis was to evaluate how silage can be efficiently included in pig diets without compromising productivity, with it also serving as an enrichment material. The ambition was also to find valid reasons for incorporating perennial leys in conventional pig farms to use a feed source, in order to benefit both crop production and pig welfare. To evaluate how the use of silage can be increased in pig production, the specific aims of this thesis were:

- Paper **I**: to evaluate how silage feeding strategies affect growth performance and carcass traits.
- Paper **II**: to measure how silage with different particle sizes influence N utilization and NH_3 volatilization in fresh manure.
- Paper **III**: to investigate how silage with different structures influence social interactions and the development of gastric lesions.
- Paper **IV**: to observe how pig behaviour and time budgets differ when pigs are fed pelleted or fresh silage.

4. Material and methods

The project and the studies included in this thesis are part of a larger, FORMAS-funded project, with a focus on evaluating the increased utilization of ley crops for pigs. The research is based on two studies (Study I and study II) and the results have been presented in four publications. Detailed descriptions on the materials and methods are presented in the printed papers provided at the end of this thesis (Papers **I-IV**). The studies were conducted at the Swedish University of Agricultural Sciences research station at Funbo Lövsta, Uppsala (latitude 60ºN). The work was approved by the Uppsala Ethics Committee on Animal Research (ethics approval number Dnr 5.8.18-14309/2019), which complies with EC Directive 86/609/EEC on animal studies.

Study I was divided into three different research focus areas, (Paper **I-III**) and investigated fattening pigs (from 30~110 kg LW). The same animals and diets were used, but the aims and research questions differed. The main objective of these three focus areas was to evaluate the effects of including silage with different pre-treatments in the diets of fattening pigs. The first focus area was to evaluate the effect of silage inclusion on pig performance and carcass traits (Paper **I**). The second area focused on N utilization and excretion, as well as looking at the potential for reducing N losses in fresh manure when silage is included in the pigs' diets (Paper **II**). The third focus area investigated the effect of silage inclusion on the pigs' social interactions and occurrences of gastric ulcers (Paper **III**).

Study II investigated the effect of silage with different pre-treatments on social interactions and time budgets in grower pigs (from 30~70kg LW) (Paper **IV**).

4.1 Pig performance and nitrogen utilization (Paper I and II)

Animals, housing and experimental design

Study I involved 128 growing/finishing pigs (Swedish Yorkshire × Hampshire) from two production batches in a batch wise production system, with a two-week interval between batches. Each batch (1 and 2) included 64 pigs. The pigs were mixed into new groups and allocated to eight pens with eight pigs per pen at 8 weeks of age. The distribution of the pigs in each pen was balanced based on birth litter, sex, and birth weight. Each pen included four gilts and four male pigs, and no siblings were housed together. The male pigs were immunocastrated using Improvac™, with their first injection at 77 days of age and their second at 105 days. After seven days of acclimatization to the new group, each group was moved to a new pen at the start of the study. At this point, the pigs were 66 days of age (± 1 d) and weighed an average of 32 kg (± 4.2 kg). The study continued until slaughter, and the pigs were sent to slaughter on three occasions for each batch, at an average LW of 115 kg (± 6.5 kg) and 150 days of age (± 7 d).

The pens had a total area of 11 m^2, with a concrete floor in the feeding and lying area and a slatted dunging area at the back of the pen (1/3 of the pen area), resulting in a floor area of 1.4 m^2 per pig. The dunging and eating/lying areas were separated by metal bars and solid walls, respectively. A 4.5 m long feed trough was provided along the front of the pen, and two water nipples were provided in the slatted area. Throughout the study period, the pigs did not have access to straw. However, all pens were provided with daily wood shavings as bedding material.

Dietary treatments

The pigs from each batch were randomly assigned to one of four dietary treatment groups: one fed a control diet consisting of commercial feed formulated for fattening pigs (Control), and the other groups being fed one of three experimental diets that included silage. Silage was either mixed with commercial feed and fed as a pellet (Pellet-S), or was fed fresh and mixed with commercial feed as part of a total mixed ration (TMR) with chopped (TMR-Ch) or intensively treated (TMR-Ex) silage. There were two replicates for each treatment and batch, resulting in a total of four pens (32 pigs) per treatment. In all experimental diets, the same green crop silage was added to replace 20% of the dietary CP content at a rate of g/kg.

To create the silage pellet for the Pellet-S diet, silage was first heat-dried and pelleted into a pure silage pellet at a dry feed producer (Genevads Grönfodertork, Laholm, Sweden), before being mixed with the commercial feed according to nutritional recommendations for fattening pigs. The TMR consisted of a commercial basal feed mixed with either chopped (TMR-Ch) or intensively treated (TMR-Ex) silage. The basal feed for the TMR was optimized so the TMR mixture met the pigs' nutritional requirements when mixed with silage at a 60:40 ratio.

Silage was collected weekly from the silage bun for the preparation of daily feed rations for the TMR-Ch and TMR-Ex treatments. The dry matter content of the silage was measured to ensure that silage made up 40% of the TMR. Half of the total amount of silage collected was kept intact and chopped for the TMR-Ch diet, while the other half was intensively treated using a bioextruder (model MSZ-B15e, LEHMANN Maschinenbau GmbH) to achieve a silage structure of 1-3mm for the TMR-Ex diet. The silage for the TMR-Ch and TMR-Ex diets were then weighed, packed into rations for each pen and feeding event, and stored in a chilled container (Cooltainer, Isolett Panelbyggen AB, Uppsala, Sweden) at approximately +4°C until feeding.

Feeding

The pigs were fed twice daily, following the Swedish nutrient recommendations for growing/finishing pigs based on the average LW of the pen (Andersson et al., 1997). The rearing period was divided into two growing phases. During growing phase 1, when the pigs had an average LW between 30-65 kg, the pigs were fed a feed ration corresponding to an *ad libitum* feeding strategy, until they reached an average LW of 65.7 kg (± 7.9 kg). During growing phase 2, from 65.7 kg until slaughter, the pigs were provided with a maximum energy supply of 25.9 MJ NE per day.

The Control and Pellet-S diets were administered using an automatic computerized feeding system, while the TMR-Ch and TMR-Ex diets were given manually as a TMR. The TMR was created by mixing the silage with basal feed in a mixer (Syntesi 140, Epox Maskin AB, Sollentuna, Sweden) before manually delivering it to the feed troughs. The silage intake comprised 20.5% of the total dry matter intake (DMI) of the TMR-Ch and TMR-Ex treatments. The chemical composition and energy value of the Control diet, Pellet-S diet, basal feed, fresh silage and TMR as fed, is presented in Table 1.

Table 1. Chemical composition (g kg^{-1} DM), energy content (MJ kg^{-1} DM) and amino acid content (% feed) of the Control diet, Pellet-S diet, basal feed for the total mixed ration (TMR), chopped (TMR-Ch) and intensively treated (TMR-Ex) silage and TMR as fed (TMR-Ch and TMR-Ex diets). TMR as fed represents the composition in a 40:60 ratio of silage and basal feed.

	Control diet	**Pellet-S diet[a]**	**Basal feed[b]**	**Chopped silage, TMR-Ch**	**Intensively treated silage, TMR-Ex**	**TMR as fed TMR-Ch diet**	**TMR as fed TMR-Ex diet**
Dry matter, %	88	89	88	34	35	66	67
Gross energy	18.3	18.9	19.5	16.7	17.2	18.4	18.6
Net energy [c]	11.0	11.0	11.8	8.1	8.9	10.3	10.6
Crude protein	191	202	205	183	178	196	194
Crude fat	36	51	69	-	-	41	41
Ash	51	59	42	95	97	63	64
Neutral detergent fibre	126	157	117	384	361	224	215

aCommercial feed + ground silage, mixed and pelleted.
bConcentrate feed optimised for mixing with silage in a total mixed ration (TMR) at 60:40 ratio.
cEstimated according to Lindberg & Andersson (1998), where energy digestibility (dE%) = 94.8 + (− 0.93 × NDF %). Digestible energy (DE) = dE × GE, ME= 0.95 × DE and NE = 0.75 × ME.

Assessment of feed intake and performance (Paper I)

In Paper **I**, the average daily feed, energy and protein intake, feed conversion ratio (FCR) and protein conversion ratio (PCR) were recorded for each pen and presented as mean values per pig. The number of days in the study was recorded separately for growing phase 1, growing phase 2 and the total growth period. FCR was calculated as: Energy intake per kg weight gain = (Mean total energy intake/(Sum of final LW - Sum of initial LW)). PCR was calculated as: Protein intake per kg weight gain = (Mean total protein intake/(Sum of final LW - Sum of initial LW)).

Starting at the beginning of the study, pigs were weighed every two weeks until they weighed approximately 90 kg, after which time weighing was done once a week. When they reached an average weight of 108 kg, they were registered for slaughter and sent to the abattoir one week later. Carcass weight was recorded, and lean meat content was determined at the slaughter facility. Dressing percentage was calculated as carcass weight divided by final weight multiplied by 100. Daily growth and daily lean meat growth were calculated using specific formulas.

Assessment of nitrogen excretion and ammonia volatilization (Paper II)

To evaluate the effect of diet on N excretion and NH_3 volatilization in Paper **II**, fresh manure was collected at the pen level. Pigs were moved to a modified pen, which allowed continuous collection of faeces and urine. From here on, the mixture of faeces and urine is referred to as manure. There were two identical pens located next to each other, which were used to collect manure from two groups of pigs at the same time. Fresh manure was sampled from two pens per day for four days from two different treatment groups each day. The pigs were moved to the collection pens 45 min after feeding in their home pen. In the collection pen, they had no access to feed, but free access to water. Manure was manually scraped off the floor and collected into a plastic container, which had a tight-fitting lid to prevent gaseous loss. Once a total of 5 L of manure had been collected, the pigs were moved back to their home pen, and the container was stored in a cool room at 4°C to minimize NH_3 loss. The time it took to collect the 5 L manure sample per pen was registered and used to calculate the average time for all the pens in each treatment. The average time per diet was then used to calculate the total daily manure production (24 h). After each sampling was completed, the collection pen was cleaned with water and left to dry until the next day's sampling.

After collecting two 5 L manure samples from each treatment group in both batch 1 and 2, the samples were merged to create a 20 L pooled sample for each treatment, as illustrated in Figure 1.

Two sub-subsamples from the 20 L manure sample were collected and sent to Eurofins (Eurofins Agro Testing Sweden AB, Kristianstad, Sweden) for chemical composition analysis, as described under "*chemical analyses*".

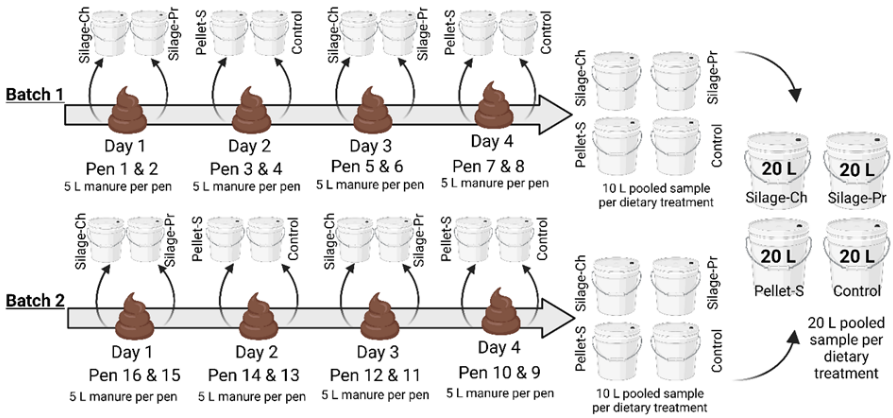

Figure 1. A schematic overview of the sampling method. Each day the pigs from two pens were moved to two different manure collection pens. In total, 5 L of manure was collected per pen. For each dietary treatment, the two 5 L manure samples were added together into a manure sample of 10 L in total. This was repeated for batch 1 and 2. Finally, the 10 L samples from each batch were pooled to create a 20 L pooled manure sample for each dietary treatment.

Calculations of nitrogen excretion (Paper II)

The expected N content in fresh manure was calculated based on Swedish standard values (Swedish Board of Agriculture, 2018), taking into account average daily feed intake (ADFI) (in kg) and average daily weight gain (ADWG) (in g/d). These calculations were compared with the N content determined by Eurofins analysis to check the correspondence between the values.

The calculated N content in fresh manure (g/d) was calculated based on the N intake (g/d) from feed during the days of manure collection (for each

specific pen) and the N (g) that is retained in ADWG (g/d). The N (g) intake was calculated as kg feed multiplied by N (g/kg) content in the diet (calculated as crude protein in diet (g/kg) divided by 6.25).
Feed intake was registered for the whole pen, and the amount of feed (kg) corresponds to the feed that was provided on the day the pigs were moved for manure collection.

Individual weighing of the pigs was performed two weeks before and two weeks after manure was collected (28 days between weighings) and ADWG was calculated as:

(Pig live weight after manure collection – Pig live weight before manure collection)/28 (1)

and the calculated content of N in manure (g) was calculated as:

N in fed feed (g) - (ADWG (g) x 0.026) (2)

where 0.026 is a constant which assumes that 2.6% of weight gain retains N (Swedish Board of Agriculture, 2018).

The time that it took to collect 5 L of manure for each pen was averaged for each dietary treatment. The collection time was then used to calculate total daily manure production (24 h). Total manure production (kg/pig/day) was calculated as:

(20 (L)/ Number of pigs in the treatment) x (24 (h)/Collection time for 5 L manure). (3)

where 20 is the total volume of collected manure per dietary treatment, assuming that 1 L of manure had a volume weight of 1:1, e.g., 1 L weighs 1 kg.

Finally, based on the measured chemical composition in the manure samples, N excretion per day (g) was calculated per treatment and then divided by the number of pigs in each dietary treatment:

(Measured content of N (g/kg) x 20) x (24 (h)/Collection time for 5 L manure))/Number of pigs in the treatment. (4)

Analysis of ammonia volatilization (Paper II)

A laboratory-scale experiment was conducted to evaluate NH_3 volatilization in fresh manure from the different diets. The 20 L pooled manure sampled from each diet was mixed and 1-L subsamples were extracted. These subsamples were placed in randomized plastic trays (50 cm x 50 cm) in a well-ventilated cool room with a controlled temperature of +10 °C. The procedure was repeated four times (Blocks 1-4), meaning there was a total of sixteen trays, four per diet. The NH_3 concentration in the air above the manure surface was measured using passive diffusion samplers (type PDS 20 x 10 mm) fitted in ventilated chambers (cuvettes), based on the work of Svensson (1993) and Larsson et al. (1999). The appropriate exposure time was determined using a Kitagawa APS-1 gas meter with a 105SD NH_3 test tube (0-20 ppm). The absorbed NH_3 was extracted and analysed in the laboratory to calculate the volatized NH_3, as described by Svensson (1993) and Larsson et al. (1999).

4.2 Pig behaviour and gastric health (Paper III and IV)

Animals, housing and experimental design

Study I also included a third focus area to investigate the effect of silage inclusion on the pigs' social interactions and the occurrences of gastric ulcers (Paper **III**). Thus, animals, housing and experimental design for the social interactions study were the same as presented in Paper **I** and Paper **II**.

Study II evaluated the effect of silage with different pre-treatments on social interactions and time budgets for growing pigs (Paper **IV**). The study included 126 growing pigs (Swedish Yorkshire × Hampshire). The study started at an average LW of 27 kg (± 4.3 kg) and 59 days of age (± 1 d). The pigs were housed in the same housing system as presented in Paper **I-III**, and the study was again conducted in two batches with two weeks between batches. Each batch included nine pens (18 pens in total), with seven pigs per pen. Each pen consisted of either four gilts and three male pigs, or vice versa. The pigs were from different birth litters and thus no siblings were included in the same pen. At weaning, pigs were allocated to one of the nine pens. Each pig group was assigned based on birth litter (to represent each sow in all treatments), weaning weight and sex to receive balanced groups. In total, each treatment included equal numbers of gilts and male pigs. When a new pig group was put together, it was randomly assigned to one of the nine pens (in each batch) by using the same Excel random number generator. The nine pens in each batch were allocated to one of the three dietary treatments in the study (three per treatment) so that treatments were evenly distributed in the stable.

Dietary treatments

The dietary treatments that were used to investigate the effect of silage inclusion on the pigs' social interactions and occurrences of gastric ulcers (Paper **III**) were the same as presented in Paper **I** and Paper **II**.

In study II (Paper **IV)**, pigs were fed one of three dietary treatments: a commercial complete feed without silage (Control); or received silage mixed with either commercial feed in a pellet (Pell-S) or in a TMR with fresh, chopped silage (TMR-S). There were three replicates for each diet and batch, resulting in a total of six pens (42 pigs) per diet. For all experimental diets, the same green crop silage was added to replace 20% of the dietary CP content (g/kg).

The silage that was used in study II was a mixture of red clover (*Trifolium pratense*) (10%), white clover (*Trifolium repens*) (5%), timothy (*Phleum pratense*) (50%), meadow fescue (*Festuca pratensis*) (20%), and perennial ryegrass (*Lolium perenne*) (15%). It was harvested in mid-July using a forage harvester and cut to a length of approximately 15-40 mm in the field. The crop was air-dried for 24 hours before being stored in a silo.

The silage pellet that was included in the Pell-S diet was produced in the same way as described in Paper **I-III**. The fresh silage was mixed with a commercial basal feed that was optimized so that the TMR-S diet (with silage substituting 20% of the CP, g/kg) had a comparable nutrient composition to the Control diet. Likewise, the Pell-S diet was also optimized to have a nutrient composition similar to the Control diet. The chemical composition and energy value of the Control diet, Pell-S diet, basal feed, fresh silage and TMR-S diet as fed are presented in Table 2.

Table 2. Chemical composition (g kg^{-1} DM), energy content (MJ kg^{-1} DM) and amino acid content (% feed) of the Control diet, Pell-S diet, the basal feed for the total mixed ration (TMR), fresh silage and TMR-S diet as fed. TMR as fed represents the composition in a 57:43 ratio of silage and basal feed.

	Control diet	Pell-S diet[a]	Basal feed[b]	Fresh silage	TMR-S diet as fed
Dry matter, %	88.0	87.3	87.3	25.4	55.6
Gross energy	17.7	18.7	18.9	17.8	18.7
Net energy[c]	10.3	10.2	11.3	8.1	10.2
Crude protein	158	166	167	189	170
Crude fat	44	82	85	36	71
Starch	436	337	432	0	313
Ash	58	66	50	105	61
Neutral detergent fibre	191	244	167	454	258

aCommercial feed + ground silage, mixed and pelleted.
bConcentrate feed optimised for mixing with silage in a total mixed ration (TMR) at 57:43 ratio.
cEstimated according to Lindberg & Andersson (1998), where energy digestibility (dE%) = 94.8 + (− 0.93 × NDF %). Digestible energy (DE) = dE × GE, ME= 0.95 × DE and NE = 0.75 ×ME.

Feeding

Feeding practices in the social interactions and gastric lesions study in Paper **III** are the same as described for Paper **I** and **II**.

In study II, to evaluate the effect of silage with different pre-treatments on social interactions and time budgets in growing pigs (Paper **IV)**, feeding was carried out twice daily. Prior to the study, daily silage rations were collected from the silo and stored in a freezer container at approximately -18°C until feeding. On the day before use, silage rations were taken out to thaw. Feed rations for the pigs in the TMR-S treatment were prepared prior to feeding by mixing basal feed and thawed silage into in a 57:43 ratio, using a mixer (Syntesi 140, Epox Maskin AB, Sollentuna, Sweden). The TMR mixture was fed to the pigs manually, whilst pigs in the Pell-S and Control treatments were fed using a computerized, automatic feeding system.

The rearing period of the pigs was divided into three phases, with feed rations being determined based on the pigs' average energy requirements at each phase, following the standard feeding and nutrient guidelines for fattening pigs outlined in Andersson et al. (1997).

The pigs were fed 12.1, 17.4 and 21.8 MJ NE during the first, second and third feeding phase respectively. The pigs had a LW of 27.6 kg (± 4.3 kg), 37.3 kg (± 5.6 kg) and 51.1 kg (± 6.7 kg) at the start of the first, second and third feeding phase respectively.

Skin lesion scoring (paper III)

Skin lesions were assessed as an indicator of negative social interactions in Paper **III**. Scoring was assessed twice based on the Welfare Quality® protocol (Welfare Quality, 2009) for growing and finishing pigs by the same observer every time. The first assessment was performed at an approximate LW of 60 kg (± 7.0 kg) and 39 days of age (± 2 d) and the second assessment at an approximate LW of 95 kg (± 9.1 kg) and 66 days of age (± 1 d).

The number of skin lesions was counted on the pig's left side, with the body divided into five regions (front, middle, hindquarter, legs and ear). Based on the number of lesions, each body region was scored from A - C (A = 0-4 lesions, B = 5-10 lesions, C = 11-15 lesions). Using the scores for each region, an overall score of 0-2 was assigned to each pig. Any pig with more than 15 lesions on any part of their body automatically received a score of 2 (Table 3). Lameness and tail lesions were also recorded during each assessment. Tail bitten pigs were treated with tar to prevent further tail biting.

Table 3. Description of the skin lesion scoring criteria used to convert the number of skin lesions counted during the skin lesion assessment into scores.

Score	Description
0	all body regions classified as 'A'
1	at least one body region with and individual score of 'B' and/or a maximum of one body region scored as 'C'
2	at least two body regions or more classified as 'C', or at least one body region with more than 15 lesions

Gastric ulcers (paper III)

At slaughter in Study I, stomachs were collected to evaluate gastric lesions in the *pars oesophagea* and the *pars glandularis* regions in Paper **III**. Stomachs were collected from 41 randomly chosen pigs within each treatment and balanced in terms of sex.

At examination, the stomachs were opened along the major curvature, emptied and carefully rinsed with water. The mucosa of all stomachs was examined and photographed by two experienced examiners, both veterinarians, one of whom specialized in pathology. Neither was made aware of the treatment groups the pigs belonged to. Based on established scoring criteria (Blackshaw et al., 1980; Carstensen et al., 2006; Jensen et al., 2017), gross lesions in both *pars oesophagea* and *pars glandularis* were scored using a graded scale which ranged from 0 for normal mucosa and increased with severity (according to Table 4)

Table 4. Description of the scoring criteria for gastric lesions in the *pars oesophagea* and the *pars glandularis*, used at the visual inspections of the stomach mucosa.

Score	Description
0	intact mucosa
1	mild hyperkeratosis[a] (<50% surface area)
2	severe hyperkeratosis (>50% of surface area)
3	hyperkeratosis and a few small erosions (fewer than 5 and shorter than 2.5 cm)
4	hyperkeratosis and extensive erosions (more than 5 erosions and/or longer than 2.5 cm)
5	hyperkeratosis and very large erosions (more than 10 erosions or longer than 5 cm) and/or ulcers

[a]Hyperkeratosis is the yellowing and roughening of the skin as a response to the prolonged exposure of acidic stomach content in the pars oesophagea (Hewetson and Tallon, 2021).

Behaviour observations (paper IV)

Behavioural observations were performed at three different occasions in Paper **IV**. Data was collected using Mangold INTERACT Software (Mangold International GmbH, Canada). The LW and age of the pigs was on average 41.1 kg (± 5.7 kg) and 76 days of age (± 1 d) in the first assessment, 54.9 kg (± 6.7 kg) and 90.4 days of age (± 1 d) in the second assessment, and 69.6 kg (± 7.3 kg) and 104.4 days of age (± 1 d) in the third assessment. Detailed information for the LW and age of the pigs in each diet are presented in Paper **IV**.

The observations followed an ethogram, and data was collected using both instantaneous (scan) and continuous sampling. Three different pens were observed each day for three days, with one pen per treatment observed each day. All pigs were observed during the scan sampling, and five focal animals were randomly selected for continuous sampling in each pen. The observations were conducted in the morning (9:00 - 12:00 AM) and afternoon (13:00 - 15:00 PM) and started with a scan sampling of all pigs in each pen. This was followed by 4 minutes of continuous observation of one focal animal in the first pen. The behaviours that occurred during the observation were recorded, and the duration of each behaviour was measured. After the continuous observation, a new scan sampling of the second pen was conducted, and the procedure continued for all three pens. Each session took about 55 minutes and was repeated three times in the morning and two times in the afternoon. Figure 2 shows the timeline for a session. The behaviours recorded are shown in an ethogram separately in paper **IV**.

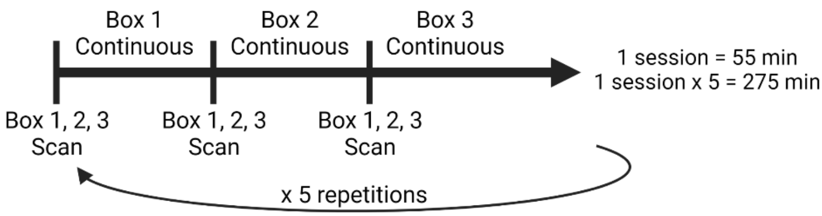

Figure 2. An overview of the timeline over a session and the procedure of data collection by instantaneous (scan) and continuous sampling.

4.3 Chemical analyses

The feed samples in study I (Paper **I-III)** were freeze-dried, milled through a 1-mm sieve, and dried at 103°C for 16 hours to determine their DM content. The ash content was assessed by combusting the samples at 550°C for 3 hours, while N content was measured following Kjeldahl's method (Nordic Committee on Food Analysis 1976) using a 2520 Digestor and a Kjeltec 8400 Kjeltec Analyser Unit (FOSS Analytical A/S Hilleröd, Denmark). CP was calculated as N x 6.25, and the GE content was determined using an Isoperibol bomb calorimeter (Parr 6300, Parr Instrument Company, Moline, IL, USA). The water-soluble carbohydrates (WSC) content was determined using an enzymatic method (Larsson & Bengtsson, 1983). To assess the hygiene quality and effects of storage, silage samples were collected and stored for seven days at +4°C. Samples were analysed on the first and seventh day to determine VFA concentrations, using the methods suggested by Andersson & Hedlund (1983). Ammonia-N concentration (% of total-N) was measured using the flow injection technique according to the manufacturer's instructions (Tecator, Application Note, ASN 50-01/92), while the pH of the silage was measured using a standard pH meter (Metrohm 654 pH meter, Herisau, Switzerland).

The feed samples in study II (Paper **IV)** were analysed as described for Paper **I-III,** although the hygienic quality of silage, VFA concentrations and WSC content were not analysed in this study. The feed samples in this study were also analysed for starch and EG-fat. Starch was analysed using the simplified enzymatic method suggested by Larsson & Bengtsson (1983), and crude fat was analysed using a Hydrotec 8000a Soxtec 8000 Extraction Unit (Foss Analytical A/S Hilleröd, Denmark) (EC, 2009).

The manure samples in study I (Paper **II)** were frozen and sent to Eurofins (Eurofins Agro Testing Sweden AB, Kristianstad, Sweden) for chemical analysis using internationally recognized standard methods. The chemical composition was analysed for DM content (%), total nitrogen (tot-N) content (g/kg), ammonium nitrogen (NH_4-N) content (g/kg), and pH. To determine DM content, the manure sample was subjected to 103 °C for 20 hours, and the DM was then calculated. Total-N and NH_4-N content were determined using the Kjeldahl + dewardas method (EC, 2009), while pH was measured directly in the sample.

4.4 Statistical analyses

For Paper **I-III** the statistical analysis was performed using the SAS program, version 9.4 (SAS Institute, Inc, Cary, NC, USA). For Paper **IV**, data related to feed and energy consumption and pig performance was analysed using the SAS program, version 9.4. The behavioural data was analysed using RStudio, version "Ghost Orchid" (RStudio, 2021), using package lme4 for generalized linear mixed effect models and package tidyr for non-parametric models. All two-way interactions between the fixed effects were tested and excluded from the model if found not to be significant (P>0.05).

In Paper **I**, descriptive statistics were analysed using Proc MEANS and analysis of performance and carcass traits was done using Proc MIXED. Multiple comparisons were analysed using the Tukey-Kramer's method. Feed, energy and protein intake, FCR and PCR were analysed using pen as the experimental unit, and the model included diet and batch as the fixed effects. Pig performance and carcass traits were analysed on an individual level with the model including dietary treatment, batch and gender as fixed effects. Pen nested within batch and birth litter nested within batch was included as random effects.

In Paper **II**, data on feed, energy, protein and neutral detergent fibre (NDF) intake and nitrogen conversion ratio (NCR) was analysed as described for Paper **I**, with pen as the experimental unit. In addition, pig performance was analysed as described for Paper **I**, with pig as the experimental unit. No statistical analysis was performed on the N content in fresh manure or NH_3 volatilization due to the design of the study.

For skin lesions in Paper **III,** Proc Glimmix with a Poisson distribution was used and multiple comparisons were analysed using the Bonferroni's method. The model included dietary treatment, batch, assessment (observation occasion) and a treatment × assessment interaction as fixed effects. Sow, pen and the individual pig nested within sow was included as random effects. To account for overdispersion, an observation-level random effect (OLRE) was also included in the model. Gastric ulcers were analysed using Proc GLIMMIX with a Gaussian distribution. The model included the fixed effects of dietary treatment, batch and sex, and the random effects of sow and pen.

The scan observations in Paper **IV** were analysed using a General Linear Model with Poisson distribution. The model included fixed effects of dietary treatment, batch, sex, assessment (observation occasion) and a treatment × assessment interaction. Random effects of sow, pen and the individual pig nested within sow was included in the model. All variables were tested for overdispersion, and an OLRE was included in the model if the variable was over- or under dispersed. Multiple comparisons were analysed using the Tukey-Kramer's method.

None of the variables in the continuous observations were normally distributed and were analysed using the non-parametric Kruskal-Wallis test, filtered on assessment (assessment = 1, 2 and 3). Multiple comparisons were analysed using Dunn's Test adjusted with Benjamini-Hochberg method.

5. Main findings

5.1 Performance and carcass traits (Paper I)

Total feed consumption (from 30-110 kg) differed between the pigs fed the TMR-Ch and TMR-Ex diets and the pigs fed the Pellet-S and the Control diets ($P<0.001$). Pigs that were fed the Control diet had an average daily feed intake of 2.4 kg per pig and pigs fed the Pellet-S diet consumed an average of 2.6 kg feed per pig and day. The energy content was lower in the TMR diets and therefore pigs fed the TMR-Ch and TMR-Ex diets consumed an average of 3.2 kg per pig daily (1.9 kg basal feed and 1.3 kg silage).

Total energy and protein intake (from 30-110 kg) was higher in the pigs fed the Pellet-S diet compared to the other diets (P=0.001 and 0.001, respectively), but was similar for pigs fed the TMR-Ch and TMR-Ex diets and for pigs fed the TMR-Ex and Control diets. However, pigs fed the Control diet had a higher energy intake and lower protein intake compared to pigs fed the TMR-Ch diet (P=0.003 and 0.020, respectively). There was no difference in FCR, expressed as MJ NE/kg weight gain, between the diets (Table 5).

Pigs fed the Pellet-S diet had the highest total daily weight gain (DWG) (P=0.001), whereas pigs fed the TMR-Ch diet had the lowest daily weight gain compared to the other diets (P=0.001). Total DWG did not differ between pigs fed the TMR-Ex diet and pigs fed the Control diet. In growing phase 1 (pig LW 30-65 kg), pigs fed the TMR-Ch and TMR-Ex diets had a lower DWG than pigs fed the Pellet-S diet (P=0.001 and P=0.050), but the DWG of the pigs fed the TMR-Ex diet was comparable to the pigs fed the Control diet. The lowest DWG was seen in pigs fed the TMR-Ch diet, which also differed from pigs fed the Control diet (P=0.001). In growing phase 2 (pig LW 65-110 kg), the DWG was higher in the pigs fed the Pellet-S diet, compared to the pigs fed the other diets (*P*=0.001) (Table 5).

Carcass weight was higher for pigs fed the Pellet-S diet compared to pigs fed the TMR-Ch diet (*P*=0.030). Pigs fed the Control diet had higher dressing percentage than pigs fed the TMR-Ch and TMR-Ex diets (*P*=0.020 and *P*=0.050, respectively); lean meat content was similar in all diets (Table 5).

Table 5. Difference in daily average intake of feed (kg), energy (MJ NE) and protein (g CP) between the four dietary treatments (Control, Pellet-S, TMR-Ch and TMR-Ex)[a] and effect of treatment on feed conversion ratio (MJ NE kg−1 growth) from the start of the study until slaughter (30-110 kg). Daily weight gain is presented for both growing phase 1 and 2 and the total daily weight gain. The results are presented as least square means and pooled standard error (SEM). Level of significance was set at $P < 0.05$.

	Control (N=32)	Pellet-S (N=30)	TMR-Ch (N=31)	TMR-Ex (N=31)	SEM	P
Total days in study	80.2^{ab}	78.7^{a}	83.8^{b}	81.9^{ab}	1.53	0.010
Feed intake	2.4^{a}	2.6^{a}	3.2^{b}	3.2^{b}	0.02	0.001
Energy intake	23.6^{a}	25.6^{c}	22.4^{b}	23.1^{ab}	0.17	0.001
Protein intake	408.2^{b}	469.8^{c}	423.8^{a}	421.1^{ab}	3.03	0.001
Feed conversion ratio	23.0	23.6	23.6	23.1	0.23	0.145
Initial weight (kg)	32.7	32.4	32.8	32.5	0.74	0.950
Final weight (kg)	114.7^{ab}	117.7^{b}	111.5^{a}	113.4^{ab}	1.50	0.014
Daily weight gain (g) 30-65 kg LW	952^{bc}	966^{c}	811a	887^{ab}	24.4	0.001
Daily weight gain (g) 65-110 kg LW	1064^{a}	1148^{b}	1022^{a}	1054^{a}	19.0	0.001
Daily weight gain (g) 30-110 kg LW	1023^{a}	1084^{b}	951^{c}	996^{a}	14.8	0.001
Carcass weight (kg)	84.6^{bc}	85.3^{b}	81.1^{ac}	82.5^{ab}	1.09	0.018
Dressing percentage (%)	73.8^{c}	72.8bc	72.5^{ab}	72.7^{ab}	0.41	0.016
Lean meat content (%)	60.7	60.8	61.5	60.9	0.51	0.832
Lean meat growth 30-110 (g day^{-1})	465.5^{b}	481.0^{b}	422.2^{a}	442.2^{a}	8.11	0.001

aPellet-S: commercial feed + ground silage, mixed and pelleted; TMR-Ch: commercial feed mixed with chopped silage fed as TMR: TMR-Ex: commercial feed mixed with intensively processed silage fed as TMR

5.2 Nitrogen utilization and ammonia volatilization (Paper II)

The comparison between calculated N in manure, based on standard values, and the chemical analysis of fresh manure indicated that the assumptions around N excretion seemed valid for the Control, TMR-Ch and TMR-Ex diets. However, the measured N excretion was lower than predicted for the Pellet-S diet (Table 6). Pigs in the TMR-Ch and TMR-Ex treatment had numerically higher tot-N (g/kg DM) compared to the Control treatment. Manure from pigs in the TMR-Ex treatment contained numerically less ammonium N (NH_4-N) compared to pigs fed the other diets (g/kg fresh manure). Pigs in the Control treatment had the numerically highest content of NH_4-N in their manure (Table 6).

It took on average 3 h to collect 5 L of manure from the pigs in the TMR-Ch and TMR-Ex treatments and 4 h from the Pellet-S and Control treatment groups. Based on this average time, total manure production was calculated, showing numerically higher manure production from the pigs in the TMR-Ch and TMR-Ex treatments compared to the pigs in the Pellet-S and Control treatments. Daily N excretion (g N/d) was thus numerically higher when the pigs were fed fresh silage (TMR-Ch and TMR-Ex) compared to pigs fed pelleted feed (Pellet-S and Control) (Table 6).

Table 6. Dry matter (DM %), total nitrogen (tot-N) (g/kg fresh manure and % DM), ammonium-nitrogen (NH_4-N) (g/kg fresh manure and % DM) and pH in fresh manure (faeces + urine) from pigs fed the four dietary treatments (Control, Pellet-S, TMR-Ch and TMR-Ex)[a]. N = number of pigs in each treatment

	Control N=32	Pellet-S N=30	TMR-Ch N=31	TMR-Ex N=31
DM (%)	18	17	14	16
Tot-N (g/kg)	8.8	8.0	7.4	7.6
Tot-N (% DM)	48.9	47.1	52.9	47.5
NH_4-N (g/kg)	3.6	2.7	2.7	2.2
pH	6.97	6.39	6.89	6.62
Measured daily manure production (kg/d)[1]	3.8	4.0	5.2	5.2
N in average daily pig weight gain (g)[2]	28.6	29.0	26.5	28.3
Calculated N excretion (g/d)[3]	36.5	44.2	39.5	38.4
Measured N excretion (g/d)[4]	33.0	32.0	38.0	39.0

aPellet-S: commercial feed + ground silage, mixed and pelleted; TMR-Ch: commercial feed mixed with chopped silage fed as TMR: TMR-Ex: commercial feed mixed with intensively processed silage fed as TMR

1Calculated as; (20 L manure/Number of pigs in the treatment) × (24/collection time for 5 L manure), where 1 L of manure has a volume weight of 1:1, e.g., 1 L weighs 1 kg.

2Calculated as; average daily weight gain × 2.6%.

3Calculated as; nitrogen intake – nitrogen in average daily weight gain.

4Calculated as; (Measured content of N (g/kg) x 20) x (24 (h)/Collection time for 5 L manure))/Number of pigs in the treatment.

Manure from the pigs in the Control treatment had the numerically highest NH_3 volatilization (17.9 g NH_3-N L^{-1}). The lowest NH_3 volatilization was observed from the TMR-Ex treatment (5.2 g NH_3-N L^{-1}), while the NH_3 volatilization was similar between the TMR-CH and Pellet-S treatments (11.3 g NH_3-N L^{-1} and 10.9 g NH_3-N L^{-1}, respectively).

Figure 3 shows that the NH_4-N content (g/kg fresh manure) correlated with NH_3 volatilization, with higher NH_4-N levels leading to greater NH_3 volatilization.

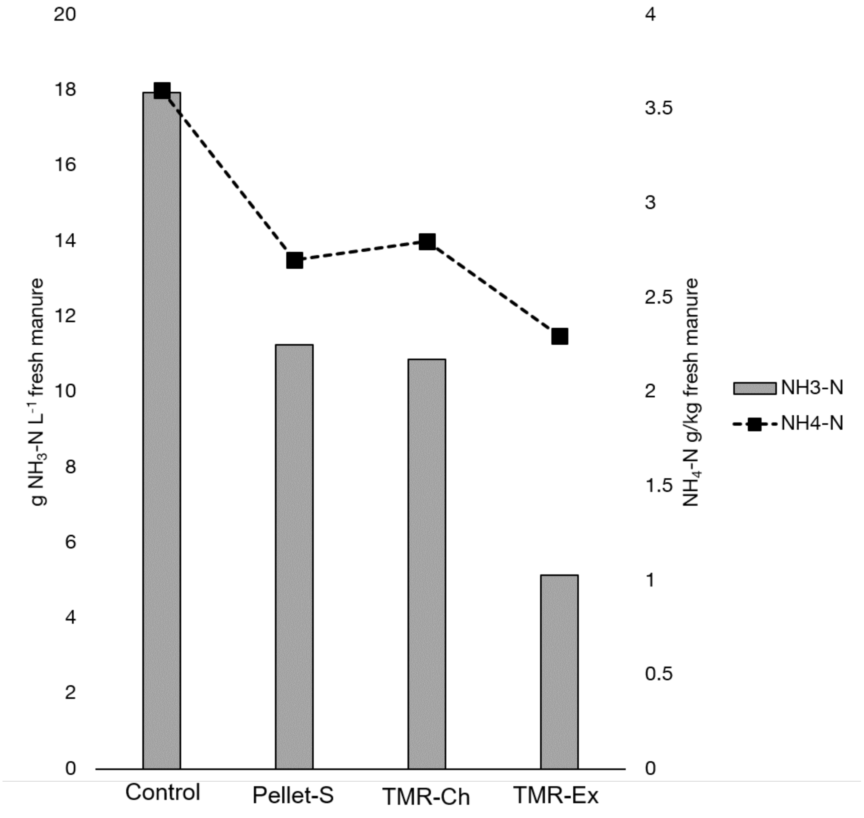

Figure 3. Effect of the four dietary treatments, Control, Pellet-S, TMR-Ch and TMR-Ex on (bars) ammonia (NH_3) volatilization (g NH_3-N L^{-1}) from 1 L of fresh manure (faeces+ urine) to the air above and (dotted line) content of NH_4-N (g NH_4-N kg^{-1}) in fresh manure.

5.3 Social interactions and gut health (Paper III)

Gastric lesions

The pigs fed fresh silage (TMR-Ch and TMR-Ex) had in a significantly lower occurrence of gastric lesions in the *pars oesophagea* region compared to the pigs fed pelleted silage or the Control diet (Pellet-S and Control) (P<0.001).

Two pigs in the TMR-Ex treatment and three pigs in the TMR-Ch treatment showed mild hyperkeratosis in the mucosa (score 1), while severe hyperkeratosis (score 2) was found in three pigs in both the Pellet-S and control treatments. Erosions and ulcers (score 3-4) were found in three pigs in the Pellets-S treatment and five pigs in the Control treatment. One observation of severe ulceration (score 5) was found in the Pellet-S treatment (Figure 4). No ulceration was found in the *pars glandularis* region, which did not differ between diets.

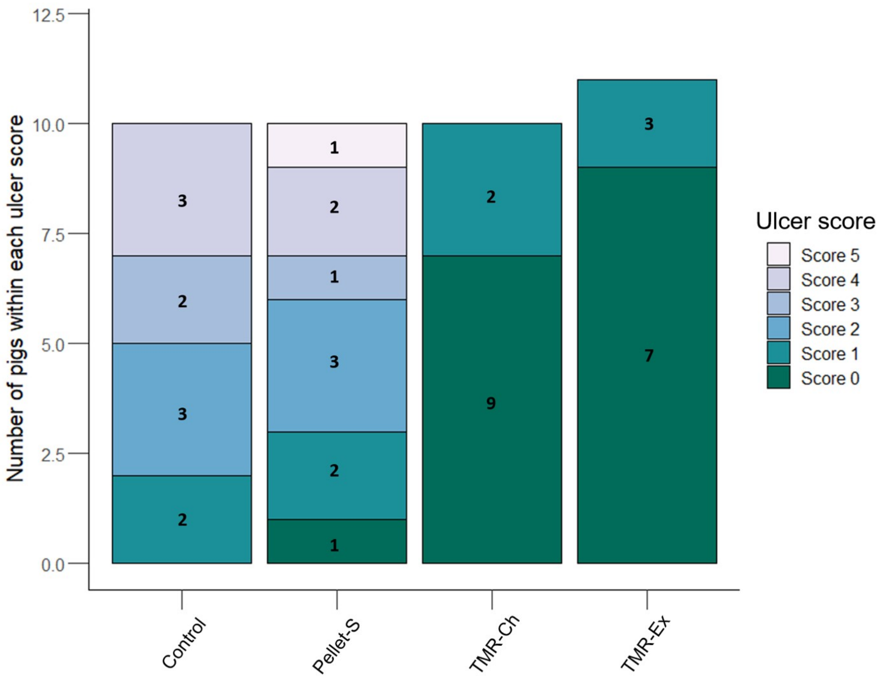

Figure 4. Number of pigs within each ulcer score (scoring criteria as described in table 4) in the Control, Pellet-S, TMR-Ch and TMR-Ex treatment groups. N=41.

Skin lesions

Number of skin lesions at each assessment is presented in Table 7. There was no significant effect of dietary treatment or assessment time on the number of skin lesions. The results, however, showed a treatment × assessment interaction on the number of total skin lesions (*P*=0.050) and skin lesions in the middle body part (*P*=0.002), the hindquarter (*P*=0.020) and the ear (*P*<0.001). However, skin lesions in the silage treatment groups were not consistently lower compared to the Control treatment, and pairwise interactions differed more within than between treatment groups. The treatment × assessment interaction and pairwise differences of skin lesions within and between assessments are presented as supplementary material in Appendix **I**.

Table 7. Number of skin lesions on each body part and a summary of the total number of lesions from each of the two skin lesion assessments in the four dietary treatments (Control, Pellet-S, TMR-Ch and TMR-Ex)[a]. Results presented as least square means and pooled standard error (SEM). N =124.

	Pellet-C	Pellet-S	TMR-Ch	TMR-Ex	SEM	P#
1st assessment						
Front	3.5	2.8	2.4	3.8	0.68	n.s.
Middle	1.3	1.5	1.1	1.7	0.38	n.s.
Hindquarter	0.4	0.4	0.4	1.0	0.17	n.s.
Ear	0.7	0.6	0.4	1.5	0.23	n.s.
Total	6.3	6.1	4.7	8.7	1.30	n.s.
2nd assessment						
Front	4.3	3.1	3.4	3.8	0.76	n.s.
Middle	2.4	0.8	0.9	1.4	0.37	n.s.
Hindquarter	0.9	0.3	0.5	0.9	0.18	n.s.
Ear	0.6	0.5	1.3	0.8	0.24	n.s.
Total	9.0	5.1	6.6	7.3	1.39	n.s.

aPellet-S: commercial feed + ground silage, mixed and pelleted; TMR-Ch: commercial feed mixed with chopped silage fed as TMR: TMR-Ex: commercial feed mixed with intensively processed silage fed as TMR

5.4 Behavioural observations (Paper IV)

Scan observations

The behaviour observations showed that the frequency of eating was significantly higher in pigs fed fresh silage (TMR-S) than pigs fed the other diets (*P*=0.001). Time also had an impact on eating frequency, which decreased over time and was lower in the third assessment compared to the first and second assessments (*P*<0.001 for both) (Figure 5)

Regarding rooting behaviour, there was a significant assessment × treatment interaction (*P*=0.020). In the first assessment, pigs fed the TMR-S diet spent significantly more time rooting compared to the pigs fed the Pell-S and Control diets (*P*<0.001 for both). The same pattern was found in the second assessment, where pigs fed the TMR-S diet rooted more compared to pigs fed the Pell-S and Control diets (*P*=0.030 and 0.020, respectively). In the third assessment, the pattern changed, time spent rooting did not differ between pigs fed the TMR-S and Pell-S diets, but pigs fed the TMR-S diet rooted more compared to pigs fed the Control diet (*P*=0.030) (Figure 5).

Pigs explored the pen equally frequently regardless of treatment, but this behaviour was not often observed (Figure 6). Also, positive and negative interactions were rarely observed, and the variables were therefore combined and analysed as social interactions; the occurrence of these was not affected by treatment or assessment time (Figure 6).

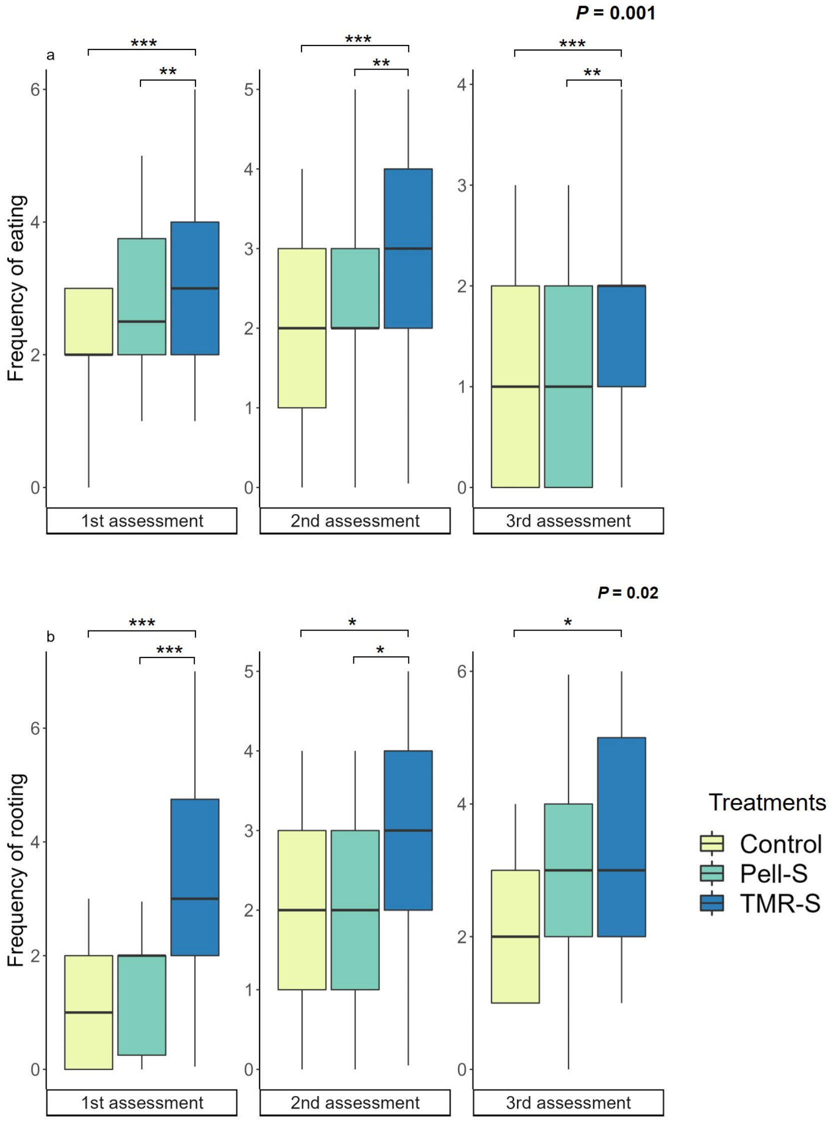

Figure 5. Effect of treatment on the frequency of a) eating and on the interaction between assessment and treatment in b) rooting on the floor in the Control, Pell-S and TMR-S treatment groups. Boxes represent the median and the upper and lower quartiles; whiskers mark the maximum and minimum values of the data points, indicating variability outside the upper and lower quartiles. Each box comprises measurements from 42 pigs (41 in Control). The effect of treatment is marked in the upper right corner. Pairwise differences between treatments at each assessment is marked in the figure: *P ≤ 0.05, ** ≤ 0.01 and *** ≤ 0.001.***P < .001, no star = not significant

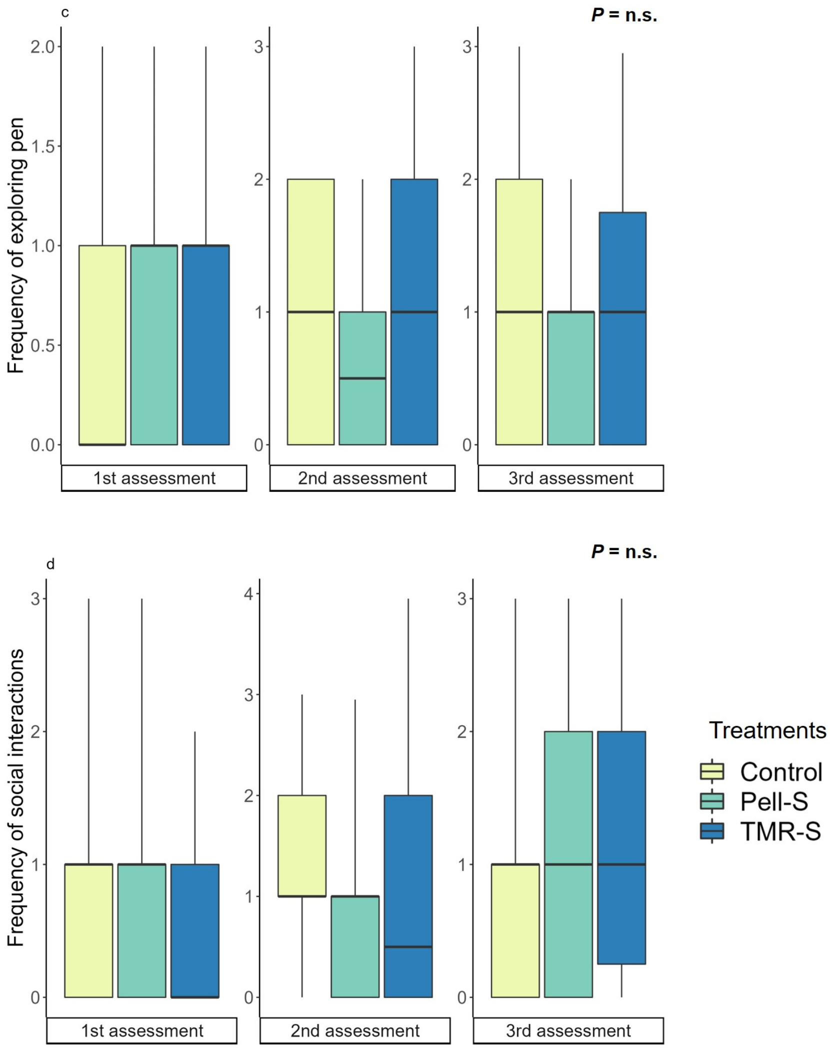

Figure 6. Effect of diet on the frequency of c) exploring the pen and d) social interactions in the Control, Pell-S and TMR-S treatment groups. Boxes represent the median and the upper and lower quartiles; whiskers mark the maximum and minimum values of the data points, indicating variability outside the upper and lower quartiles. Each box comprises measurements from 42 pigs (41 in Control). The effect of treatment is marked in the upper right corner. Pairwise differences between treatments at each assessment is marked in the figure: *$P \leq 0.05$, ** ≤ 0.01 and *** ≤ 0.001.***$P < .001$, no star = not significant

Continuous observations

The duration of eating was significantly influenced by treatment (P<0.001), pigs fed the TMR-S diet spent more time eating compared to pigs fed the Pell-S and Control diets (P=0.001 and 0.002, respectively). In the first and third assessments, the TMR-S fed pigs were more occupied with eating compared to pigs fed the Pell-S and Control diets (P=0.004 and 0.030 respectively), but no difference was found between any of the treatments at the second assessment (Figure 7).

In the first assessment, pigs fed the TMR-S diet rooted for an average of 36.3 seconds, which was significantly longer than the 6.6 and 3.5 seconds done by the pigs fed the Pell-S and Control diets (P=0.001 and P<0.001). However, in the second and third assessments, the time that the pigs spent rooting did not differ between treatments (Figure 7).

There were no significant differences in the time that pigs spent exploring the pen between any of the treatments (Figure 8), nor was the duration of positive and negative interactions between the pigs affected by treatment. However, pigs fed the TMR-S diet had numerically longer negative interactions than pigs fed the Pell-S and Control diets at the second assessment (4.2, 3.2 and 2.2 s for the TMR-S, Pell-S and Control diets, respectively) and the third assessment (4.6, 4.0 and 3.5 s for the TMR-S, Pell-S and Control diets, respectively); these differences were not significant (Figure 8).

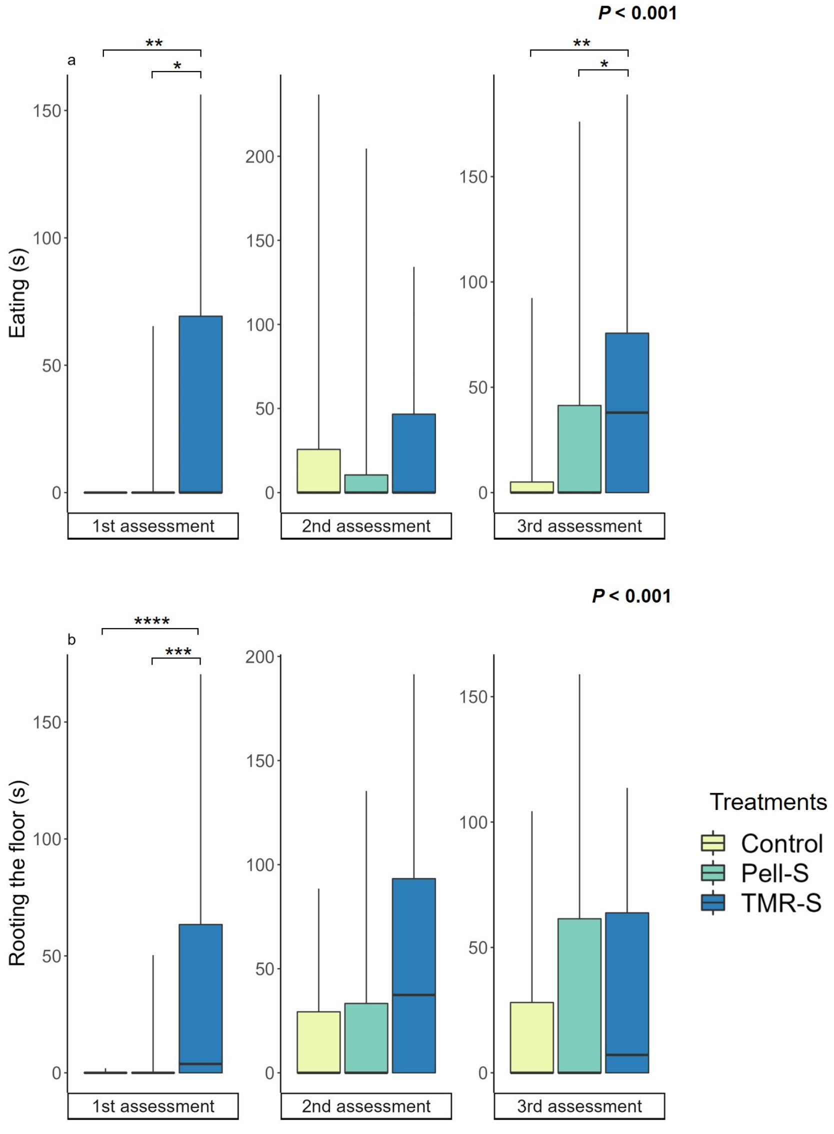

Figure 7. Effect of treatment on the duration of a) eating and b) rooting on the floor in the Control, Pell-S and TMR-S treatment groups. Boxes represent the median and the upper and lower quartiles; whiskers mark the maximum and minimum values of the data points, indicating variability outside the upper and lower quartiles. Each box comprises measurements from 42 pigs (41 in Control). The effect of treatment is marked in the upper right corner. Pairwise differences between treatments at each assessment is marked in the figure: *P ≤ 0.05, ** ≤ 0.01 and *** ≤ 0.001.***P < .001, no star = not significant

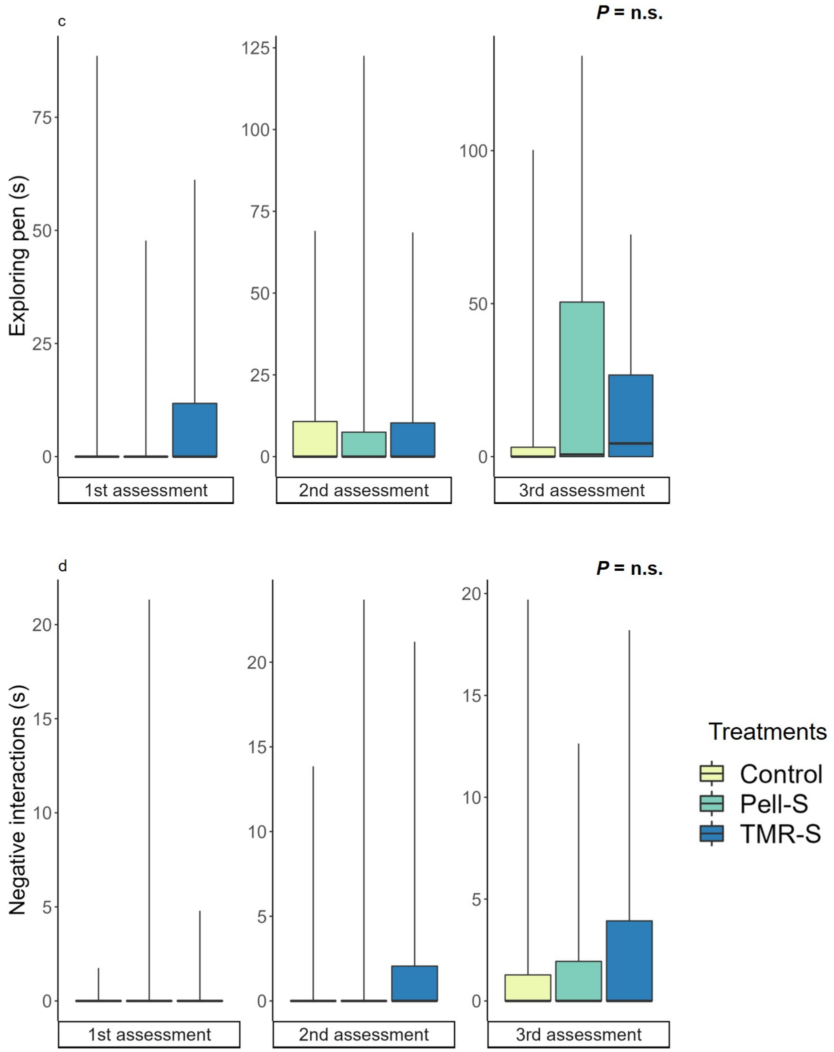

Figure 8. Effect of diet on the duration of c) exploring the pen and d) negative social interactions in the Control, Pell-S and TMR-S treatment groups. Boxes represent the median and the upper and lower quartiles; whiskers mark the maximum and minimum values of the data points, indicating variability outside the upper and lower quartiles. Each box comprises measurements from 42 pigs (41 in Control). The effect of treatment is marked in the upper right corner. Pairwise differences between treatments at each assessment is marked in the figure: *P ≤ 0.05, ** ≤ 0.01 and *** ≤ 0.001.***P < .001, no star = not significant

6. General discussion

This thesis focuses on the applicability of using silage as a source of nutrients for fattening pigs, and the ways in which feeding strategy influences pig performance, behaviour and health. The goal was to find strategies to increase the utilization of ley crops, for example, on organic farms where ley is already present in the crop rotation, but mainly serving as enrichment material for behavioural purposes. By using silage as a feed ingredient in feed formulation for pigs, the ley crops could also contribute to the production system as a locally and sustainable nutrient source, with possible effects on farm productivity. Additionally, the thesis brought up possibilities of including silage in the diets of conventional pigs. This could improve the housing conditions for pigs raised in confined pens and be utilized as a nutrient source when included in the crop rotation. The studies included in the different parts of this thesis were performed on conventionally housed pigs. This might have influenced the results as conventional and organic housing systems are different. If the same dietary treatments had been tested in an organic production system, it is possible that the pigs would have responded in another way. For example, pigs that are kept outdoors require more energy for growth, due to the greater proportion of their energy being used for maintenance and movement (Stern & Andresen, 2003; Millet et al., 2004). Pigs in organic systems are also already supplied with roughage, which might have influenced the enrichment effect of including silage in the diet. However, one aim of this thesis was to evaluate the potential for using silage as a feed ingredient for pigs, with a focus on production and well-being. The studies were performed in a controlled environment to evaluate how a feeding strategy with silage as a feed ingredient could function, and how it could then be applied in an organic or conventional production system.

6.1 Pig performance

In organic production, silage is often provided either in the outdoor area, in racks in the pen or directly on the floor. Round-bale silage provides benefits from an enrichment perspective, and studies confirm that aggressive interactions, negative oral behaviours and lesions on the body are reduced with its use (Olsen, 2001; Høøk Presto et al., 2009; Presto et al., 2013; Holinger et al., 2018). Studies have also evaluated the use of silage as a part of the pigs' feed ration and how it influences performance and pig behaviour (Presto et al., 2013; Wallenbeck et al., 2014; Wüstholz et al., 2017; Presto Åkerfeldt et al., 2018).

It was shown that when replacing 20% of the diet with round-bale silage or chopped silage, significant amounts of spillage and residue were found, as a great part of the silage was manipulated by the pigs, causing it to be rooted onto the floor and be left un-eaten by the pigs (Presto et al., 2013; Wallenbeck et al., 2014; Presto Åkerfeldt et al., 2018). A high amount of residues, and un-eaten silage reduces the pig's energy intake, which results in decreased daily weight gains (Bikker et al., 2014; Wallenbeck et al., 2014; Presto Åkerfeldt et al., 2019). Even when silage was chopped and mixed with cereal-based feed in a TMR, the pigs sorted out the silage and ate the pelleted cereal feed while the silage was partly rooted onto the floor (Presto et al., 2013). Reduced growth is costly for the farmer, and in addition, there is extra work created by the need to clean out residues and keep the pen clean.

In the study by Presto et al. (2018), pigs were fed a TMR with finely chopped silage, or silage that was processed in a bio-extruder. The particle length of the silage was 1-3 cm and <0.5 cm, respectively, and the pigs consumed major parts of the chopped silage and almost all of the intensively processed silage. The fresh silage that was fed in Paper **I** had a particle length of 4-15 mm and <0.5 cm respectively, and all diets were completely consumed. Visual inspections indicated that more residues was seen during the first week of the study, but thereafter the pigs seemed to have adapted to the pelleted silage and the TMR diets, eating the entire ration.

Fibrous diets are not commonly used in intensive fattening pig production because they can lower the digestibility of other nutrients (Lindberg, 2014). However, growth performance in Paper **I** was only marginally affected in the pigs fed the TMR-Ch and TMR-Ex diets. In addition, the feed conversion ratio was similar in all pigs, which further indicates that they were able to utilize comparable amounts of energy for growth. Pigs fed the intensively processed silage (TMR-Ex) had an equivalent daily growth as the pigs fed the Control diet in the first growth phase (30-65 kg). This indicates that the pre-treatment of the silage in the TMR-Ex diet influenced digestibility, and the pigs seemed to be able to utilize it to a greater extent than chopped silage. Reducing the particle size of silage has been found to improve growth performance in pigs, which is suggested to be caused by greater nutrient digestibility (Bikker et al., 2014). One reason for this might be the reduced particle size increasing the surface area for the digestive enzymes, which could improve nutrient absorption (Lindberg, 2014).

It is known that pig's capacity to digest fibre increases with age, as their gastrointestinal tract develops. Moreover, dietary fibre (DF) digestibility is further improved when the gut microflora has adapted to increased fibre digestion (Noblet & Le Goff, 2001; Wenk, 2001; Bindelle et al., 2008; Li et al., 2021). This could explain the improved growth performance at the second growth phase (65-110 kg) for the pigs fed chopped silage (TMR-Ch). Several studies have also concluded that pigs can compensate for restricted nutrient intake though compensatory growth, meaning that they have the ability to grow faster more efficiently after a period of dietary restriction (Fabian et al., 2004; Reynolds & O'Doherty, 2006; Millet & Aluwé, 2014). This may also have contributed to the improved performance in the TMR-Ch diet in the second phase. No difference in daily weight gain was found between the two TMR fed pigs or between the TMR-Ex treatment and the Control treatment in the second phase. The TMR-Ch fed pigs had a numerically lower final weight than the pigs fed the Control diet, but this was not significantly lower. The significant difference between pigs fed the TMR-Ch diet and those fed the Control diet for the total growth period was due to the reduced growth of the TMR-Ch fed pigs in the first phase.

Overall, the pigs fed the pelleted silage (Pellet-S) in Paper **I** performed better than the pigs fed the other diets. The ambition was for all diets to give similar results in terms of their chemical composition, but the analysis showed that the Pellet-S diet had a higher energy and protein content, and the pigs in the Pellet-S diet also had the highest energy intake, which may have influenced their growth. In previous studies, pigs fed pelleted feed with silage inclusion in the same ratio as this study, also performed comparably to the pigs fed a commercial diet without silage (Wallenbeck et al., 2014).

In agreement with Wallenbeck et al. (2014), the results from the study in Paper **I** support the inclusion of silage in pellet form in pig diets. In addition, using pelleted feed is practical, as it can be fed to pigs using an automatic system.

The silage inclusion did not affect carcass quality and the measured traits were very similar among the pigs regardless of diet. A lower dressing percentage was found in pigs that were fed silage, which was caused by their larger gastrointestinal tract and higher gut fill, this is in accordance with previous studies (Dierick et al., 1989; Wallenbeck et al., 2014). The inclusion of silage in the pigs' diet did not have an impact on the leanness of the carcass, and the lean meat content was similar across all four diets (ranging from 60.7% to 61.5%). These results are consistent with previous findings by Wüstholz et al. (2017) and suggest that all pigs were able to consume enough energy for fat deposition, regardless of their diet.

6.2 Nutrient utilization

Currently, it is standard that N content in manure produced on the pig farm is calculated based on pig diets and their performance. Thus, the farmer is able to know how much N the manure will contribute to the fertilization plan for the crop production. The procedure is simpler and requires fewer regular samples and analyses of manure stocks. Previous research has established methods for determining models that can calculate the anticipated excretion of N by considering factors such as the N content in feed, feed intake, and the N present in daily weight gain (Poulsen & Kristensen, 1998; Vu et al., 2009; Poulsen et al., 2006). The utilization of this standardized approach, which subtracts N retention in growth from N intake, was found to be highly precise in predicting N excretion. In Sweden, it has been established that 2.6% of the pigs' live weight is N (Swedish Board of Agriculture, 2018). Therefore, N excretion per pig during the fattening period (approx. 30-110 kg) can be calculated based on the total N intake and N content in the final LW of the pig (which is Final LW × 0.026). However, the weakness of the standardized tabulated values is that they rely on a standard diet for and performance from the pigs. When new feed ingredients are used, the standardized equations may therefore not be valid. This can lead to the value of manure N being under- or overestimated in the management of manure, which also increases the potential risk of N losses to the environment.

One aim of the study in Paper **II** was, therefore, to test whether the standardization of N excretion was applicable when feeding fresh silage. Calculated values based on standardized assumptions were compared with the analysis of fresh manure. The calculations seemed accurate for the Control, TMR-Ch and TMR-Ex diets, as the calculated and analysed values were similar. However, for the Pellet-S diet, the assumption was found to be invalid since the N excretion was lower than expected. One reason for this might be that the fibre content differed between the diets. The NDF content varied across diets, with the Pellet-S diet specifically containing more processed silage with lower NDF compared to the diets containing fresh silage. Despite the same source of fibre, the pre-treatments of the silage and the differences in NDF content are believed to have affected fibre digestibility and, consequently, N excretion. For example, reducing NDF content by pelleting the silage seems to have improved the fibre digestibility and reduced N content in manure, compared to what was expected. These findings suggest that a more detailed analysis, particularly with respect to digestibility and availability of N in the diet, is necessary when testing new feed sources and exploring the effects of various pre-treatment methods.

Dietary fibres in pig diets

Several studies have evaluated the effect of adding DF to the diet of fattening pigs, and how this influences energy digestibility and N utilization. However, most previous studies have only covered fibre sources rich in soluble NSP such as soybean hulls and sugar beet pulp (Canh et al., 1998; Zervas & Zijlstra, 2002; Galassi et al., 2010 etc.). Grasses, on the other hand, have a higher degree of insoluble fibre, in the form of cellulose, hemi-cellulose and lignin, which can only be degraded in the hindgut through microbial fermentation.

Previous studies have reported a shift in the N excretion pattern, from urinary-N towards more faecal-N, but with no change in total N excretion between low- and high-fibre diets (Zervas & Zijlstra, 2002; Shriver et al., 2003; Bindelle et al., 2008; Galassi et al., 2010). In the study presented in Paper **II**, N excretion did not follow the same patterns as in other studies and the daily N excretion increased when the fibre intake was higher. The reason for higher N excretion might be the higher daily manure production from these pigs. The inconsistent results in comparison to other research are likely due to different sources of fibre. Measured on g/kg DM fresh manure, the N content was numerically higher in the pigs fed the TMR-Ch diet with intact, chopped silage compared to the pigs fed the Control diet without silage. This might be due to lower digestibility of protein in the TMR-Ch diet, and more N being excreted as either undigested-N or microbial-N. The intensive processing of the silage, however, resulted in similar N content in manure (g/kg DM) as the manure from the Control fed pigs. This indicates that the processing influences the digestibility of the fibres and the proteins that might be bound to them. A common procedure for analysing digestibility and excretion patterns for different diets is to keep pigs in metabolic cages, giving the ability to separate urine and faeces. In Paper **II**, the manure collection was performed at a pen level, and it was not possible to separate the urine from the faeces. Although it was not possible to fully evaluate the digestibility of the silage in the diets, the overall results from Paper **I** and **II** indicate that silage provided sufficient energy and protein for the deposition of adipose tissue. It would, however, be valuable to conduct further research with more detailed digestibility trials to better evaluate the digestibility of fresh silage and its nutrient contribution when used in pig diets.

Ammonia volatilization

One clear effect of feeding DF is the shift from N excretion in the urine towards more faecal-N excretion (Noblet & Le Goff, 2001; Galassi et al., 2010; Lindberg, 2014). The shift is caused by the increased microbial fermentation, which requires N for microbial growth. Shifting the form of which N is excreted, from urea-N in urine to more stable forms of N, e.g. microbial-N or undigested dietary-N in faeces, results in a reduced NH_3 volatilization from manure (Noblet & Le Goff, 2001; Galassi et al., 2010).

Pigs fed the silage diets in Paper **II** showed a significant reduction in NH_3 volatilization from fresh manure (urine + faeces), which is in resemblance to previous research (Canh et al., 1998; Zervas & Zijlstra, 2002; Nahm, 2003; Shriver et al., 2003; Aarnink & Verstegen, 2007; Philippe et al., 2015). The NH_3 volatilization from manure can be affected by various factors e.g. pH as mentioned, but also initial total ammonium nitrogen (TAN) concentration (Ni et al., 1999). In this study, diet did not have an impact on the pH of the manure. However, feeding silage led to a reduction of TAN content in the fresh manure by approximately 25-40% compared to the Control diet. In addition, NH_3 volatilization was reduced by 35-70%. This result suggests that using grass-based feed sources for pigs could significantly reduce NH_3 losses from fresh manure. However, it's important to note that these experimental findings only apply to a 24-hour period within a specific housing environment. Therefore, further studies are necessary to determine the NH_3 volatilization over the entire pig production period from 30 kg to slaughter. Anyhow, the findings put extra light on the potential of using silage as feed to reduce the environmental load from pig housing.

6.3 Pig behaviour

Social interactions

Previous studies have found that the provision of silage, either in addition to straw or as a part of the feed ratio, has reduced negative social interactions and the number of lesions on the body (Olsen, 2001; Presto et al., 2013). This is in contrast to the study in Paper **III**, where the addition of silage in the diet had no clear effect on the occurrence of skin lesions.

Contrary to our expectations, skin lesions were not reduced when the pigs were fed fresh silage (TMR-Ch and TMR-Ex). In a previous study, pigs fed silage mixed with commercial feed selected only the desirable parts of the TMR ration and rooted the undesirable parts onto the floor (Presto et al., 2013). The pigs then rooted the silage on the floor, which led to more interactions and, as a consequence, they also performed more head knocking and biting behaviour towards their pen mates, which resulted in more skin lesions at the head and front of the body.

The study in Paper **III** did not include any continuous behavioural observations and it is therefore harder to conclude what caused the numerical increase of skin lesions in the pigs fed the TMR-Ch and TMR-Ex diets. It could be speculated that the increase was due to more interactions as the pigs wanted to root in the same area, which triggered competition, similarly to the observations by Presto et al. (2013). Pigs fed the pelleted silage had a tendency to have fewer skin lesions over time compared to pigs fed cereal-based feed. This is in agreement with Presto et al. (2013), who also found that skin lesions were reduced in pigs fed dried, milled silage compared to cereal-based feed only. However, the results in Paper **III** were not significant, so further research would be needed to evaluate the connection between feeding silage and occurrence of skin lesions, preferably with a larger sample size. In addition, it would be valuable to combine the counting of skin lesions with continuous observations to correlate this parameter to other behaviours. Moreover, previous studies have used silage with longer straw lengths compared to the silage that was used in Paper **III**. It could be speculated that the lack of differences in skin lesions in this study compared to other studies, is due to pigs consuming all the silage that was provided. In previous studies, more silage has been left over, or it has been fed in racks and not included in the diet. Since the pigs in Paper **III** consumed all the silage, even the parts that were rooted to the floor, there was no material left to manipulate. This complete consumption differed from previous studies, in which there was silage left which could be continuously manipulated.

In Paper **IV,** it was observed that negative interactions lasted numerically longer for the pigs fed the fresh silage (TMR-Ch), even though the difference was not significant. Fighting or longer periods of negative interactions were rarely seen. However, short interactions, including head knocking or other biting occurred sometimes around the feed trough and when rooting. The findings in study II (Paper **IV**) did not show a clear reduction in negative oral behaviours when pigs were provided silage, which has been observed in previous studies (Olsen, 2001; Høøk Presto et al., 2009; Presto et al., 2013; Holinger et al., 2018). The pigs were only observed for three days of the total production period. This may have influenced the results, since the pigs might show aggressive behaviours on other occasions, with these not necessarily being captured in the observations. The observers were also present in the pig barn, which could have influenced the behaviour repertoire among the pigs. It would therefore be interesting to perform longer behavioural observations, preferable video recordings, to capture behaviours over a longer time period.

Activity behaviour

The greatest effect of feeding fresh silage in Paper **IV** was the frequency and duration of eating and rooting and the overall activity of the pigs. The results from this study are in agreement with previous research, where provision of silage increased the time spent on eating, exploring and performing active behaviours (Olsen, 2001; Presto et al., 2013; Presto Åkerfeldt et al., 2019). Interestingly, pigs that were fed the pelleted diets in Paper **IV** also performed rooting behaviours frequently, even though they were provided with only wood-shavings and no additional rooting material. This highlights the pigs' need to root even if there is no manipulative material present. Rooting also increased over time and at the same time eating frequency decreased. The largest difference was observed at the third assessment and may be due to the pigs' LW and age. The pigs were larger and had a higher consumption capacity, hence the feed being consumed faster. When there is a lack of food or an increase in hunger, appetite foraging may appear (Studnitz et al., 2007; de Leeuw et al., 2008). The most obvious increase in rooting frequency over time was observed in pigs fed the Pell-S and Control diets, which could be linked to their limited access to rooting material and a higher need to search for food. Pigs fed the TMR-S diet, on the other hand, spent considerable amount of time rooting in all three assessments. In addition, they were more active than those fed the Pell-S and Control diets. However, the pigs fed the Pell-S diet was more active than the Control fed pigs. They also had numerically longer eating and rooting durations compared to the Control fed pigs. In a study by Presto et al. (2013), pigs fed pelleted silage had less aggressive interactions compared to pigs fed cereal based feed only. It was suggested that the pelleted silage led to longer periods of satiety, which influenced the social interactions in the pig group. The higher fibre content might be the reason for the different time budgets between pigs fed the Pell-S diet and the Control diet in the study in Paper **IV**.

Even if this was not significant, it indicates that the pelleted silage provided more activation and fulfilment than commercial feed, which might correlate with higher satiety. Hunger is most likely a cause of stress (Verbeek et al., 2012, 2014) and may contribute to the increase in redirected negative behaviours observed in pigs fed a concentrate diet (Lawrence et al., 1989). Increasing the bulk capacity can influence the feeling of satiety and could therefore reduce behavioural problems caused by hunger. Overall, the results from the instantaneous (scan) and continuous observations demonstrated that feeding fresh silage provided more activation in the form of eating and rooting and activated the pigs to a greater extent compared to pelleted silage and commercial cereal-based feed. From an animal welfare perspective, these results suggest that pigs would benefit from extra provision of silage in their daily feed rations.

6.4 Gastrointestinal health

Pigs in intensive housing systems are at higher risk of developing gastric ulcers (Blackshaw et al., 1980). The underlying cause of ulceration is not fully understood and is most likely multifactorial. However, some of the factors are infection, nutrition, stress and gastric acidity (Blackshaw et al., 1980; Amory et al., 2006; Mößeler et al., 2014; Holinger et al., 2018). Among these, the structure and particle size of the feed has a significant impact: finely ground and pelleted diets that lack sufficient structural characteristics can increase the risk of gastric ulcers due to fluid stomach content and rapid digesta emptying (Regina et al., 1999; Mößeler et al., 2014; Peralvo-Vidal et al., 2021). On the other hand, fibre-rich diets can reduce incidences of gastric lesions by slowing the emptying of the stomach and acting as a protective layer that impedes the mixing of stomach contents (Regina et al., 1999; Jensen et al., 2017; Peralvo-Vidal et al., 2021).

The results in Paper **III** clearly demonstrate how feeding fresh silage reduces the development of gastric lesions. Pigs that were fed the TMR-Ch and TMR-Ex diets showed either no or very little change in their gastric mucosa. In contrast, pigs fed the two pelleted diets (Pellet-C and Pellet-S) had hyperkeratosis as well as erosion in the mucosa. Similar results were seen in the growing pigs (30-70 kg), where pigs that were fed a TMR with fresh silage had few occurrence of gastric lesions, as compared to pigs fed pelleted silage or commercial feed, which had a higher prevalence of mucosal changes in the *pars oesophagea* region (manuscript in preparation).

Research suggests that there is a connection between the gut, microbiota, and the brain, indicating the involvement of the gut microbiota in neural development and function, both in the enteric nervous system and the brain (Foster et al., 2017). Since the composition of feed, especially DF, affects the microbiota, the interplay between fibre intake and the gut-brain axis of microbiota may have a significant impact on short- and long-term pig behaviour (Foster et al., 2017; Wang et al., 2020; Kobek-Kjeldager et al., 2022). The interplay between diet, the gut microbiota and behaviour is not yet fully understood, and more research is needed to evaluate the connection between the gut microbiome, the intestinal wall, the pig's brain, and the behavioural repertoire of the pigs. However, it seems that feeding silage, both in pellet form and fresh in a TMR, influences the microbiota in the gut, with observable differences throughout the intestinal tract (manuscript in preparation). It would therefore be interesting to further investigate how the feeding strategy of silage (pelleted or fresh) affects the microbiome and evaluate if there is a correlation with the behaviours that were observed in Paper **IV**.

7. Main conclusions

The results in this thesis show that silage can be a suitable feed source for fattening pigs promoting good growth performance and with beneficial effect on pig behaviour and welfare. In addition, the increased fibre intake seem to have a reducing effect on NH_3 volatilization from fresh manure, which could contribute to the lower climate impact from pig production.

Pig performance

- Feeding silage with a small particle size fed as a total mixed ration (TMR), or in a pellet, positively affected feed intake, and pigs consumed the total amount of silage.
- Pelleted silage can be used without negative effect on the growth performance from start of the fattening period until slaughter.
- Earlier in the rearing period, pigs that were fed fresh silage in a TMR had lower daily weight gain, but compensated and grew similarly as pigs fed commercial feed without silage, at a later stage in the fattening period.
- Carcass composition was not negatively affected by silage inclusion, however daily lean meat growth was reduced in pigs fed fresh silage.

Pig behaviour and gastric lesions

- Feeding silage as part of the diet had no effect on the occurrences of skin lesions.
- The frequency and duration of eating and rooting increased when silage was fed fresh in a TMR compared to feeding pelleted silage.

- Fresh silage fed as a TMR increased the pigs' activity and the feeding strategy gave them better opportunities to perform feed related behaviours.
- Feeding fresh silage can prevent the development of gastric lesions.

Nutrient utilization and ammonia volatilization

- Using standardized values to estimate N in manure was valid for all treatments, except for the pelleted silage, which was lower than expected.
- The pre-treatment of silage influenced the manure production and consequently total N excretion, which was higher in pigs fed fresh silage.
- Including silage in pig diets can decrease the total NH_4-N content and reduce NH_3 volatilization in fresh manure.

8. Future research

This thesis has provided promising results regarding the use of silage in pig diets. However, there is still need for more knowledge regarding the characteristic of a good “pig-silage”. More information about e.g. harvesting times, nutrient composition and dry matter content is essential in order to produce a nutritionally good quality and palatable silage for the pigs. Also, the hygienic quality and strategies for storage silage to secure a good hygienic quality and reduce workload needs to be considered. Future studies regarding the silage characteristics should:

- Evaluate the nutritional characteristics and which ley crops that are most suitable in a good silage for pigs, and study the best practices for how the silage should be harvested and stored.

Practical implications also relate to how the silage should be included in the feeding system without heavy workload or technical problems. The TMR feeding is interesting but needs to be evaluated in practice, i.e. in constructions with feeding tables and silage and feed mixers, much like those that are found in dairy barns. For liquid feeding systems there are examples from the Netherlands, where roughage is chopped before entering the mixing tank, to avoid that the fibres get stuck in the screws, which will cause the system to stop. This is interesting also for Swedish pig production, as a large part of Swedish pigs are fed in liquid feeding systems. Also, feeding systems with automatic straw or silage spreaders that can be included in the pig facilities are interesting. Future studies regarding the practical implications of feeding silage should:

- Evaluate how silage could be fed by using existing feeding systems and to develop innovative or new systems to simplify and make the inclusion of silage in the feeding system more efficient.

In the present studies, silage did not affect social interactions, but occurrence of severe aggressive interactions between pigs with dietary silage inclusion have been observed previously, possibly due to the higher DF content and longer periods of satiety. An area for future research is the effect of DF on the interaction between the gut microbiome, the brain and pig behaviour. Dietary fibre might induce a shift in the microbiota composition, which could affect stress-related physiology and behaviour of pigs. Additionally, feeding fresh silage could be seen as a way to reduce the incidences of gastric lesions in pigs, but research is needed to understand and confirm this. More knowledge social behaviours feeding silage Future studies regarding the effect of silage in the diet on behaviour and gut health should:

- Use alternative methods, e.g. video recordings, to allow observations of behavioural repertoires for a longer period of time, to minimize the risk of missing behaviours.
- Evaluate the combination of feeding pelleted silage and providing fresh silage and its effect on performance, behaviour and gut health.
- Further study the connection between diet, gut microbe, the brain and behaviour of pigs.
- Include more pigs to study the effect of diet on occurrences of gastric lesions.

Finally, the thesis showed that silage-based diets reduced the ammonia volatilization from fresh manure. The study only covered a short time frame of the fattening period. There is also limited knowledge regarding digestibility of fresh silage. Future studies regarding silage digestibly and N losses from manure when feeding silage should:

- Record N excretion and NH_3 volatilization during the entire fattening period.
- Evaluate the digestibility of fresh silage, by performing detailed digestibility trials.

9. Reflections

Martin Ragnar (Ragnar, 2015) describes in his book “The history of the pig” the cultural journey pigs have taken throughout the history of Sweden, from the ancient time of the Vikings to the present day, with high-tech housing systems and efficient production.

Until the mid-19th century, domestic pigs in Sweden were often kept as semi-wild animals known as "ollonsvin", which roamed freely in the Swedish forests, especially in Halland, Skåne and Blekinge, and mainly searched their own feed such beechnuts and acorns. However, from this time, farmers started to feed these pigs and consequently also started to house them more indoors (Ragnar 2015). During the mid-18th century and the 19th century, pig breeding started in Sweden and Europe, and many breeds were imported and exported between countries such as Sweden, Germany, and Britain (Ragnar 2015). This marked the starting point of modern pig production as we know it today.

Modern pig production is far from those semi-wild pigs, roaming for beechnuts and acorns in the woods of southern Sweden. Although modern genetics have developed highly productive pig breeds, the pig per se is still the same as those from the mid-19th century. In Sweden, the animal welfare is highly prioritized and pigs would not be productive if they were not healthy. However, it is still a concern that that this curious and explorative animal is kept in confined pens with little opportunity to forage and explore their surroundings, which is so important to them. The findings from the studies in this thesis has raised many thoughts regarding modern pig production. During the years that I have worked with my PhD project, I have heard stories about grandfathers and old relatives that raised pigs and gave them hay or silage, since it was “good for them”, and the pigs got “nice gut health”. The reason why this feed ingredient is not normally used is due to that it is considered to reduce the pig performance. However, pigs can obviously utilize nutrients from silage-based diets, depending on how it is fed. Moreover, it has a very positive effect on the gut health, and contributes as enrichment material as it benefits the pigs' eating and foraging behaviour.

The only actual drawback found in the studies performed in the thesis, was that pigs fed chopped silage in a TMR had a lower daily weight gain, and a slightly reduced performance. Perhaps combining pelleted silage with fresh silage as rooting material could be an effective strategy. The pelleted silage can easily be fed in an automatic feeding system, while fresh silage encourages pig eating and foraging. One question that I think is important to consider, is whether a reduction in growth performance can be accepted, if other parameters of the production is improved. The carcass traits of the pigs fed fresh silage was not negatively affected, it only took a few more days to reach the goal weight. In addition, the pigs benefited from the provision of fresh silage as it allowed them to perform forage related behaviours and it reduced occurrence of gastric lesions. Considering consumers demand for a more ethical animal production with high animal welfare standards, the feeding strategies that have been evaluated in this thesis show potential to improve housing conditions and meet the demand for high animal welfare standards. In addition, utilization of ley crops as a feed source positively influences several other parameters such as increased local production, carbon storage, biodiversity, improved soil conditions and overall crop production. It also seems like the use of silage in pig diets lowers the climate impact per kg meat, as suggested by Zira et al. (2023), which further highlights the potential of using silage as a feed ingredient. Maybe it is possible to establish a concept of silage-fed pigs that is marketing the aspects of increased welfare, the use of locally produced feed sources and reduced climate impact?

One important factor, however, to keep in mind when evaluating new feed sources is the effect on the final meat product. It is important that including silage in the pigs' diets does not negatively affect meat quality parameters. Meat samples from pigs in study I (Paper **I**, results not included in the thesis) was therefore also evaluated for the quality parameters, pH, drip loss and WHC in a separate study (Ohlsson, 2022). The results showed that none of these parameters differed between pigs that were fed silage based diets compared to the Control diet without silage. In addition to the technological quality parameters, sensory analysis have been performed to test the effect of feeding silage on different sensory parameters. The consumers' sensory experience is an equally important factor when evaluating meat quality. To study this, meat samples from the same study (meat from pigs in Paper **I**, results not included in the thesis) was evaluated in a sensory analysis. Preliminary data from the sensory analysis indicates that the diet had no effect on the evaluated sensory parameters such as tenderness, aromas and flavors (manuscript in preparation).

In the end, the consumer's willingness to pay extra for a premium product determines whether the concept will be successful. However, the findings from the studies in this thesis support an opportunity to develop a new concept. With this, it might be possible to compensate the minor reduction in growth by highlighting the value of increased sustainability, pig health and welfare. In the future, it would be interesting to develop a concept of silage-fed pigs and evaluate its potential to be considered as a premium product.

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Popular science summary

Swedish pig production faces several challenges. Consumers demand a more animal-friendly production and there is a need to reduce the import of e.g. soy and use more resource-efficient and circular raw materials that have a significantly lower environmental and climate impact. The availability of locally and sustainably produced feed with good protein quality, i.e. the right balance of the amino acids that the pig needs, and that does not compete with food for humans, is limited. This has led to increased interest in using ley crops, i.e. grass and clover in the feed for pigs. In terms of nutrition, ley crops are of good nutrient quality and pigs can digest the nutrients to a quite high extent. When grass and legumes are grown in the fields, they also contribute to several positive environmental effects such as storing carbon in the soil and increasing biodiversity. If the ley crops are harvested and stored as silage, it can serve as local high-quality feed all year round.

However, silage is not yet commonly used in pig diets. Pigs can, via microbial fermentation in the large intestine, break down and utilize nutrition in fibres to a higher degree than humans, but less than ruminants. On the other hand, the fibre content can result in a poorer absorption of the nutrition from other ingredients in the diet. An excessive addition of fibres is therefore not desirable, if the goal is for the pig to grow as good as possible, i.e. to use the feed as efficiently as possible. Anyhow, several studies have shown that pigs that are given extra access to silage, in addition to the daily supply of e.g. straw, perform fewer unwanted behaviours such as biting other pigs or the pen interior. Silage can also be beneficial for the pig's gut health as it contains a higher proportion of fibres that can counteract the occurrences of ulcers in the stomach. It is also known that when pigs are fed with more fibre, the ammonia losses from the manure is reduced, which is due to an increased microbial fermentation of the fibre in the pig's large intestine. In other words, there are various arguments that suggest that an increased inclusion of silage in the pig's feed can be favourable from several perspectives.

There is potential to increase the utilization of forage in pig production, but there is a lack of practical solutions to be able to use it effectively in the pig's diet.

The purpose of this thesis was to investigate how feeding strategy and silage straw length affect pig growth, carcass characteristics, behaviour, stomach health and nitrogen utilization. The results are based on two studies, study I and II. Study I was divided into three different focus areas; growth, behaviour and gut health as well as nitrogen utilization, with the aim to investigate the effect of silage pre-treatment and feeding strategy. The aim of study II was to investigate how pelleted or fresh silage affected activity level and foraging-related behaviours in the pigs.

In the first study (Study I), the pigs were fed either commercial pig feed without silage as a control or with silage mixed with commercial feed, either as pellets or as complete feed (so-called total mixed ration, TMR) with chopped or intensively processed fresh silage. The chopped silage had a straw length of approx. 4-15 mm and the intensively processed silage approx. 1-3 mm. In study II, pigs were fed either a Control diet of commercial feed without silage or a dried, ground silage mixed with commercial feed in a pellet or fresh chopped silage mixed with commercial feed as complete feed (TMR). The chopped silage in this study had a straw length of about 1-4 cm. In both studies I and II, silage was included so that it replaced 20% of the crude protein content of the feed (g/kg feed).

The results from study I showed that the pigs grew well. The pigs fed the pelleted silage had the highest daily growth (1084 grams per day) compared to the pigs in the other treatments. The pigs fed TMR with intensively processed silage gained 996 grams per day, which was similar to the pigs fed the Control diet (1023 grams per day). The pigs that ate TMR with chopped silage had on average the lowest daily growth (951 grams per day), but the growth was still comparable to the average growth of commercial pigs in Sweden in the year 2020, which was 973 grams per day. In all treatments, the pigs consumed all of the allocated feed. There was no difference in the carcass traits of the pigs in the different treatments.

The results showed no differences in the occurrence of aggressive behaviours, measured as the number of skin lesions on the body, in pigs with or without silage. In contrast, feeding fresh silage in TMR resulted in a much lower incidence of gastric ulcers; all pigs receiving TMR had little or no changes in the gastric mucosa, while the majority of pigs fed pelleted silage or the Control diet without silage had ulcerations in the stomach. The experiment was also able to show that all three treatments that contained silage resulted in a reduction in the ammonia losses from fresh manure, compared to the manure from the pigs that ate control feed without silage.

The results of the behavioural observations in Study II showed that pigs fed a TMR diet with fresh silage spent more time at the feed troughs and had longer eating times than pigs fed pelleted silage or a Control diet without silage. TMR with fresh silage also enabled the pigs to root longer than the pigs that received pelleted feed. Also in study II, there was no clear effect of treatment on social interactions between the pigs, neither positive nor negative.

The main conclusions of this thesis are that silage fed as a TMR increases the silage consumption and provide the pigs with sufficient nutrition for good growth. It was also clear that feeding fresh silage prevents the development of gastric ulcers and also increases the pigs' activity level, prolongs their eating times and gives them better opportunities to perform foraging behaviours. Including silage in a pellet is an interesting alternative as it results in good growth. However, it does not stimulate the pigs' foraging behaviour to the same extent as fresh silage in a TMR and it does not reduce the occurrence of stomach ulcers. Finally, feeding more fibre, in this case silage, appears to affect ammonia losses from manure compared to manure from pigs fed a Control diet without silage.

The results from the studies in this thesis show that silage is an interesting feed for slaughter pigs, with the possibility to increase the use of ley crops on pig farms as a locally grown feed resource that can be used all year round. Including silage in pig diets benefits crop production and biodiversity and improves the pigs’ health and welfare, without impairing production.

Populärvetenskaplig sammanfattning

Svensk grisproduktion står inför flera utmaningar. Konsumenter efterfrågar en mer djurvänlig produktion och det finns behov av att minska importen av t.ex. soja och använda mer resurseffektiva och cirkulära råvaror som har betydligt lägre miljö- och klimatpåverkan. Tillgången på lokalt och hållbart odlade fodermedel med god proteinkvalitet, dvs rätt balans av de aminosyror som grisen behöver, och som inte konkurrerar med råvaror som människan skulle kunna äta direkt är begränsad. Detta har lett till att intresset för att använda vall, dvs gräs och klöver i fodret till grisar har ökat. Näringsmässigt har vallgrödor bra kvalitet och grisar kan tillgodogöra sig näringen från dem i ganska hög utsträckning. När gräs och baljväxter odlas på åkrarna bidrar de också med flera positiva miljöeffekter såsom att lagra in kol i marken, öka mullhalten i jorden och ökar den biologiska mångfalden. Skördas grönmassan och lagras som ensilage kan det fungera som lokalt högkvalitativt foder året runt.

Ensilage är däremot ännu inte vanligt förekommande i foderstaten till grisar. Grisar kan via mikrobiell fermentering i grovtarmen, bryta ned och nyttja näring i fibrer till en högre grad än människor, men sämre än idisslare. Däremot kan fiberinnehållet ge ett sämre upptag av näringen från andra ingredienser i foderstaten. En alltför stor inblandning av fibrer är därför inte önskvärt, om målsättningen är att grisen ska växa så effektivt som möjligt, dvs utnyttja fodret så effektivt som möjligt. Hur som helst har flertalet studier visat att grisar som ges extra tillgång på ensilage, utöver den dagliga tillförseln av strömedel, tex halm, utför färre oönskade beteenden såsom att skada andra grisar eller att bita på boxinredningen. Ensilage kan även vara gynnsamt för grisens maghälsa då det innehåller en högre andel fibrer som kan motverka uppkomsten av magsår i magsäcken. Det är också känt att när grisen utfodras med mer fibrer så minskar ammoniakavgången från träcken, vilket beror på en ökad mikrobiell nedbrytning av fibrerna i grisens grovtarm. Det finns med andra ord olika argument som talar för att en ökad inblandning av ensilage i grisens foderstat kan vara gynnsamt ur flera perspektiv.

Det finns potential att öka utnyttjandet av vallfoder inom grisproduktionen, men det saknas praktiska lösningar för att effektivt kunna nyttja det i grisens foderstat.

Syftet med denna avhandling var att undersöka hur utfodringsstrategi och ensilagets strålängd påverkar grisens tillväxt, slaktkroppsegenskaper, beteende, maghälsa och kväveutnyttjande. Resultaten baseras på två studier, studie I och II. Studie I delades upp i tre olika fokusområden; tillväxt, beteende och maghälsa samt kväveutnyttjande där syftet var att undersöka hur ensilage som förbehandlats på olika sätt och utfodringsstrategi påverkade nämnda egenskaper. Syftet med studie II var att undersöka hur pelleterat eller färskt ensilage påverkade aktivitetsnivå och födosöksrelaterade beteenden hos grisarna.

I den första studien (studie I) utfodrades grisarna antingen med kommersiellt slaktgrisfoder utan ensilage som en kontroll eller med ensilage blandat med kommersiellt foder, antingen som pellets eller som fullfoder (så kallad total mixed ration, TMR) med hackat eller intensivt bearbetat färskt ensilage. Det hackade ensilaget hade en strålängd på ca 4-15 mm och det intensivt bearbetade ensilaget ca 1-3 mm. I studie II utfodrades grisarna med antingen ett kontrollfoder med kommersiellt slaktgrisfoder utan ensilage eller med ett torkat, malt ensilage blandat med kommersiellt foder i en pellet eller med färskt, hackat ensilage blandat med kommersiellt foder som fullfoder (TMR). Det hackade ensilaget hade i denna studie en strålängd på ca 1-4 cm. I både studie I och II ingick ensilage så att det ersatte 20% av råproteininnehållet i foderstaten (g/kg foder).

Resultaten från studie I visade att grisarna växte bra. Grisarna som åt pelleterat ensilage hade den högsta dagliga tillväxten (1084 gram per dag) jämfört med grisarna i de andra behandlingarna. Grisarna som åt TMR med intensivt bearbetat ensilage växte 996 gram, vilket var i likhet med de grisar som åt kontrollfodret (1023 gram per dag). De grisar som åt TMR med hackat ensilage hade i genomsnitt den lägsta dagliga tillväxten (951 gram), men tillväxten är ändå jämförbar med den genomsnittliga tillväxten för kommersiella grisar i Sverige under året 2020, som var 973 gram per dag. I alla behandlingar åt grisarna upp hela den tilldelade fodergivan. Det var ingen skillnad på slaktkroppen för grisarna i de olika behandlingarna.

Resultaten visade inga skillnader i förekomst av aggressiva beteenden, mätt som antalet rivsår på kroppen hos grisar med eller utan ensilage. Däremot gav utfodring med färskt ensilage i TMR mycket lägre förekomst av magsår; samtliga grisar i som fick TMR hade lite eller inga förändringar i magsäckens slemhinna, medan flertalet av grisarna som utfodrades med pelleterat ensilage eller kontrollfodret utan ensilage hade förhårdnader och sårbildning i magsäcken. Försöket kunde också visa att samtliga tre behandlingar som innehöll ensilage resulterade i en sänkning av ammoniakavgången från färsk gödsel, jämfört med gödseln från de grisar som åt kontrollfoder utan ensilage.

Resultaten från beteendestudierna i studie II visade att grisar som utfodras med fullfoder med färskt ensilage spenderade mer tid vid foderträgen och hade längre ättider än grisar som utfodrades med pelleterat ensilage eller kontrollfoder utan ensilage. Fullfoder med färskt ensilage gjorde även att grisarna bökade längre stunder än grisarna som fick pelleterat foder. Inte heller i studie II var det någon tydlig effekt av behandling på sociala interaktioner mellan grisarna, varken positiva eller negativa.

De huvudsakliga slutsatserna av denna avhandling är att utfodring med ett fint hackat ensilage och som ges som fullfoder (TMR) till grisar gör att grisarna äter upp hela givan av ensilage och minskar mängden foderspill. Ensilage kan förse grisarna med tillräcklig mängd näring för en bra tillväxt. Det var också tydligt att utfodring med färskt ensilage förebygger uppkomsten av magsår och även ökar grisarnas aktivitetsnivå, förlänger deras ättider och ger dem bättre möjligheter till att utföra födosöksbeteenden. Utfodring med pelleterat ensilage är ett intressant alternativ då det resulterar i en god tillväxt. Däremot stimulerar inte pelleterat ensilage grisarnas födosöksbeteende i samma utsträckning som fullfoder med färskt ensilage och det minskade inte heller uppkomsten av magsår. Slutligen verkar utfodring med mer fibrer, i detta fall ensilage, påverka ammoniakavgången från gödsel jämfört med gödsel från grisar som ätit en kontrollfoderstat utan ensilage.

Resultaten från studierna i denna avhandling visar att ökad inblandning av ensilage i grisens foderstat har potential att kunna bidra med fördelar för odlingsklimatet och den biologiska mångfalden och samtidigt förbättra grisens hälsa och välfärd, utan försämrad produktion.

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And last, but not least, to you **Doktor Friman**, you did it! Hell yeah 🤘

Appendix

Appendix **I.**

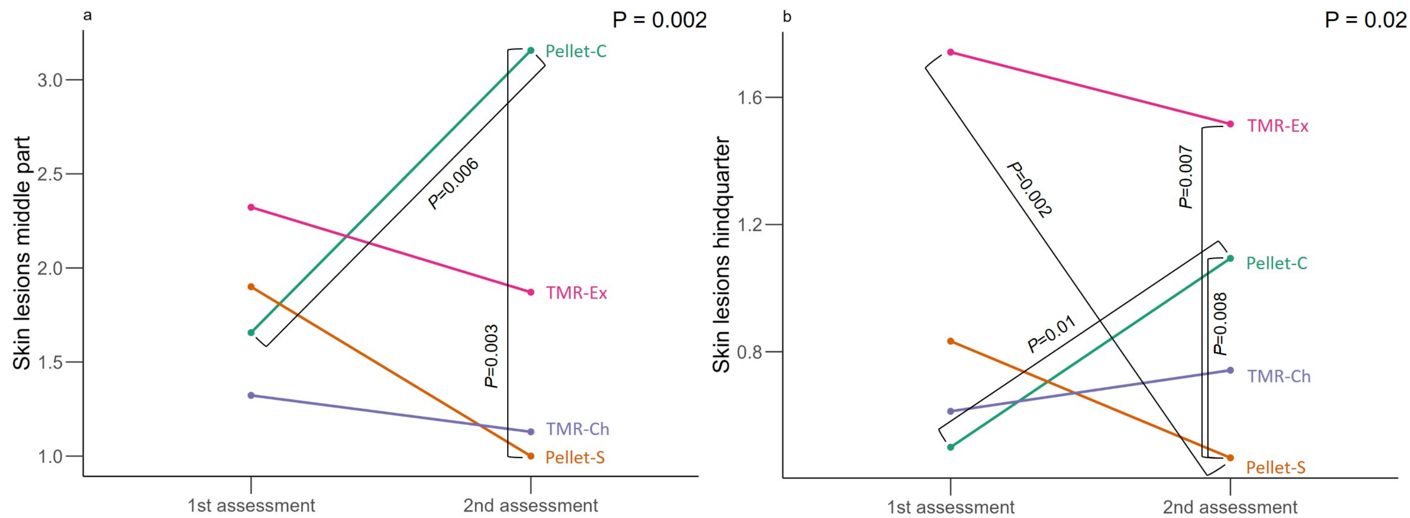

Figure A1. The figure presents the significant assessment x treatment interaction for skin lesions in the body parts a) middle and b) hindquarter for the treatments Pellet-C, Pellet-S, TMR-Ch and TMR-Ex. The overall p-value for the interaction is presented in the right upper corner. Within the figure, lines between points indicate significant pairwise differences ($P<0.05$), either between or within assessments. The p-value is presented next to the line. If there is no line, there was no significant difference between those values.

Appendix **I.**

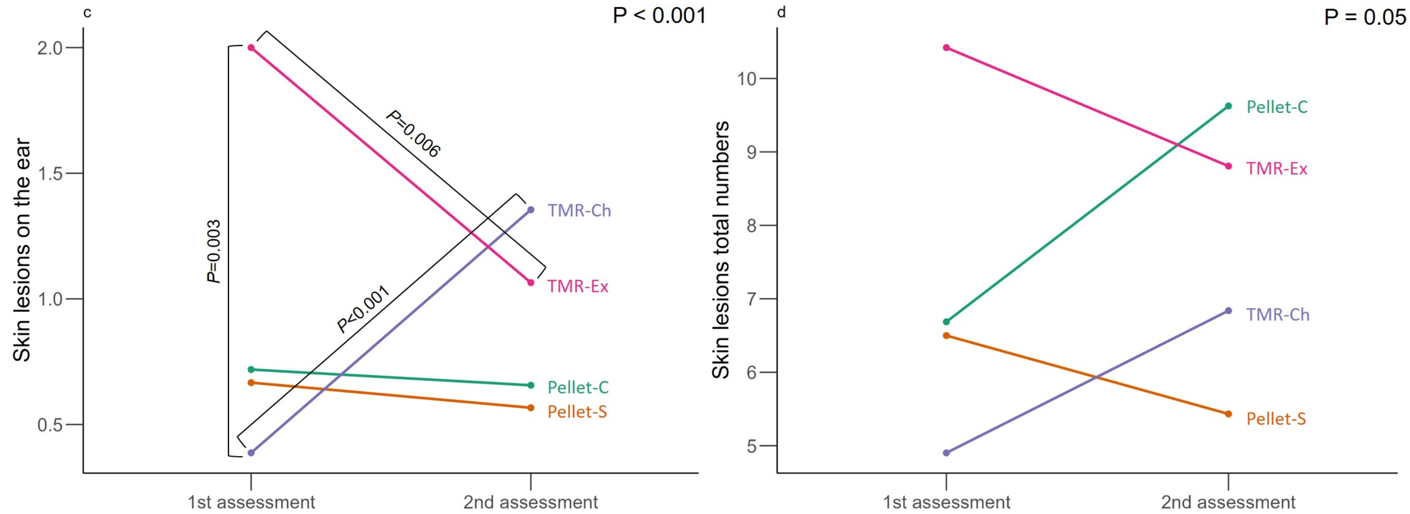

Figure A2. The figure presents the significant assessment x treatment interaction for skin lesions in the body parts c) ear and d) total numbers of skin lesions for the treatments Pellet-C, Pellet-S, TMR-Ch and TMR-Ex. The overall p-value for the interaction is presented in the right upper corner. Within the figure, lines between points indicate significant pairwise differences ($P<0.05$), either between or within assessments. The p-value is presented next to the line. If there is no line, there was no significant difference between those values

I

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Grass/clover silage for growing/finishing pigs – effect of silage pre-treatment and feeding strategy on growth performance and carcass traits

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ABSTRACT

This study evaluated the influence of feeding strategy and grass/clover silage pre-treatment on pig growth performance and carcass traits. In total, 128 pigs weighing 30–110 kg were fed either a commercial control feed or received silage in a pellet (SP) or in a total mixed ratio (TMR) containing chopped silage (SC) or intensively treated silage (SE). Silage replaced 20% of dietary crude protein content (g/kg). Diet affected weight gain ($P = 0.001$), with pigs fed the SP diet showing best overall growth performance. Pigs fed the SC diet had the lowest weight gain ($P = 0.001$), while pigs fed the SE diet performed similarly to those fed the control diet. Carcass weight and dressing percentage differed between the diets ($P = 0.016$ and $P = 0.018$), but there was no difference in lean meat content ($P = 0.832$). The results show satisfactory growth performance and carcass traits, indicating that silage can replace other protein sources in growing/finishing pig diets.

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Growing/finishing pig; silage; legumes; TMR; growth performance; carcass traits

Introduction

Increasing demand for sustainable animal protein and increasing competition for agricultural land for food production makes it essential to find alternative feed proteins for farm animals (Kim et al., 2019; Stødkilde et al., 2019). One key challenge to enhanced sustainable pig production is finding viable feed sources that have a low environmental impact, can tolerate climate change and meet the nutritional requirements of pigs. Limited access to high-quality feed protein, especially in organic production where synthetic amino acids are banned, has made it necessary to evaluate alternative protein sources for organically reared pigs. Green legumes are high-yielding and their ability to fix atmospheric nitrogen (N) makes them an important component of crop rotations in organic production (Hermansen et al., 2017; Manevski et al., 2018). Interest in using silage from ley crops as a protein source for pigs is increasing due to its possibility for use as a local, year-round protein feed (Kambashi et al., 2014; Kim et al., 2019) and the amino acid composition of grass and clovers are comparable to those of e.g. soybean meal (Hermansen et al., 2017). Despite well-known positive effects of feeding roughage on pig behaviour and welfare (Olsen, 2001; Kallabis & Kaufmann, 2012; Holinger et al., 2018; Presto Åkerfeldt et al., 2019) silage from grasses and clover are seldom used as an ingredient in formulation of pig feed rations. However, silage has potential for use as a protein ingredient in feed rations for growing/finishing pigs (Wallenbeck et al., 2014; Wüstholz et al., 2017; Presto Åkerfeldt et al., 2019). Previous research indicates that feeding technique, type of roughage and pre-treatment of the silage (e.g. mechanical shortening of straw length, minimising the particle size of the silage) strongly influence the capacity of pigs to consume silage (Wallenbeck et al., 2014; Presto Åkerfeldt et al., 2018).

Research on the effects of feeding technique and pre-treatment on the nutritive value of silage is still limited, but studies to date have shown that inclusion of silage in commercial pelleted pig diets does not reduce daily weight gain (DWG) or impair carcass conformation of growing/finishing pigs (Wallenbeck et al., 2014). Feeding pigs intact (whole stem length) and chopped (3–5 cm stem length) silage has been found to reduce DWG, as a result of silage residuals and lower energy intake (Bikker et al., 2014; Wallenbeck et al., 2014). Reducing the particle length to < 0.5 cm by intensive processing in a bioextruder, where the cellulose structure is broken down, increased silage intake and reduced silage residuals, however, bioextrusion did not improve

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silage nutrient digestibility in that study (Presto Åkerfeldt et al., 2018). Wüstholz et al. (2017) concluded that chopped and extruded alfalfa silage can supply pigs with protein, although pigs fed extruded alfalfa silage showed lower growth and poorer carcass performance than pigs fed chopped alfalfa. Studies in which pigs were fed silage mixed with commercial feed as a total mixed ratio (TMR) report high potential of this as a feeding strategy applicable at farm level. Feeding silage in a TMR can prevent the pigs from sorting out feed compounds, but silage structure (straw length, particle size) affects silage intake and the ability of pigs to select more favourable compounds (Bikker et al., 2014; Wallenbeck et al., 2014; Presto Åkerfeldt et al., 2018).

The effect of silage pre-treatment before feeding to pigs needs to be further evaluated in terms of how it affects nutrient utilisation, feed intake and overall pig performance. The aim of this study was thus to evaluate the effects of pre-treatment and inclusion of silage in diets to growing/finishing pigs on pig performance and carcass traits. The starting hypothesis was that reducing the particle size of silage and feeding it as a TMR or pellets increases silage intake by limiting the ability of pigs to exclude less desirable feed components, resulting in comparable growth and carcass performance to that in pigs fed a commercial compound feed.

Material and methods

The study was performed at the pig research facility at the Swedish Livestock Research Centre, Funbo Lövsta, Uppsala, Sweden, during January–May 2020. The study was approved by the Uppsala Ethics Committee on Animal Research (ethics approval number Dnr 5.8.18-14309/2019), which is in compliance with EC Directive 86/609/EEC on animal studies.

Animals and housing

A total of 128 growing/finishing pigs (Swedish Yorkshire × Hampshire) from two production batches in a batch-wise production system with two weeks between batches were included in the study. Each batch (1 and 2) included 64 pigs. At 8 weeks of age, the pigs in each batch were mixed into new groups and allocated to one of eight pens, with eight pigs per pen. The distribution of the pigs was balanced regarding birth litter, sex and birth weight. No siblings were included in the same pen and each pen included four gilts and four male pigs with mean weaning weight 12.3 (±1.42) kg for batch 1 and 13.2 (±1.97) kg for batch 2. The male pigs were immunocastrated with Improvac™, with their first injection at 77 days of age and their second at 105 days. After seven days of acclimatisation to the new group, each group was moved to a new pen at the start of the study. The pigs were then 66 days of age (±1 d) and weighed on average 32 kg (32.5 ± 4.2 kg), and the study continued until slaughter. Pigs were sent to slaughter on three occasions for each batch, at an average live weight (LW) of 115 kg (114.3 ± 6.5 kg) and 150 days of age (147 ± 7.2 d).

The total area of the pen was 11 m^2, with a concrete floor in the feeding and lying area and a slatted dunging area in the back of the pen (1/3 of pen area), giving a floor area of 1.4 m^2 per pig. The pens were divided by metal bars in the dunging area and solid walls in the eating and lying area. A feed through 4.5 m long was provided along the front of the pen and two water nipples were provided in the slatted area. During the study period, the pigs did not have access to straw, but all pens were provided daily with wood shavings as bedding material.

Diets and feeding

Green crop silage

The silage used in the study was from the second cut, harvested in July 2019, of a first-year grass ley with a high proportion of clover. The biomass consisted of a mixture of red clover (*Trifolium pratense*) (10%), white clover (*Trifolium repens*) (5%), timothy (*Phleum pratense*) (50%), meadow fescue (*Festuca pratensis*) (20%) and perennial ryegrass (*Lolium perenne*) (15%). The grass was cut in the field with a forage harvester and chopped to 4–15 mm particle size. During harvesting, a silage additive (ProMyr NT570, Perstorp Holding AB, Malmo, Sweden) was added at a rate of 5 litres per 1000 kg of fresh matter. Using additives to improve silage quality is a standard procedure in conventional production and emerging in organic production, due to increased variation in conditions at harvest. The crop was ensiled in a silage bun, with plastic wrap covering the ground, directly after harvesting.

Dietary treatments

The pigs in each batch were allocated to one of four diets: a control diet with commercial feed for growing/finishing pigs or one of three experimental diets in which silage was mixed with commercial feed as pellets (SP), or fed as part of a TMR as chopped (SC) or intensively treated silage (SE). There were two replicates for each diet and batch, resulting in a total of four pens, i.e. 32 pigs, per diet. In all experimental diets, the same green crop silage was included to replace 20% of the dietary crude protein (CP) content (g/kg).

Formulation of diets and preparation of feed rations

The control diet was a commercial complete feed, optimised according to the nutritional recommendations for growing/finishing pigs, produced at a commercial feed plant (Swedish Agro, Kalmar, Sweden). To produce the feed for the SP diet, silage was sent to a dry feed producer (Genevads Grönfodertork, Laholm, Sweden), where it was heat-dried, pelleted into pure silage pellets and then sent to the commercial feed plant. The pure silage pellets were mixed with commercial feed to produce a pelleted feed with silage inclusion, optimised according to nutritional recommendations for growing/finishing pigs. The TMR consisted of a commercial basal feed mixed with either SC or SE silage. The basal feed for the TMR mixture was optimised to meet the nutritional recommendations for growing/finishing pigs when included in the TMR at a 60:40 ratio and was produced at the same commercial feed plant as the control and SP feeds (Swedish Agro, Kalmar, Sweden). The ingredient composition in the control feed, the SP feed and the basal feed for the TMR diets are shown in Table 1.

Once a week during the study, silage was collected from the silage bun for preparation of daily rations of the SC and SE diets. DM content of the silage was determined to ensure that silage (kg) constituted 40% of the TMR. When collecting silage, half of the total amount of silage was kept intact (chopped 4–15 mm) for the SC diet and the other half was intensively treated in a bioextruder (model MSZ-B15e, LEHMANN Maschinenbau GmbH) for the SE diet. The bioextruder was equipped with rotating double-screws and set at 60% rotation speed to get a structure of 1–3 mm of the silage. The SC and SE silages were then weighed, packed into rations per pen and feeding event, and stored in a chilled container (Cooltainer, Isolett Panelbyggen AB, Uppsala, Sweden) at approximately +4°C until feeding.

Table 1. Ingredient composition (% of ingredients per kg feed), estimated energy content (MJ kg^{-1} DM) and crude protein content (g kg^{-1} DM) of the control feed, the silage pellet feed (SP) and the basal feed for the total mixed ration (TMR) diets.

	Control feed	SP feed	Basal feed
Wheat	43	51.83	30
Barley	25.53	–	–
Rye	–	–	12.69
Field beans	13.38	20.3	20
Peas	–	–	10
Rapeseed meal	12	–	–
Rapeseed	–	–	7.96
Soybean meal	0.95	–	–
Potato protein	–	4.37	5.2
Maize meal	–	–	10
Silage pellet	–	20	–
Limestone	1.11	0.89	0.6
Premix finishing pigs	0.12	0.12	0.22
Estimated energy and crude protein content			
Dry matter, %	87	88	87
Net energy	10.8	10	12.2
Crude protein	184	198	207

Feeding

Feeding was carried out twice daily (morning and afternoon) according to the Swedish nutrient recommendations for growing/finishing pigs, based on the average pen LW. The rearing period was divided into two growing phases with a restricted feeding regimen (Andersson et al., 1997). During growing phase 1, when the pigs had an average LW between 30 and 65 kg, the feed allowances in MJ of NE was 14.5, 18.3, 22.1 and 25.9 at 30, 40, 50 and 60 kg, thus corresponding to an ad libitum feeding strategy, until they reached an average LW of 65.7 (±7.9) kg. During growing phase 2, from 65.7 kg until slaughter, the pigs were provided with a maximum feed ration of 25.9 MJ NE per day. The control and SP diets were fed by an automatic computerised feeding system, while the SE and SC diets were fed manually as a TMR. For the TMR, the silage was mixed with basal feed in a mixer (Syntesi 140, Epox Maskin AB, Sollentuna, Sweden) and the TMR was then transferred by hand to the feed troughs. Silage intake accounted for 20.5% of total dry matter intake (DMI) of the SC and SE diets. Chemical composition and energy value of the control diet, SP diet, the basal feed and TMR as fed is shown in Table 2.

Chemical analyses

Feed samples of the control diet, the SP diet and the basal feed used in the TMR diets were collected at the start of the study. Feed samples of the intact (SC) and intensively treated (SE) silage were collected on four occasions during the study period, frozen (−20°C) and then pooled to one representative sample. All feed samples were freeze-dried, milled through a 1-mm sieve and dried at 103°C for 16 h for determination of DM content. Ash content was determined after combustion at 550°C for 3 h. Nitrogen content was analysed according to Kjeldahl (Nordic Committee on Food Analysis, 1976) using a 2520 Digestor and a Kjeltec 8400 Kjeltec Analyser Unit (FOSS Analytical A/S Hilleröd, Denmark). CP was calculated as N x 6.25. Gross energy (GE) content was measured with an Isoperibol bomb calorimeter (Parr 6300, Parr Instrument Company, Moline, IL, USA). Water-soluble carbohydrates (WSC) content was determined using an enzymatic method (Larsson & Bengtsson, 1983). To analyse the hygiene quality and influence of storage, silage samples were collected and stored for 7 days at +4°C. One sample was

Table 2. Chemical composition (g kg^{-1} DM), energy content (MJ kg^{-1} DM) and amino acid content (% feed) of the control feed, the silage pellet (SP) feed, the basal feed for the total mixed ration (TMR) and the chopped (SC) and intensively treated (SE) silage, and TMR as fed (SC and SE). TMR as fed represents the composition in a 40:60 ratio of silage and basal feed.

	Control feed	SP feed[a]	Basal feed[b]	Chopped silage, SC	Intensively treated silage, SE	TMR as fed SC	TMR as fed SE
Dry matter, %	88	89	88	34	35	66	67
Gross energy	18.3	18.9	19.5	16.7	17.2	18.4	18.6
Net energy[c]	11.0	11.0	11.8	8.1	8.9	10.3	10.6
Crude protein	191	202	205	183	178	196	194
Crude fat	36	51	69	–	–	41	41
Ash	51	59	42	95	97	63	64
Neutral detergent fibre	126	157	117	384	361	224	215
Lysine	0.945	0.890	1.02	0.727	0.690	0.903	0.888
Methonine	0.270	0.247	0.282	0.288	0.269	0.284	0.277
Threonine	0.629	0.713	0.765	0.720	0.684	0.747	0.733
Valine	0.742	0.846	0.857	0.880	0.895	0.866	0.872

[a]Commercial feed + ground silage, mixed and pelleted.
[b]Basal feed optimised for mixing with silage in a TMR.
[c]Estimated according to Lindberg and Andersson (1998), where energy digestibility (dE%) = 94.8 + (− 0.93 × NDF %). Digestible energy (DE) = dE × GE, ME = 0.95 × DE and NE = 0.75 × ME.

taken for analysis on day 1 and a second sample on day 7, and frozen (−20°C) and stored until analysis. The analysis involved squeezing the liquid from the thawed silage and then determining the concentration of volatile fatty acids (VFA), lactic acid, ethanol, formic acid and butandiol using the methods of Andersson and Hedlund (1983). Ammonia-N concentration (% of total-N) was analysed using the flow injection technique according to the manufacturer's instructions (Tecator, Application Note, ASN 50-01/92). Silage pH was measured using a standard pH meter (Metrohm 654 pH meter, Herisau, Switzerland). Amino acids were analysed according to ISO 13903:2005 (Eurofins Agro Testing Sweden, Kristianstad, Sweden).

Measurements and calculations

Feed intake

Average daily feed, energy and protein intake, feed conversion ratio (FCR) and protein conversion ratio (PCR) were recorded pen-wise and presented as mean values per pig. Number of days in the study was recorded separately for growing phase 1, growing phase 2 and the total growth period. FCR was calculated as: Energy intake per kg weight gain = (Mean total energy intake/(Sum of final LW – Sum of initial LW)). PCR was calculated as: Protein intake per kg weight gain = (Mean total protein intake/(Sum of final LW – Sum of initial LW)).

Weighing and carcass assessment

All pigs were weighed at the start of the study, then every second week until an approximate LW of 90 kg and thereafter once a week until slaughter. In each batch, pigs were sent to slaughter on three occasions, with two weeks between the first and second occasion and one week between the second and third occasion. When the pigs reached an average LW of 107.7 kg (107.7 ± 5.5 kg), they were registered for slaughter and sent to the abattoir one week later. Thus, the final LW was calculated as: LW one week prior to slaughter + ADG × 7 days. At slaughter, carcass weight was recorded and lean meat content was determined with the Hennessy Grading Probe (Hennessy Grading Systems, Auckland, New Zealand) (Sather et al., 1991). The dressing percentage was calculated as: ((Carcass weight/Final LW) × 100). Daily growth from start of the study to slaughter was calculated as: (Final LW – Initial LW)/(Days in the study).

Daily lean meat growth was calculated as: (Percentage lean meat content × (Carcass weight – (Initial LW × 0.72))/Days in the study), with a value of 0.72 representing hypothetical dressing percentage at the start (Andersson et al., 2012).

Statistical analyses

Of the 128 pigs that entered the study, five were culled or died during the study period, due to illness unrelated to the study. Data on the culled pigs were excluded from the statistical analysis, and the results are based on 124 pigs for feed consumption and growth parameters and 123 pigs for the carcass parameters. The statistical analyses were performed with SAS, version 9.4 (SAS, 2021). Descriptive statistics were produced using Proc MEANS and the effect of diet was evaluated using Proc MIXED. Pig performance and carcass traits were analysed using a model (with pig as experimental unit) including the fixed effects of diet (SE, SC, SP, control), batch (1 and 2), sex (male and female) and the random effects of pen nested within batch (pens 1–16, 8 pens/batch, i.e. including the effect of the unique pig group) and birth litter nested within the batch. When analysing DWG, initial weight was included as a continuous covariate in growing phase 1 and for the total growth period. Carcass weight was included as a covariate when lean meat content was analysed. For feed, energy and protein intake, FCR and PCR the model included diet (control, SP, SC and SE) and batch (1 and 2) as fixed effects, with pen as the experimental unit. Level of significance was set at $P < 0.05$. All variables were tested for two-way interactions, but interactions were found to be non-significant and therefore excluded from the model. Results are presented as least square means (LS-means) with pooled standard error (SEM) unless otherwise stated.

Results

Feed analysis and feed intake

The feed rations for all four diets were based on the estimated energy content (MJ kg^{-1} feed) optimised by the commercial feed plant (Table 1). Extrusion of the silage resulted in lower CP content and neutral detergent fibre (NDF) content compared with the SC, while DM content and energy value of the silage were not affected by the extrusion process (Table 2). The content of essential amino acids are presented in Table 2.

Throughout the study, the provided feed rations were totally consumed by the pigs in all four treatments. Daily inspections of the silage indicated satisfactory hygiene quality and signs of mould growth were not found at any time. Storage did not influence the hygiene quality of the silage (Table 3). Regarding average daily feed intake, it was found that pigs on the SP diet consumed a higher amount of feed per day, compared with pigs on the control diet in all growing phases (Table 4). The average daily feed intake in pigs fed the SC and SE diets was on average 1.9 kg basal feed and 1.3 kg silage (Table 4).

During growing phase 1, average daily intake of energy (MJ NE) and crude protein (g CP) was higher in pigs fed the SP diet compared to pigs in the control, SC and SE diets ($P = 0.003$ and $P = 0.002$ for energy and protein) (Table 4). Energy intake was similar in growing phase 2 for all diets, except for pigs in the SP and SC diets ($P = 0.02$) and protein intake only differed between pigs on the control and SP diet ($P = 0.01$). The overall average intake of energy and protein was higher in pigs on the SP diet ($P = 0.001$ and 0.001). Pigs on the SE diet had similar energy and protein intake as pigs on the SC and control diets, however, pigs on the control diet had significantly higher energy intake and lower protein intake compared to pigs on the SC diet ($P = 0.003$ and 0.02).

Table 3. Chemical composition and hygiene quality of fresh silage used in the chopped (SC) and intensively treated (SE) silage diets, and of the same silage after one week of storage at 4°C.

	Fresh silage	Silage stored for 1 week
Dry matter %	35	34
Crude protein (CP, g kg^{-1} DM)	183	184
Gross energy (GE, MJ kg^{-1} DM)	16.7	17.4
Water-soluble carbohydrates (g kg^{-1} DM)	118	122
pH	4.22	4.15
Fermentation products, % of dry matter		
Lactic acid	4.7	4.8
Formic acid	1.2	1.2
Acetic acid	0.8	0.9
Propionic acid	0.2	0.2
Butyric acid	< 0.02	<0.02
2,3-butandiol	0.04	0.06
Ethanol	0.1	0.1
Ammonia-nitrogen (% of total nitrogen)	3.3	3.4

Performance

Pigs on the SC and SE diet had lower FCR compared to pigs on the control and SP diet in growing phase 1, however, the difference was not significant ($P = 0.15$). No significant difference in FCR was found in growing phase 2 ($P = 0.99$) or when compared for the overall study period ($P = 0.145$) (Table 4). Overall, PCR was highest in pigs on the SC diet and lowest in pigs on the control diet ($P = 0.001$). Pigs on the SP and SC diets had significantly higher PCR in growing phase 1 than pigs on the control diet ($P = 0.046$ and 0.01), but in growing phase 2 no difference in PCR was found between diets ($P = 0.154$)

Diet had a significant effect on growth performance of the pigs ($P = 0.001$) (Table 5). During growing phase 1 (pig LW 30–60 kg), pigs on the SC and SE diet had significantly lower DWG than pigs on the SP diet ($P = 0.001$ and $P = 0.049$). However, pigs on the SE diet had comparable DWG to pigs on the control diet. Pigs fed the SC diet had the lowest DWG, which also differed from the pigs on the control diet ($P = 0.001$) (Table 5). During growing phase 2 (pig LW 60–110 kg), pigs on the SP diet had higher DWG than pigs on all other diets ($P = 0.001$) (Table 5). This difference was reflected in DWG during the total period, where pigs on the SP diet had the highest DWG and pigs on the SC diet had the lowest ($P = 0.001$) (Table 5). No significant difference in total DWG was found between pigs on the SE and control diets ($P = 0.333$) (Table 5).

Final weight was lowest in pigs on the SC diet (111.5 kg), followed by pigs on the SE, control and SP diets (113.4, 114.7 and 117.7 kg) (Table 5), with a

Table 4. Difference in daily average feed (kg), energy (MJ NE) and protein (g CP) intake between diets (SP = pellet with silage inclusion, SC = Basal feed + chopped silage fed as TMR, SE = Basal feed + intensively treated silage fed as TMR) and effect of diet on feed- and protein conversion ratio (MJ NE kg^{-1} growth and g CP kg^{-1} growth), presented for growing phase 1, 2 and all phases. The results are presented as least square means and pooled standard error (SEM). Level of significance was set at $P < 0.05$.

	Control (*N* = 32)	SP (*N* = 30)	SC (*N* = 31)	SE (*N* = 31)	*SEM*	$P^{\#}$
Phase 1 30–65 kg						
Days in phase 1	28.5	28.5	28.5	28.5	0.02	0.42
Feed intake	2.52^{a}	2.78^{a}	3.35^{b}	3.35^{b}	0.06	0.001
Energy intake	24.4^{a}	27.2^{b}	23.1^{a}	23.8^{a}	0.85	0.003
Protein intake	423.1^{a}	499.6^{b}	436.3^{a}	434.3^{a}	11.02	0.002
Feed conversion ratio	25.6	28.2	28.6	26.8	0.93	0.15
Protein conversion ratio	443.7^{a}	517.4^{b}	540.2^{b}	490.4^{ab}	17	0.01
Phase 2 65–110 kg						
Days in phase 2	51.7^{ab}	50.2^{b}	55.3^{a}	53.4^{ab}	1.53	0.01
Feed intake	2.40^{a}	2.53^{a}	3.22^{b}	3.22^{b}	0.05	0.001
Energy intake	23.4^{ab}	24.8^{b}	22.2^{a}	22.9^{ab}	0.49	0.02
Protein intake	403.2^{a}	455.4^{b}	420.1^{ab}	417.8^{ab}	9.04	0.01
Feed conversion ratio	21.9	21.7	21.7	21.7	0.48	0.99
Protein conversion ratio	379.2	397.6	410.6	396.5	8.83	0.15
All phases 30–110 kg						
Total days in study	80.2^{ab}	78.7^{a}	83.8^{b}	81.9^{ab}	1.53	0.01
Feed intake	2.43^{a}	2.61^{a}	3.25^{b}	3.25^{b}	0.02	0.001
Energy intake	23.6^{a}	25.6^{c}	22.4^{b}	23.1^{ab}	0.17	0.001
Protein intake	408.2^{b}	469.8^{c}	423.8^{a}	421.1^{ab}	3.03	0.001
Feed conversion ratio	23.0	23.6	23.6	23.1	0.23	0.145
Protein conversion ratio	398.7^{c}	433.8^{ab}	446^{b}	421.8^{a}	4.23	0.001

#Probability: Different superscript letters within rows indicate pairwise differences at $P < 0.05$.

significant difference between pigs on the SC diet and the SP diet (P = 0.05). A similar pattern of differences between diets was found for carcass weight ($P = 0.018$), where pigs on the SC diet differed significantly from pigs on the SP diet ($P = 0.025$) (Table 5). Pigs on the control diet had a higher dressing percentage than pigs on the SC and SE diets ($P = 0.022$ and $P = 0.047$) but a similar value to pigs on the SP diet ($P = 0.10$) (Table 5). Diet did not affect lean meat content ($P =$ 0.832), but had a significant effect on daily lean meat growth ($P = 0.001$), with lower growth among pigs on the SC and SE diets than pigs on the control and SP diets ($P = 0.001$) (Table 5).

No differences were found between batches, but sex influenced some growth traits. Castrates had better DWG in phase 2 (1.14 kg) and in the total period (1.057 kg) than gilts (1.0 kg in phase 2, 0.970 kg in total) ($P = 0.001$) (Table 5). Dressing percentage was 72.2% for castrates and 73.7% for gilts ($P = 0.001$) (Table 5).

Discussion

Silage has the potential to function as an energy and protein supply for growing/finishing pigs, but the capacity of pigs to utilise the nutrients in silage is affected by their age and LW, the structure and nutritive composition of the silage, and the feeding technique (Dierick et al., 1989; Noblet & Henry, 1993; Carlson et al., 1999). The present study evaluated the effect of feeding technique and pre-treatment of the silage on feed intake, growth and carcass traits. The overall

Table 5. Effect of sex and effect of diet (SP = pellet with silage inclusion, SC = Basal feed + chopped silage fed as TMR, SE = Basal feed + intensively treated silage fed as TMR) on weight gain and carcass traits. The results are presented as least square means and pooled standard error (SEM). Level of significance was set at $P < 0.05$.

	Diet						Sex†			
	Control (*N* = 32)	SP (*N* = 30)	SC (*N* = 31)	SE (*N* = 31)	*SEM*	$P^{\#}$	m	f	*SEM*	$P^{\#}$
Initial weight (kg)	32.7	32.4	32.8	32.5	0.74	0.95	32.9	32.2	0.7	0.217
Final weight (kg)	114.7^{ab}	117.7^{b}	111.5^{a}	113.4^{ab}	1.5	0.014	116.6	112.1	1.02	0.001
Daily weight gain 30–65 kg (g)	952^{bc}	966^{c}	811^{a}	887^{ab}	24.4	0.001	905	904	14	0.956
Daily weight gain 65–110 kg (g)	1064^{a}	1148^{b}	1022^{a}	1054^{a}	19	0.001	1141	1003	17	0.001
Daily weight gain 30–110 kg (g)	1023^{a}	1084^{b}	951^{c}	996^{a}	14.8	0.001	1056	971	11.6	0.001
Carcass weight (kg)	84.6^{bc}	85.3^{b}	81.1^{ac}	82.5^{ab}	1.1	0.018	83.8	82.9	0.95	0.183
Dressing percentage (%)	73.8^{c}	72.8^{bc}	72.5^{ab}	72.7^{ab}	0.41	0.016	72.2	73.7	0.32	0.001
Lean meat content (%)	60.7	60.8	61.5	60.9	0.5	0.832	60.0	61.8	0.26	0.001
Lean meat growth 30–110 (g day^{-1})	465.5^{b}	481.0^{b}	422.2^{a}	442.2^{a}	8.1	0.001	0.460	0.446	0.01	0.01

N = number of pigs in each treatment diet group.
†m = castrated male (immunocastrated with Improvac™), f = gilt.
#Probability: Different superscript letters within rows indicate pairwise differences at $P < 0.05$.

results showed satisfactory growth performance regardless of diet, with DWG ranging from 951 to 1084 g/day, which is in compliance with national (973 g/day) and international (914 g/day) standards on pig growth performance (Gård & Djurhälsan, 2020).

In the present study, silage accounted for an estimated 20.5% of the pigs' total DM intake/day, which is similar to that in other studies, where grass/clover silage has been included at up to 19% of DMI (Bellof et al., 1998; Carlson et al., 1999; Bikker & Binnendijk, 2014; Wüstholz et al., 2017; Presto Åkerfeldt et al., 2018).

To avoid possible silage residuals and compare the effect of the silage intake per se, silage was included in pelleted form (SP diet). In the study by Wallenbeck et al. (2014), pigs fed pelleted feed with silage inclusion (20% on metabolisable energy (ME) basis) consumed all feed and performed similarly to control pigs that did not receive any silage. In the present study, overall performance was similar or improved in pigs fed the SP diet than in pigs on the control diet, despite a lower intake of lysine and methionine. Ingredient composition differed between the SP and control diets, with inclusion of potato protein in the SP diet, which provides a high amount of digestible amino acids. It is conceivable that the improved growth performance was due to higher nutrient digestibility and improved nutrient absorption in the SP diet. Pigs on the SP diet had higher energy and protein intake per day, which might be an additional explanation for the improved performance on the SP diet.

FCR was numerically higher for the silage-fed pigs in growing phase 1. Interestingly, all diets had similar FCR in growing phase 2 and did not differ in general. This indicates that utilisation of the silage increase with age and higher LW. These findings suggest that freshly processed silage with a finer structure and fed as a complete feed can supply nutrients to growing pigs. However, PCR was higher in pigs fed the control diet than in silage-fed pigs. This could be explained by increased passage rate of the digesta and binding of proteins to the fibre in silage, limiting absorption and digestion of proteins in the small intestine (Dierick et al., 1989; Varel & Yen, 1997; Andersson & Lindberg, 1997; Lindberg & Andersson, 1998). It has been suggested that feeding fine-structured silage mixed with commercial feed impedes the ability of pigs to sort out more palatable parts of the feed (Bikker et al., 2014; Presto Åkerfeldt et al., 2018). In the study by Presto Åkerfeldt et al. (2018), feeding chopped (1–3 cm) and intensively treated (<0.5 cm) silage in a TMR resulted in complete or near-complete consumption of silage. The particle size of the SC used in the TMR diets in the present study was even smaller (4–15 mm) than that evaluated in previous research, while the particle size of the intensively treated (SE) silage was similar to that in e.g. Presto Åkerfeldt et al. (2018). The finer structure of the silage and the strategy of feeding a TMR might be the reasons for the improved silage consumption in our study. In the present study, pigs fed a TMR with SC diet had the lowest DWG over the total study period even though they consumed all silage in the diet. However, feeding pigs a TMR with intensively treated silage (SE diet) improved the DWG. The extrusion process might increase the digestibility of nutrients in the silage, which could explain the improved growth performance in pigs on the SE diet compared with pigs on the SC diet. Mechanical reduction of particle size in lupin (*Lupinus angustifolius*) has been shown to increase the digestibility of amino acids in growing pigs, due to improved interaction between digestive enzymes and microbes responsible for digestion of nutrients (Kim et al., 2009). In a study by Acosta et al. (2019), reducing the particle size by milling improved the energy and nutrient digestibility of maize (*Zea mays*). The higher weight gain in pigs fed intensively treated silage (SE) in the present study further indicates that destroying the cell structure and reducing the particle size by extrusion could improve the availability of nutrients, as suggested by Wüstholz et al. (2017). However, in the digestibility study by Presto Åkerfeldt et al. (2018) this could not be proven. Interestingly, the pigs fed a TMR with intensively treated silage (SE diet) had similar weight gain for the whole period as pigs on the control diet, which did not receive any silage.

Silage inclusion in the diet did not affect the leanness of the carcass and lean meat content was similar for all four diets (range 72.5%–73.8%). This supports findings by Wüstholz et al. (2017) and indicates that all pigs were able to consume and utilise sufficient amounts of energy for deposition of adipose tissue, regardless of diet. However, pigs on the SC diet required a longer period to reach slaughter weight. Leaner carcasses in silage-fed pigs have been reported in previous studies (Hansen et al., 2006; Wallenbeck et al., 2014; Hermansen et al., 2017), where they were explained by insufficient energy intake and reduced capability to gain adipose tissue. In accordance with earlier studies, pigs fed silage in the present study had a lower dressing percentage than pigs on the control diet, as reflected by greater size of the gastrointestinal tract and higher gut fill at slaughter (Dierick et al., 1989; Wallenbeck et al., 2014).

With a growing demand for sustainably produced animal protein with high animal welfare standards finding alternative protein sources is important to maintain and improve sustainable pig production (Jakobsen et al., 2015; Hermansen et al., 2017; Damborg et al., 2018; DiGiacomo & Leury, 2019; Kim et al., 2019). Perennial grasses, clovers and legumes have the capacity to increase soil conditions and carbon storage and lower the risk of field N and phosphorus losses compared with annual crops (Aronsson et al., 2007; Franzluebbers & Stuedemann, 2008; Eriksson et al., 2010; Aronsson et al., 2014). Furthermore, ley crops increase biodiversity and reduce pests and weeds (Nemecek et al., 2008; Kambashi et al., 2014).

When replacing other feed ingredients with silage and using it as a source of nutrients, it is essential that the pigs consume all the silage provided, to ensure efficient energy and protein intake. In the present study, all silage provided was consumed, showing that it can replace other ingredients in the diet and supply energy and protein with maintained growth performance of the pigs. The potential of silage as a valuable feed ingredient and enrichment substrate for pig behaviour makes it an interesting option in conventional production systems too, as a strategy for improving the environmental footprint and pig welfare. Lowering the inclusion of imported protein, such as soybean, and using more locally produced feed ingredients could reduce the total environmental impact from feed production, through reduced transport (Cederberg & Flysjö, 2004; Stern et al., 2005). Silage can therefore function as an economically and environmentally sustainable protein ingredient in all pig production (Kim et al., 2019). Further studies are needed to confirm the role of silage production on the environmental impact and overall production economics of conventional and organic pig production.

Conclusions

Feeding silage with finer particle size as part of a TMR can improve silage intake in pigs and prevent them sorting out less desirable parts of the diet. Provided that pigs consume all silage allocated in the feed ration, inclusion of silage at 20% of dietary CP can replace other feed ingredients and supply the pigs with sufficient energy and protein for high performance. A pig feeding strategy involving silage can be an interesting option to increase the proportion of ley crops in a rotation, with benefits for the climate and biodiversity, while also serving as a local year-round nutrient resource and enhancing animal welfare in pig production.

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This thesis evaluated the use of silage in the diet to fattening pigs and how feeding strategy influenced pig performance, behaviour, gut health and nitrogen utilization. The results from show that silage is a suitable feed ingredient for fattening pigs, with potential to improve pig health and welfare.

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