Institut für Landtechnik

Resource-efficient feeding of fattening pigs based on body composition related performance groups – Studies on technical and environmental aspects

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Meinen Eltern

„Würdest du mir bitte sagen, wie ich von hier aus weitergehen soll?“
- „Das hängt zum großen Teil davon ab, wohin du möchtest“, sagte die Katze.
(aus »Alice im Wunderland« von Lewis Carroll, 1865)

Abstract

Livestock husbandry is increasingly confronted with the growing demands for more animal welfare and better environmental protection. As the largest component of agricultural animals in meat production, fattening pig husbandry plays a particularly important role. The high protein input in the feeding of fattening pigs leads to an excess of nitrogen being released into the environment. Stricter regulations regarding nitrogen inputs, as well as international agreements to reduce ammonia emissions, require new feeding strategies for fattening pigs. Feeding according to nutritional requirements is desirable and necessary in terms of resource efficiency and animal welfare as well as from an economic point of view. The aim of this dissertation is therefore to investigate and evaluate a new resource-efficient feeding concept for fattening pigs with regard to the environmental impact and technical aspects of implementation.

Study 1 and 2 of this thesis dealt with the questions if fattening pigs can be divided into performance groups on the basis of body condition, and if their feed intake can be controlled by different fiber contents in the diet. Additionally, the influence of fiber supplemented feeding on ammonia emissions and floor pollution in the barn was investigated. Results showed that by means of ultrasound examinations different performance groups can be distinguished on the basis of the back fat to back muscle ratio. The feed intake correlated negatively with the crude fiber content in the diet, so that the feed intake could be controlled via the crude fiber content. At the same time, ammonia emissions were reduced and no increase in floor pollution was observed.

Study 3 dealt with the question whether different body conditions lead to differences in body surface temperature, which can be made visible by using infrared thermography. It was further investigated whether it is possible and technically feasible to differentiate performance groups based on the thermographic images. The back fat thickness correlated negatively with the body surface temperature. However, it was not possible to differentiate between the individual performance groups on the basis of the thermographic images.

This dissertation provides important insights into the individual differences in the needs and development potential of fattening pigs and how these can be technically taken into account in feeding. It also provides first approaches for the application of infrared thermography in the feeding of fattening pigs. The results of the studies show that resource-efficient feeding of fattening pigs is technically possible and desirable in terms of animal welfare and environmental protection.

Zusammenfassung

Die Nutztierhaltung ist zunehmend mit den wachsenden Anforderungen an mehr Tierwohl und stärkeren Umweltschutz konfrontiert. Als größter Anteil landwirtschaftlicher Nutztiere in der Fleischproduktion, nimmt die Mastschweinehaltung hierbei einen besonders großen Stellenwert ein. Der hohe Proteineinsatz bei der Fütterung von Mastschweinen führt zu einem überschüssigen Eintrag von Stickstoff in die Umwelt. Strengere Regularien bzgl. der Stickstoffeinträge, sowie internationale Abkommen zur Reduktion der Ammoniakemissionen, erfordern neue Fütterungsstrategien für Mastschweine. Eine bedarfsoptimierte Fütterung ist sowohl im Sinne der Ressourceneffizienz und des Tierwohls, als auch aus ökonomischer Sicht erstrebenswert und notwendig. Ziel dieser Dissertation ist es daher, ein neues, ressourceneffizientes Fütterungskonzept für Mastschweine, hinsichtlich der Umweltwirkung und technischer Aspekte der Umsetzung, zu untersuchen und zu bewerten.

Studie 1 und 2 befassten sich mit den Fragestellungen, ob sich Mastschweine anhand der Körperkondition in Leistungsgruppen unterteilen lassen, und ob diese durch unterschiedliche Fasergehalte in der Ration in ihrer Futteraufnahme kontrolliert werden können. Darüber hinaus wurde der Einfluss der faserergänzten Fütterung auf die Ammoniakemissionen und die Buchtenverschmutzung im Stall untersucht. Die Untersuchungen zeigten, dass mittels Ultraschalluntersuchungen unterschiedliche Leistungsgruppen, auf Basis des Rückenspeck-Rückenmuskel-Verhältnisses unterschieden werden können. Die Futteraufnahme korrelierte negativ mit dem Rohfasergehalt in der Ration, sodass die Futteraufnahme über den Rohfasergehalt gesteuert werden konnte. Gleichzeitig konnten die Ammoniakemissionen reduziert und keine Verschlechterung der Buchtenhygiene festgestellt werden.

Studie 3 befasste sich mit der Fragestellung, ob unterschiedliche Körperkonditionen zu Unterschieden in der Körperoberflächentemperatur führen, welche mithilfe von Infrarot Thermographie sichtbar gemacht werden können. Es wurde der Frage nachgegangen, ob eine Einteilung in Leistungsgruppen durch Thermographieaufnahmen möglich und technisch umsetzbar ist. Die Rückenspeckdicke korrelierte negativ mit der Körperoberflächentemperatur. Eine Unterscheidung der einzelnen Leistungsgruppen auf Basis der Thermographieaufnahmen war jedoch nicht möglich.

Diese Dissertation liefert wichtige Erkenntnisse hinsichtlich der individuellen Unterschiede bzgl. des Bedarfs und des Entwicklungspotentials von Mastschweinen und wie dieser bei der Fütterung technisch berücksichtigt werden kann. Sie liefert darüber hinaus erste Ansätze für die Anwendung der Infrarot Thermographie in der Fütterung von Mastschweinen. Die Ergebnisse der Studien zeigen, dass eine ressourceneffiziente Fütterung von Mastschweinen technisch möglich und hinsichtlich Tierwohl und Umweltschutz erstrebenswert ist.

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List of Abbreviations

Ø	Mean
AC	Amino acid
ADF	Acid detergent fiber
BHZP	Bundes Hybrid Zucht Programm / German Federal Hybrid Breeding Program
BLE	Bundesanstalt für Landwirtschaft und Ernährung / Federal agency for agriculture and food
BMEL	Bundesministerium für Ernährung und Landwirtschaft / Federal ministry of food and agriculture
BW	Body weight
CCM	Corn-Cob-Mix
CD	Control diet
CF	Complete feed
CFD_S	Crude fiber diet summer
CFD_W	Crude fiber diet winter
CO_2	Carbon dioxide
$CO(NH_2)_2$	Urea
C_S	Control summer
C_W	Control winter
d	Day
DLG	Deutsche Landwirtschafts-Gesellschaft / German Agricultural Society
DM	Dry matter

DSW	Deutsche Stiftung Weltbevölkerung / German Foundation for World Population
DüV	Düngeverordnung
FAO	Food and Agriculture Organization of the United Nations
FAWC	Farm Animal Welfare Council
GfE	Gesellschaft für Ernährungsphysiologie / Society of Nutrition Physiology
GHGs	Greenhouse gases
HF	Heavy fat
HL	Heavy lean
H_2O	Water
IRT	Infrared thermography
LF	Light fat
LL	Light lean
LU	Livestock unit
MD	Measurement day
ME	Metabolizable Energy / Maximal ellipse
MJ	Megajoule
N	Nitrogen
NH_3	Ammonia
NH_4^+	Ammonium
PAS	Photoacoustic-infrared-spectroscopy
REGWQ	Ryan-Einot-Gabriel-Welsch multiple-range test

RFID	Radio-frequency identification
SC	Standardized circle
SchwHKlV	Schweineschlachtkörper-Handeslklassenverordnung / Pig carcasses-Trade Classification Ordinance
SE	Standard error
SF	Supplementary feed
TierSchG	Tierschutzgesetz / Animal Protection Law
TierSchNutztV	Tierschutz-Nutztierhaltungsverordnung / Animal Welfare – Animal Husbandry Ordinance
UBA	Umweltbundesamt / Federal Environment Agency
US	Ultrasound
WPS	Whole plant silage
V_S	Variant summer
V_W	Variant winter

1 General Overview

1.1 General Introduction

Agricultural livestock husbandry has been characterized by constant change in recent years. Climate and environmental protection, as well as animal welfare, are current core topics of social discussion in the context with modern agriculture. Stricter legal requirements for animal and environment protection, make an accommodation and restructuring of the agricultural animal husbandry unavoidable (BMEL, 2017).

In the year 2050 the prospective world population will amount to 10 billion humans (DSW, 2019). Future agriculture is faced with the challenge of securing food supplies and at the same time conserving and saving existing resources (BMEL, 2019).

Digitalization and innovative technologies have already applied to agricultural animal husbandry. Various types of sensors such as pedometers or transponders like RFID ear tags make it possible to obtain animal-specific data on animal behavior, health status and individual performance. The analyses of these data offer great potential to get conclusions regarding animal welfare but also about the efficiency of operational processes. Thus, deficits and weaknesses can be identified and improvement, standardization and optimization of all mentioned points can be achieved (Jungbluth et al., 2017).

The production of pork is the most important part of meat production in Germany, but also in the European Union (Deutscher Bauernverband e.V., 2019). Therefore, especially new developments in fattening pig husbandry and production can lead to improvements for a wide range of agricultural livestock.

1.1.1 Ammonia and Ammonia Emissions from Fattening Pig Husbandry

Ammonia is a pungent smelling, colorless gas consisting of one nitrogen and three hydrogen atoms with the molecular formula NH_3. It is highly soluble in water and reacts alkaline. In aqueous solution it is in dissociation equilibrium with ammonium (NH_4^+) depending on temperature and pH value (Aarnink, 1997). About three percent of the total nitrogen (N_2) is found bound in organic mass (Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg, 2008). During the decomposition of nitrogen-containing organic substances, the bound nitrogen is returned to the natural cycle as NH_3 during the ammonification process (Monteny, 2000).

In Germany, 95% of ammonia emissions are caused by agriculture, of which 75% are attributed to agricultural animal husbandry. Pig husbandry makes up the second largest contribution (Rösemann et al., 2019; UBA, 2020a).

The excrements of the animals are the main source of ammonia release. In the environment, ammonia is produced by the hydrolytic decomposition of urea by the enzyme urease:

$$CO(NH_2)_2 + H_2O \xrightarrow{Urease} 2NH_3 + CO_2$$

Urease is formed by microorganisms contained in the feces.

During protein metabolism, ammonia is formed by the decomposition of amino acids (AC). Since ammonia acts as a cytotoxic agent in the body, it is converted to urea in the liver and excreted in feces and mainly urine (Engelhardt, 2010). Only a small amount of the nitrogen taken up with the feed can be used in metabolism. In fattening pigs, only about 30% of the supplied nitrogen is bound as endogenous protein. The remaining 70% is excreted (Aarnink, 1997). Consequently, the amount of urea excreted and thus of potentially convertible ammonia is determined by the protein and nitrogen content of the animal's diet (Canh et al., 1998).

The release of the produced ammonia depends on the ammonia-ammonium equilibrium in solution, as mentioned before, and on the mass transfer of the dissolved ammonia into gaseous ammonia (Arogo et al., 2006).

Ammonia emissions have multiple effects on the environment. Eutrophication and acidification of soils and waters, as well as direct toxicity of ammonia lead to a sustainable shift and reduction of biodiversity (UBA, 2020b). Besides the environmental impact of ammonia emissions, high ammonia concentrations inside barns have a massive impact on air quality and consequently on animal welfare. Furthermore, ammonia has negative effects on the health of both animals and humans (Drummond et al., 1980; Ryer-Powder, 1991). According to current legislation, ammonia concentrations in pig barns must not exceed 20 ppm (TierSchNutztV, 2006). For humans, the occupational exposure limit for ammonia is also 20 ppm (e. V. Deutsche Gesetzliche Unfallversicherung, 2020). If these concentrations are exceeded for a longer period of time, the mucous membranes, especially the respiratory tract and the conjunctiva, are affected. The natural defense mechanisms are limited by damage to the mucous membranes, so that pathogens can penetrate more easily into the lower respiratory tract and cause infections (Kristensen & Wathes, 2000). Reduced performance due to reduced feed intake and susceptibility to infections, as well as the occurrence of behavioral anomalies, are due to increased ammonia concentrations (Aarnink, 1997).

The European Union Directive 2001/81/EG on the National Emission ceilings regulates the maximal limits for emissions such as ammonia. Since 2010 in Germany a limit of 550 thousand tons ammonia must not be exceed. Germany has committed itself to reduce ammonia emissions by 29% until 2030 compared to 2005. Since agricultural livestock husbandry makes up the largest amount on ammonia emissions, great potential for emission reduction can be seen here (UBA, 2020a).

1.1.2 Fattening Pig Husbandry

1.1.2.1 Legal Requirements

In Germany, pig husbandry is legally regulated by the Animal Welfare - Animal Husbandry Ordinance (Tierschutz-Nutztierhaltungsverordnung; TierSchNutztV.). While section 1, §§ 3 and 4 stipulate generally valid aspects of livestock husbandry, section 5, §§ 21-30 specifically describes the requirements for pig husbandry. The Ordinance implements the requirements of Council Directive 2008/120/EC of 18 December 2008 on the "Minimum standards for the protection of pigs" into national law. In addition, the Animal Protection Law (Tierschutzgesetz, TierSchG) is generally applied to the protection and housing of animals in Germany (Hornauer et al., 2020).

In general, housing facilities for pigs must be designed in a way that the animals are able to have visual contact with other members of their species at any time. They must be able to lie down and stand up without restriction and must not come into contact with their excreta more than is unavoidable. A dry lying area must be available and there must be no risk of injury to the animals. For fattening pigs, in the case of concrete slatted floors, the slat width shall not exceed 18 mm and the total degree of perforation shall not exceed 15%. Fattening pigs must be kept in groups, with a certain area available to the animals depending on their average weight. For each animal weighing between 50 and 110 kg, an unrestricted surface area of 0.75 m^2 must be available. Animals with a body weight of $\geq$ 110 kg must receive an unrestricted surface area of 1.0 m^2. At least half of this must be available as lying area. Each pig must have access at all times to harmless enrichment material that can be examined, moved and modified by the animals. The lighting intensity inside barns must be at least 80 lux for 8 hours a day. As air quality parameters, 20 ppm ammonia, 3.000 ppm carbon dioxide and 5 ppm hydrogen sulphide must not be exceed (TierSchNutztV, 2006).

1.1.2.2 Housing Systems

There are many different housing systems for fattening pigs, whereby individual systems can also be combined with each other. In general, a distinction can be made between littered and unlittered systems. In addition, fattening pigs can be kept in thermally insulated or outdoor climate housing. A differentiation must be made between indoor and free-range systems (Jungbluth et al., 2017). In Germany, the largest proportion of fattening pigs is kept without litter on a fully slatted floor (approx. 65%), the second largest proportion on a partially slatted floor (approx. 25%). The remaining 10% are kept on litter, in other indoor housing systems or in free-range systems (Deblitz et al., 2019).

In the case of housing on fully slatted floors, there is no separation of functional areas within the pen based on the floor structure (Ziemke, 2006). These housing systems are basically forced-ventilated and thermally insulated. This form of housing is economically advantageous, as it requires the smallest amount of space per animal, allows rational labor management and good animal control. In contrast, there are high climatic demands in the barn and a low-stimulus environment for the animals (Jungbluth et al., 2017). In a barn with a partially slatted floor, the lying area is separated from the defecation area by a solid floor. This results in a better structuring of the pen for the animals. However, the soiling of the lying areas is a disadvantage, especially at high barn temperatures, as the animals then use the cooler slatted floor as a lying area (Aarnink, 1997). Outdoor climate housing is characterized by different climate areas. While the lying area is usually solid and thermally insulated in the form of resting boxes, the activity and defecation areas are perforated and freely ventilated. The free ventilation results in lower energy costs and usually a better barn climate. In addition, the structure is more animal-friendly. However, economically, a higher space requirement per animal and elaborately constructed resting boxes are disadvantageous. Furthermore, animal control is more difficult due to the closed boxes (Jungbluth et al., 2017).

Depending on the group size, a distinction can be made between small group and large group housing. Small groups are those with a group size of about 20 animals (LfL, 2007). With the implementation of non-rationed feeding with sensor troughs, the keeping of large groups of traditionally 40 to 50 animals was made possible (KTBL, 2011). A comparably young method is keeping fattening pigs in large groups in combination with a sorting gate (Jungbluth et al., 2017). Since the studies carried out in the context of this thesis were carried out with this husbandry method, it will be described in detail in the following.

1.1.2.3 Large Group Housing with Sorting Gates

In contrast to conventional large group housing, in this housing system up to 400 animals are kept in one group here. The central aspect of this method is the subdivision of the compartment into resting and activity areas as well as a spatially separate feeding area. The sorting gate connects the different areas and the animals have to pass through the sorting gate to get from the activity to the feeding area (Jungbluth et al., 2017).

Sorting gates are similar in structure regardless of the manufacturer. From the activity area, the animal enters the sorting gate via an electronically controlled entrance door. Inside the sorting gate, the animal's bodyweight is determined by means of a scale and/or optical methods and the data are processed and stored by a connected computer. Once the animal data has been recorded, the pig is given access to the feeding area via an electronically controlled exit door. Usually, there are two exit doors, through which two spatially separated feeding areas can be reached. This enables the feeding of different diets according to the body weight data. After feed intake, the animals leave the feeding area via one-way exit doors and return directly to the activity area (KTBL, 2011). An example of a sorting gate is given in Figure 1.1.

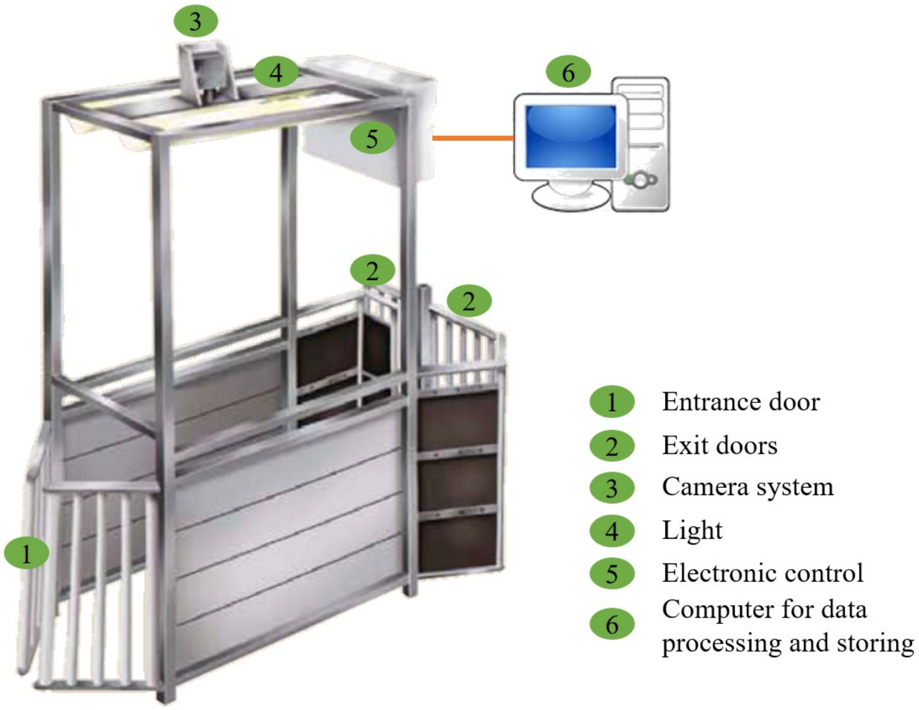

Figure 1.1 Sorting gate with optical weight determination (modified according to Hölscher + Leuschner).

Optical weight determination is carried out by means of camera technology installed above the sorting gate. The camera records the contour of the pig's body and at the same time determines the height of the animal using two lasers. Through analysis with specially developed software, the bodyweight of the animals can be estimated on the basis of mathematical equations (LfL, 2007). Simultaneously, the weights of individual body sections such as ham can be determined, respectively (Hölscher + Leuschner GmbH & Co. KG). In their studies, Cielejewski et al. (2005) were able to verify that the optical weight determination is sufficiently accurate and that there are no significant differences compared to the mechanical weight determination.

Since the animals have to pass through the sorting gate several times a day to reach the feeding area, the weight development of the animals can be closely monitored and recorded. This also enables to adjust the diet according to the changing nutritional needs of the animals. Furthermore, the separate feeding areas allow to feed fast-growing animals with a lower energy content than slow-growing animals (KTBL, 2001).

Currently, one of the main applications of the sorting gate is selection for marketing the fattening pigs. The software can be used to set a specific target weight. At the end of the fattening period, one of the feeding areas can be used as a marketing pen. Animals which have reached the target weight are recognized by the sorting gate and can be guided into the marketing pen for selection. The automatic selection process saves working time and ensures that only animals that have reached the desired target weight are marketed (LfL, 2007).

1.1.2.4 Ethology and Future Requests on Fattening Pig Husbandry

The concept of the five freedoms is the basis for the evaluation of animal welfare. The five freedoms include freedom from hunger and thirst; posture-related complaints; pain, injury and disease; fear and stress as well as freedom to live out normal behavior patterns (FAWC, 1979). Specific indicators are used to assess animal welfare within agricultural husbandry (Zapf & Schultheiß, 2015) whereby the possibility of expressing species-specific behavior is of particular importance (BMEL, 2015).

The species-specific behavior of pigs can be described by different functional fields. Each functional field refers to specific behavior of the pigs, which must be lived out for high animal welfare. The most important functional fields for the evaluation of fattening pig husbandry are resting, locomotion, feed intake, excretion, exploratory behavior and social behavior (Sambraus, 1978).

Under natural conditions, pigs live in social groups of about 20-30 animals (Schrader et al., 2009). They show a distinctive social behavior with a strict hierarchy within the group (BLE, 2009). Pigs have a biphasic activity behavior, with activity peaks in the morning and afternoon, and resting periods in between and during the night (Hoy, 2009). They are very active in movement. Naturally, a behavioral change is always associated with a change of location (Schrader et al., 2009). If it is possible for the animals, the different functional areas are also separated from each other spatially. So under natural conditions they move away from their lying or feeding area to excrete urine and feces. The separation of excrement areas and the remaining activity and resting areas is connected on the one hand to the strong aversion to the species-specific excrements. On the other hand, pigs prefer areas where there is little movement for excreting, because they have to take an instable body position (BLE, 2009).

Pigs have a highly developed exploratory behavior, which under natural conditions is expressed to 70-80% by foraging. Using the snout disc, the animals fulfil their burrowing behavior, but they also use their front claws for scratching. Although pigs eat synchronously, they keep a distance of 2-4 m to conspecifics, if possible (Hoy, 2009).

Although in Germany regulations of livestock husbandry are more specific and progressive compared worldwide or to other EU members, it is still under criticism and described as in need of improvement (World Animal Protection, 2020). The demand for "more animal welfare" is increasingly being voiced by consumers (BMEL, 2015).

Looking at the natural behavior of pigs and transferring this to the husbandry methods predominantly used in Germany, the discrepancy becomes very clear. The main challenge in developing modern husbandry systems is to combine animal welfare, environmental protection, consumer orientation and economic efficiency (BLE, 2018). However, the resulting conflicts often prevent a fast implementation of new concepts and elimination of deficiencies (BMEL, 2015). Thus, the economic viability of agricultural farms is often a decisive factor when trying to improve the other aspects mentioned. For example, smaller livestock populations, kept on larger areas, with litter or free-range, as demanded by consumers and as could contribute positively to animal welfare, are usually hardly economically viable for most farms (BMEL, 2017). Furthermore, adjustments in animal husbandry often cannot be implemented immediately, especially if they are linked to major building changes. But there are also other conflicts, for example between animal welfare and environmental protection. So, increased space, the use of bedding materials or access to a free-range area can lead to an increase in emission released. In the idealized imagination of many consumers of free-range animal husbandry, an increased risk of infection with pathogens or ectoparasites, which in turn can have a negative effect on animal health and thus animal welfare, must not be disregarded (BMEL, 2015).

In order to solve the conflicts and reach the increasing demands on modern animal husbandry, a constant and close cooperation between politics, agricultural practice, research, veterinary science and consumers is unavoidable. Public information and advisory work, financial support and the development and investigation of new techniques, systems and strategies are particularly important in order to achieve long-term success (BMEL, 2019).

1.1.3 Feeding of Fattening Pigs

1.1.3.1 Physiological Nutritional Requirements

Pigs are omnivores and belong to the monogastric animals. In addition to efficient digestion of easily available nutrients in the cranial gastrointestinal tract, they are also able to ferment crude fiber or precaecal indigestible proteins in the colon using microorganisms (Kamphues et al., 2014). The resulting short-chain fatty acids can be absorbed by the animals and used for energy supply (Jeroch et al., 1999).

The aim of fattening pig husbandry is to produce high-quality carcasses with high muscle meat and low fat content (SchwHKlV, 1990). The daily requirement of the animals is composed of a requirement for energy (metabolizable energy; ME), as well as a requirement for protein or amino acids, minerals and vitamins (Jeroch et al., 1999). The need for energy and nutrients depends on factors such as genetics, age, sex, production and performance level (Lindermayer, 2004). The calculation of requirements is basically divided into maintenance and performance requirements. The maintenance requirement includes the supply of energy and nutrients necessary for organ function, thermal regulation and metabolism. Performance requirements are the energy and nutrients that are available for production beyond the maintenance requirements. This can include increased exercise, growth (fattening or pregnancy) and lactation (Jeroch et al., 1999). The protein requirement of fattening pigs can be described as the amino nitrogen and amino acid (AC) requirement. While non-essential ACs can be produced in the metabolism, essential ACs must be supplied with the diet. For both, maintenance and performance metabolism, the available ACs must be provided at a certain ratio. Therefore, the protein supply cannot be equated with the crude protein content of the diet. Qualitatively, dietary proteins are therefore evaluated according to their AC composition (Kamphues et al., 2014).

During the fattening period, the body composition of fattening pigs changes and consequently so do their nutritional requirements. While the protein content per kg of body weight (BW) decreases from 170 g kg^{-1} (30 kg BW) to 145 g kg^{-1} (120 kg BW), the fat content increases from 170 g kg^{-1} BW to 420 g kg^{-1} BW. Consequently, energy absorbed towards the end of fattening is not used for muscle development, but is stored as fat tissue. The changes in live mass gain are shown in Figure 1.2.

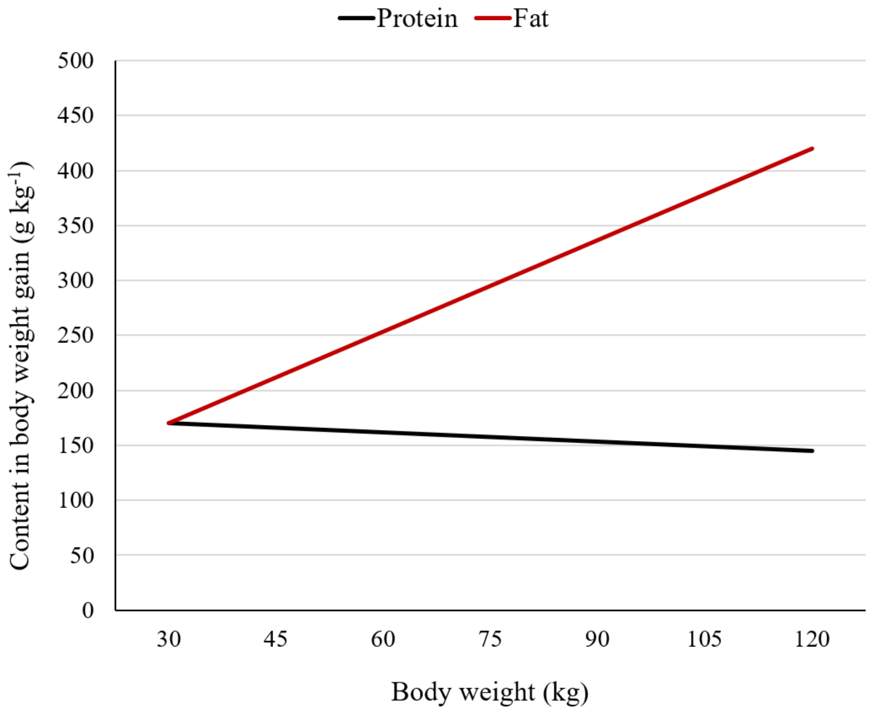

Figure 1.2 Changes in protein and fat content in body weight gain of fattening pigs (modified according to GfE 2006).

The feed intake capacity is important for the supply of nutrients and energy. Young animals have a lower feed intake capacity than older animals (Kamphues et al., 2014). However, since young animals in particular need to consume a lot of energy and protein to meet the requirements for growth and muscle development, they tend to require a more nutrient-concentrated diet. In order to avoid fattening of the animals at an advanced age, the energy and protein density should be adjusted accordingly. Furthermore, there are gender-specific differences. Castrated male animals have a higher feed intake capacity and a higher fat accumulation capacity than female animals, which is due to differences in the endocrine system (Jeroch et al., 1999). Therefore, an excess energy supply has a negative effect on carcass quality, especially in male castrates (Brade & Flachowsky, 2006; Jeroch et al., 1999).

Besides the economic aspects, an oversupply of nutrients, especially protein, should be avoided, particularly for environmental reasons. With an average feed intake of 250 kg per animal and fattening period and an average crude protein content of 16.5% (DLG e.V., 2019), this corresponds to a protein intake of 41.25 kg per animal. As crude protein contains 16% nitrogen on average (Kamphues et al., 2014), one can assume approx. 6.6 kg nitrogen per animal and fattening period. In fattening pigs, only about 30% of the consumed nitrogen remains in the body while approx. 70% of the nitrogen is excreted in feces and mainly urine (Aarnink, 1997). At the assumed amount of nitrogen, this corresponds to 4.62 kg nitrogen per animal, which is released unused into the environment. An adjustment of the protein supply during fattening is therefore mandatory to avoid excess nitrogen inputs into the environment. Figure 1.3 illustrates the potential for reducing ammonia emissions by reducing the crude protein content in the diets of pigs and cattle as shown by Sajeev et al. (2018).

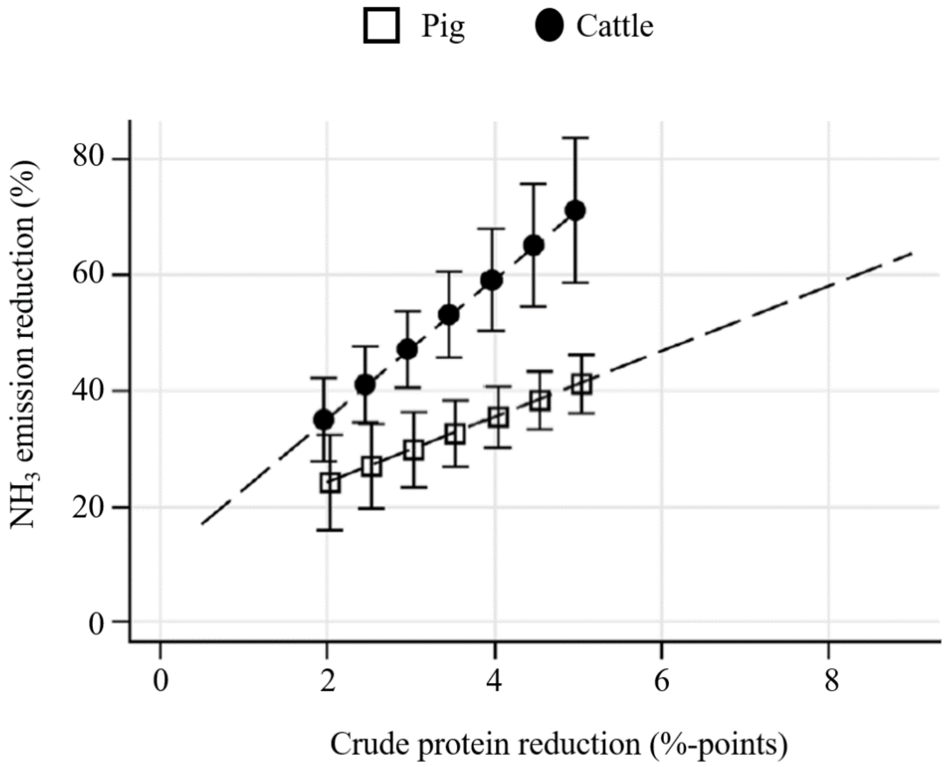

Figure 1.3 Ammonia emission reduction for pigs and cattle under varying crude protein reductions and final crude protein levels. The higher the crude protein reduction and the lower the final crude protein level (tested 12 to 16%), the greater the ammonia emission reduction (modified according Sajeev et al., 2018).

1.1.3.2 Feeding Techniques for Fattening Pigs

There are many different feeding systems for fattening pigs. In addition to the former main objective of providing a defined feed mixture to the animals at the desired time in order to feed them, nowadays much higher demands are placed on modern feeding systems. Factors such as nutrient optimization, feed consumption record, hygiene standards and potential cost-, resource-, and energy savings are increasingly important. However, the basic principles of feeding are still justified today, as well as in the future, and are constantly being improved (BLE, 2019; Jungbluth et al., 2017).

Generally, feeding methods for fattening pigs can be differentiated into dry and liquid feeding according to the type of feed provided. On the other hand, a distinction can be made between rationed and *ad libitum* feeding (diet for free intake) according to the feeding regime (Jungbluth et al., 2017). Depending on the number of feedings per day, rationed (one feeding per day) and daily rationed (2-3 feedings per day) feeding can be further differentiated (Averberg et al., 2012). The animal: feeding place ratio that must be available in the barn results from the used feeding regime. If feeding is rationed once a day, one feeding place must be available for each animal. In the case of daily rationed feeding, an animal: feeding place ratio of 2:1 is prescribed, whereas in the case of *ad libitum* feeding, 4 animals are allowed to share one feeding place (TierSchNutztV, 2006). The width of a feeding place depends on the weight of the animals. Depending on dry or liquid feeding as well as feeding regimes, the feed can be presented via longitudinal and transverse troughs, automatic feeders, pulp dispensers or troughs with sensors (Jungbluth et al., 2017). All mentioned feeding systems include advantages and disadvantages. Pure dry feeding systems are easy to handle, require little technology and are therefore cost-efficient (Averberg et al., 2012). However, there are limitations with regard to the type of feed that can be used and the transport options from the feed storage to the feed trough. Liquid feeding systems, on the other hand, require more technical effort and have higher hygiene requirements. However, they also allow the use of all feedstuffs, including low-cost by-products such as whey, lead to labor savings and enable simple implementation of multiphase feeding (Jungbluth et al., 2017). Which system is used on a farm depends on many different factors and must always be decided individually (Averberg et al., 2012). As described above, under natural conditions pigs spend a large part of their day foraging and eating, so *ad libitum* feeding corresponds most closely to natural behavior. Here, the animals can decide themselves when they want to eat and take in feed individually and at any time. In contrast to rationed feeding where all animals eat at the same time and can be observed, *ad libitum* feeding makes animal control more complex and difficult. Sick animals can less easily be noticed because not all animals go to the feeding trough at the same time. With *ad libitum* feeding, special attention must therefore be paid to ensure extensive animal control (BLE, 2019; Jungbluth et al., 2017).

1.1.3.3 Fiber Supply

In feed analysis, crude fiber is defined as the organic component insoluble in acids and alkalis, which consists mainly of the structural plant components cellulose and lignin

(Kamphues et al., 2014). Pigs do not have the necessary enzymes for the digestion of these substances. Nevertheless, the animals are able to metabolize the crude fiber energetically. By microorganisms in the large intestine, the plant components are converted into short-chain fatty acids which can be absorbed and utilized via the intestinal mucosa (Brade & Flachowsky, 2006).

In the feeding of fattening pigs, energy-rich, finely ground feed mixtures are mainly used. Usually, the diets contain only a very small amount of crude fiber (Schrader et al., 2009). As the crude fiber content increases, the digestibility of the organic matter in the pig's diet decreases (Drochner, 1993). On average, the digestibility of organic matter in pigs decreases by 1.68 units per 1% crude fiber in the diet. This value varies depending on the animal species and is also influenced by type and structure of the fiber (Jeroch et al., 1999; Kamphues et al., 2014). One reason for this is that fiber reduces the energy density in the diet (Drochner, 1993; Jeroch et al., 1999). In the production of fattening pigs, this is not economical, so that fiber is largely dispensed within the diet. However, the composition of the diet should not only be considered in terms of nutrient supply and economic efficiency. Increasingly, the health and welfare of the animals become an important part of the feeding. The use of fiber is of decisive importance in this context (BLE, 2019).

Fiber has various nutritional effects that have a positive impact on the animal. Due to its structure, the retention time in the stomach is extended, which, in addition to the increased volume, contributes to the satiation of the animals (de Leeuw et al., 2008). Furthermore, a diet rich in fiber prevents the development of gastric ulcers (Jeroch et al., 1999). Fiber has a high water-binding capacity, which also increases the volume in the intestine and accelerates the passage of ingesta (Drochner, 1993). Thus, constipation and the absorption of harmful mycotoxins can be prevented. The growth of microorganisms in the large intestine is supported by fiber. This contributes to the intestine health, but also promotes microbial nitrogen fixation and can thus reduce nitrogen excretion (BLE, 2019).

In addition to the nutritional aspects, fiber is important as enrichment material. The Ordinance on Animal Welfare and Farm Animal Husbandry stipulates that pigs must at all times have access to harmless enrichment material which can be examined, moved and modified by the pigs (TierSchNutztV, 2006). This includes materials rich in fiber such as straw or hay (BLE, 2019).

On average, a pig needs only a few minutes to consume conventional feed mixtures. With rationed feeding, the animals only receive feed twice a day (Schrader et al., 2009). Looking at the natural feed intake behavior of pigs (see chapter 1.1.2.4), it becomes clear that the feed intake under housing conditions is not sufficient to satisfy their natural behavior (Lawrence & Illius, 1989). Due to its structure, fiber prolongs the feed intake time, as the animals are occupied much longer with selection and crushing in the mouth. Furthermore, the use of fiber as an enrichment material can additionally contribute to satisfying the strongly developed exploration behavior of pigs. Both of these factors have a positive effect on animal welfare by counteracting the development of stereotypical behavior and cannibalism (Schrader et al., 2009).

1.1.4 Thermoregulation of Fattening Pigs

As mammals, pigs belong to the homoiothermic animals (Engelhardt, 2010). Physiologically, their body core temperature is between 38 °C and 39 °C (Boehringer Ingelheim, 2016). For a constant body temperature, the heat production must be equal to the heat release. They are therefore able to maintain their body temperature by thermoregulatory mechanisms and to react to changing ambient temperatures. Basically, four mechanisms for thermoregulation can be distinguished: Conduction, convection, radiation and evaporation (Fuquay, 1981). The first three presuppose a temperature gradient and are described as sensitive heat release, while evaporation represents a latent heat release and is increasingly important in pigs from an ambient temperature of ≥ 24 °C (Wegner, 2014).

With conduction, the animals transfer their body heat to cooler surfaces, such as the lying areas. Here, the temperature difference, the size of contact area and the conductivity are important. With convection, heat is released to the ambient air and is essentially dependent on the airflow rate. In the case of internal heat stress, the body surface temperature can be increased by vasodilatation in the skin and thus heat can be released by radiation. In contrast to the other three mechanisms, evaporation is a moist heat release. It is the only way to release heat against a temperature gradient. As pigs do not have sweat glands, this form of heat regulation is only possible for them by breathing or by external moisturization of the skin. Through an increased respiratory frequency, the inhaled air is warmed up and saturated with water vapor. However, this form of heat release is only possible to a certain extent because hyperventilation can lead to respiratory alkalosis and, in addition, increased work of the respiratory muscles also generates heat which must be dissipated (Engelhardt, 2010).

The thermoneutral zone describes the body temperature range in which the energy required for maintaining the body's core temperature is minimal. If this range is exceeded, heat must be released as described before. If this cannot be done to a sufficient extent, hyperthermia and even heat death can result. Conversely, if the temperature drops below the thermoneutral zone, heat must be produced. If there is not enough energy to be utilized, hypothermia and cold death will follow. Pigs are much more tolerant for cold than for heat. While they can tolerate a difference of 15-25 °C in cold, it is only 3-6 °C in heat (Bianca, 1976).

1.1.5 Principles and Applications of Infrared Thermography

Infrared thermography (IRT) enables the measurement and visualization of thermal energy emitted as radiation by a body or object (Gerß, 2014). Infrared radiation belongs to a wavelength range between 0.76 µm and 1000 µm. The more heat is emitted, the shorter the wavelength that can be measured (Bernhard, 2004). By using an infrared camera, this radiation can be made visible for humans (visible wavelength: 0.38-0.75 µm) with a thermogram. This assigns a defined temperature to each pixel (Zhang et al., 2020). In the creation of thermograms, the wavelengths range from approx. 0.8 µm to approx. 20 µm is important. In the infrared wavelength range, animals emit 40-60% of their thermal radiation (Kleiber, 1961). As a non-reactive, contactless measuring technique, IRT offers many advantages and a wide range of possible applications (Bernhard, 2004). For example, it is used in the construction and plastics industries, fire monitoring and air conditioning technology. But IRT is also increasingly being used in human and veterinary medicine and livestock husbandry (Gerß, 2014). For example, Traulsen et al. (2010) used IRT for hot spot detection and diagnostic of the mastitis-metritis-agalactia complex, while Loughmiller et al. (2005) investigated changes in metabolism due to changes in feeding parameters, by means of IRT.

1.2 Problems and Research Questions

Nowadays, many feeding concepts in fattening pig husbandry aim at a protein-adapted and nitrogen-reduced feeding in order to reduce excess input of harmful substances and emissions into the environment. While universal feeding without adaptation during the fattening period was used in the past, many fatteners have implemented phase feeding or multi-phase feeding concepts. Here, the diet is adapted to the changing needs of the animals several times during the fattening period. Specific amino acid supplementation and highly nitrogen- and phosphorus-reduced diets are also common strategies to reduce oversupply.

Although resource savings can already be achieved, with the mentioned feeding methods, there is still potential for improvement. The current concepts of phase feeding are based on the "average animal" of the entire group when calculating the diets. Individual differences in nutrient requirements and performance potential are not sufficiently taken into account. The consequence of an "average diet" is that animals with requirements above the average are undersupplied. On the one hand, this should be avoided for reasons of animal welfare, but also from an economic point of view, as the animals cannot achieve their full performance. On the other hand, animals with a demand below the average are over-supplied. Oversupply should be avoided, especially with regard to saving resources and protecting the environment, as described above. Furthermore, animals with a particularly high feed intake capacity additionally consume excess nutrients.

In the context of this dissertation, the development and investigation of a new resource-saving feeding concept was addressed. The general idea of the concept provides for a fully automated classification of the fattening pigs into performance groups by means of a sorting gate. Daily body condition measurements are to be used to automatically adjust the feed rations to the exact daily requirements of the individual performance groups. The performance groups are intended to take better account of individual needs. At the same time, with the help of the daily adaptation of the diet, an optimal adjustment of requirements is to be achieved in order to save resources and reduce excess nutrient inputs into the environment. Various hypotheses arose for the investigations of the new feeding concept:

- There are differences with regard to the individual fattening performance potential of the animals.
- The fattening performance potential can be predicted by determining the back fat to back muscle ratio.
- The use of fiber in the diet can regulate the feed intake of the animals.
- Individual performance groups react differently to different levels of crude fiber in the diet.
- Ammonia emissions can be reduced by increasing the use of fiber and by feeding according to performance groups.

- There is no deterioration in floor pollution inside the barn due to increased use of fiber.
- There is a correlation between the back fat to back muscle ratio and body surface temperature.
- Thermography can be used to distinguish "fat" from "lean" animals and thus divide them into performance groups.

Study 1 and 2 of this dissertation dealt with the questions of feeding and environmental effects. Study 1 was conducted in equal parts by two working groups, each of which dealt with one of the two aspects mentioned. The focus of this thesis is on the investigations of the environmental impacts. These are therefore given special attention in the concluding discussion.

Study 3 dealt with the question how an automated classification of animals into performance groups can be technically enabled. For this purpose, the question was investigated whether different body conditions of the animals can be recognized on the basis of the body surface temperature and whether a classification into performance groups is possible on the basis of this.

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2 Study 1

Validation of a New Resource-Efficient Feeding System for Fattening Pigs Using Increased Crude Fiber Concentrations in Diets: Feed Intake and Ammonia Emissions

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2.1 Simple Summary

The feeding of fattening pigs and its associated ammonia emissions are current core problems in social debate that affects climate change and sustainability. Feeding methods offer great potential to increase animal welfare and sustainability, and negative impacts on the environment can be reduced. Fattening pigs differ in their performance potential and in their nutrient requirements. A high feed intake capacity can lead to luxury consumption. Diets rich in crude fiber should prevent excess feed intake and cause better nitrogen fixation by microorganisms in the animals' large intestines. In a pig fattening farm, it was investigated whether and how diets rich in crude fiber can influence feed intake and ammonia emissions. The animals were divided into feeding groups according to their presumed performance potential by ultrasound examinations. Therein, body compositions were evaluated, and feed intake capacity and body weight were automatically recorded. The aim of the study was to enable adapted feeding of the animals by regarding their individual differences in body composition and performance potential. Roughage-based diets had significant influence on feed intake and did not increase ammonia emissions. Based on the results of this study a performance-based control of the feed intake should be made possible.

2.2 Abstract

The housing of fattening pigs, their feeding, and the emissions associated with this process are subjects of criticism. In order to reduce emissions and ensure resource efficiency, new paths must be taken; animals must be fed closer to their actual needs. In a pig fattening farm, 655 animals were grouped according their body weight and their body composition, consisting of weight and muscle-fat-ratio, which was determined by ultrasound examinations. The influence of different concentrations of triticale whole plant silage (WPS) (from 2.5% to 10%) on the feed intake capacity (3.88 kg to 2.71 kg (88% dry matter (DM))) of each group and the ability to control it was determined. Ammonia emissions were measured and the pens floor pollution was assessed. The animals could be distinguished significantly from each other by ultrasound examinations. The crude fiber influenced the level of daily feed intake. Ammonia emissions were not negatively influenced and could be partly reduced. There was no negative impact on surface contamination due to the increased use of crude fiber. The amount of daily feed intake was controlled by crude fiber rich diets. If these findings are adapted to certain types of pigs, a reduction of emissions and an increased resource efficiency can be expected.

Keywords: feeding technology; roughage-based diet; animal welfare; environmental impacts; liquid feeding system; body composition evaluation; sorting gate; sustainability

2.3 Introduction

Livestock production has negative impacts on the environment due to the production of greenhouse gases (GHGs) and ammonia (NH_3) emissions. Almost 95% of global NH_3 emissions and 18% of anthropogenic GHG emissions arise due to livestock production (FAO., 2019; Philippe et al., 2015b; Steinfeld et al., 2006). Besides cattle farming, pig husbandry is the second largest source of NH_3 emissions in Germany (Rösemann et al., 2019). The main effects of ammonia on the direct environment are eutrophication and acidification of the soil as well as groundwater pollution and indirect nitrous oxide emissions (Aarnink, 1997; Arogo et al., 2006; Krupa, 2003; Sutton et al., 1993). The fattening pig husbandry has been characterized by an increasing regional concentration particularly in the northwestern regions of Germany over the last few years (BMEL., 2017; Deblitz et al., 2019; Statistisches Bundesamt, 2020a; Statistisches Bundesamt, 2020b). This development also leads to negative effects of NH_3 emissions, which are particularly pronounced in these regions (UBA., 2020a).

As part of the protocol to abate acidification, eutrophication, and ground-level ozone and the European Union (EU) Directive 2001/81/EG on the National Emission ceilings, Germany, like all other EU members, has committed itself to reduce NH_3 emissions by 2030 by 29% (compared to 2005). Since 2010, the maximum of 550 thousand tons of ammonia per year may no longer be exceeded. The limit could not be kept since it was set (UBA., 2020b). Therefore, further activities to reduce NH_3 emissions are urgently needed.

In the protein metabolism of animals, nitrogen is mainly excreted as urea in the urine (50%) while a small amount is excreted in feces (20%). Only about 30% of the ingested protein is metabolized efficiently and used to gain muscle mass (Aarnink, 1997). The enzyme urease produced by bacteria in the feces converts urea in the urine to ammonia, which is then released to the environment (Arogo et al., 2006). The aim in fattening pigs is a body composition with maximum muscle and minimum fat content (SchwHKlV, 1990). The difficulties arise in the limitations of protein utilization as well as different capacities of feed intake (Jeroch et al., 1999), which is influenced, for example, by genetics, gender, age, or the social position of the individual within the group (Nyachoti et al., 2000). Different studies have already shown that a reduction of crude protein in the diet of fattening pigs can reduce NH_3 emissions (Hansen et al., 2014; Hayes et al., 2004; Seradj et al., 2018). Moreover, the possibility of influencing nitrogen excretion and NH_3 emission by using crude fiber is well known (Galassi et al., 2010). In their study, Philippe et al. (2015a) describe in detail the positive effects of diets rich in crude fiber in fattening pigs. For example, they increased intestinal health and improved the intestine immune system to prevent pathogenic infections. Additionally, increased crude fiber content extends feeding times and functions as enrichment material. Compensatory behavior such as cannibalism due to frustration can be reduced and animal welfare can be improved (Werner & Sundrum, 2008). It has also been shown that multi-phase feeding strategies with adaption to the changing protein requirements of the animals during the fattening period are preferable to single-phase feeding, with regard to nitrogen excretion of up to 17% (Lenis & Jongbloed, 1999; Philippe et al., 2011). However, since current concepts of phase feeding are only based on the average nutrient requirements of the animals, the individual needs are not sufficiently taken into account. Pigs with a high capacity of feed intake consume more protein and energy than they can efficiently utilize. The use of crude fiber is intended to control feed intake and prevent excess intake (Kyriazakis & Emmans, 1995). Animals with an excess feed intake develop fatter tissue, especially at the end of the fattening period (Jeroch et al., 1999). In addition, excess protein intake leads to increased nitrogen excretion and to an increased release of ammonia. On the other hand, animals below average are not fed sufficiently and are unable to fully achieve their fattening performance potential (Kamphues et al., 2014).

Sorting gates are an established technology in large group housing of fattening pigs for many years. This technology enables the automatic selection for slaughtering by means of optical and mechanical weight determination. Furthermore, it is possible to assign the animals to different feeding areas (Cielejewski et al., 2005; Tscharke & Banhazi, 2013). Until now, the selection and classification of the animals by the sorting gates was based exclusively on the body weight determination. Thus, the animals were divided into “light” and “heavy” animals and could be fed differently according to the average body weight of the group. However, there is still a high potential for saving resources since animals above or below the new average of the two groups (heavy/light) are not supplied efficiently. In order to adapt the feeding of fattening pigs to the current state of the art, a new resource-efficient feeding concept was developed. By introducing new, additional parameters (backfat thickness and the diameter of the *m. longissimus dorsi*), the classification should be refined and the diets should not only be based on average body weight. Feed intake will be used as a quantitative parameter to adjust diets. Furthermore, the different "types of pigs" will be determined by the individual body compositions. Thus, the genetic fattening potential should be used optimally, which is desirable both economically and with regard to resource efficiency. By adapting the diet to the daily measurement data, it should be possible to optimize the protein intake and thus reduce the NH_3 emissions. For the first time, such new feeding strategy is investigated under barn conditions. In this study, different aspects of the new feeding technology are investigated. On the one hand nutritional aspects like the influence of crude fiber supplemented diets on feed intake of the animals were examined. On the other hand, the influence on NH_3 emissions and floor pollution was analyzed.

We hypothesize that firstly the feed intake correlates negatively with the crude fiber content in the diet. Secondly, the different "types" of pigs will react differently in their feed intake capacity. Thirdly, the crude fiber does not negatively influence ammonia emissions and floor pollution. Consequently, an individual feeding, resource-efficient, and fattening performance-related feeding concept will be possible.

2.4 Materials and Methods

2.4.1 Animals and Housing

This study was carried out on a pig fattening farm in Lower Saxony, Germany. Three barns were available. Barn I was used to collect data on feed intake and growth performance of the animals under the crude fiber supplemented diet. In addition, ammonia emissions and floor pollution were recorded and investigated. This trial was conducted during a summer fattening period.

In Barn II and III measurements during a fattening period with crude fiber supplemented diet (Barn II; same diet as described for Barn I) and during a period with standard diet as control (Barn III) were done in winter. In this trial only data on the environmental aspects were collected, due to technical conditions. Figure 2.1 gives an overview of the measurements done in Barns I–III.

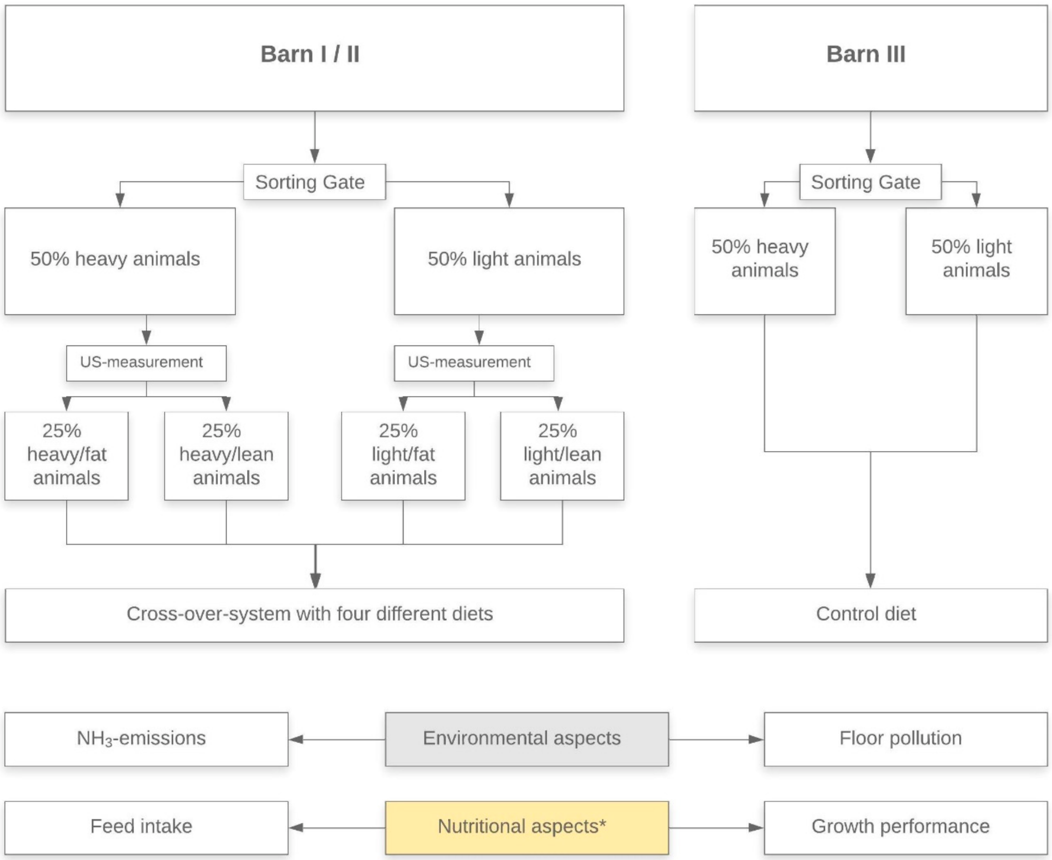

Figure 2.1 Overview of the measurements done in the different barns. Barn I and II were used for experimental groups with crude fiber supplemented diets. Barn III was used for control group with standard diet (US stands for ultrasound). *Data of nutritional aspects only collected in barn I.

2.4.1.1 Barn I

Barn I was subdivided into two pens (I.1 and I.2). It was designed for large group housing with a capacity of up to 656 animals in total and 328 for each pen. In each pen, there was a sorting gate of the company Hölscher + Leuschner (®Hölscher + Leuschner GmbH and Co. KG, Emsbüren, Germany), which connected the activity and lying areas from two separate feeding areas (feeding area “A” and “B”). In Barn I, there were a total of four feeding areas (two per pen). The sorting gate consisted of an entrance door, a measuring area (including a scale, 3D-camera as well as ear tag recognition) and two exit doors through which the animals can be guided depending on their specific setting. The animals had to pass the sorting gate to reach the feeding areas. The sorting gates allowed for the detection and recording of individual animal data via transponder ear tags. By means of camera technology, which was installed above the sorting gate, each animal was recorded when it entered the gate and the live weight was calculated by measuring the height and width of the animal with the assistance of special software (optiSORT, Hölscher + Leuschner GmbH and Co. KG, Emsbüren, Germany). In addition, a mechanical weighbridge was integrated in the bottom of the sorting gate so that the current body weight of each animal could be determined. The correlation of optical and mechanical weight determination was verified by Cielejewski et al. (2005) and used as the basis for this study. In each feeding area there was a trough, which was filled via a feeding valve (valve 1–6) with a feed in liquid form in different composition.

Barn I had a surface area of 556 m^2, so approximately 278 m^2 per pen and a volume of 1780 m^3 in total. 655 animals were housed in Barn I for the trial. Per animal, there was a usable surface area of > 0.8 m^2. Barn I was used only for measurements under experimental conditions. Approximately 40% of each pen were equipped with a structured plastic slatted floor (Comfi-Floor, Hölscher + Leuschner GmbH and Co. KG, Emsbüren, Germany) with a void percentage of 3.8%, and 12 mm rectangular openings (Hölscher + Leuschner GmbH and Co. KG; 2020). The remaining 60% were equipped with concrete slatted floor with a void percentage of 15% and rectangular openings of 17 mm in width. The barn was force ventilated with fresh air supply along the eaves and the decentralized over floor extraction by means of two exhaust fans with a diameter of 1090 mm. Figure 2.2 shows an outline of Barns I–III.

2.4.1.2 Barn II and Barn III

Barn II and III were identical in their construction and also designed for large group housing with up to 700 animals per barn. Each barn was subdivided in a bigger area (II.1 or III.1) and a smaller area (II.2 or III.2). Area II.1 and III.1 had a surface of 452 m^2 and a volume of approximately 1650 m^3 each. Area II.2 and III.2 had a surface of 133 m^2 and a volume of 486 m^3. The access to the smaller areas was closed at the beginning of the fattening period and was opened after the first quarter of the period to provide more space to the animals. Per animal there was a usable surface area of > 0.75 m^2. Each barn was equipped with two sorting gates that connected the activity and lying areas from separated feeding areas. Barn II was used for measurements under experimental conditions, while Barn III was used as the control barn. Approximately 60% of the surface area were equipped with a structured concrete slatted floor with a void percentage of 6% and rectangular openings of 17 mm in width. The other 40% were equipped with concrete slatted floor, as described for Barn I. Moreover, as described above for Barn I, each barn was force ventilated with four exhaust fans with 980 mm diameter (Figure 2.2).

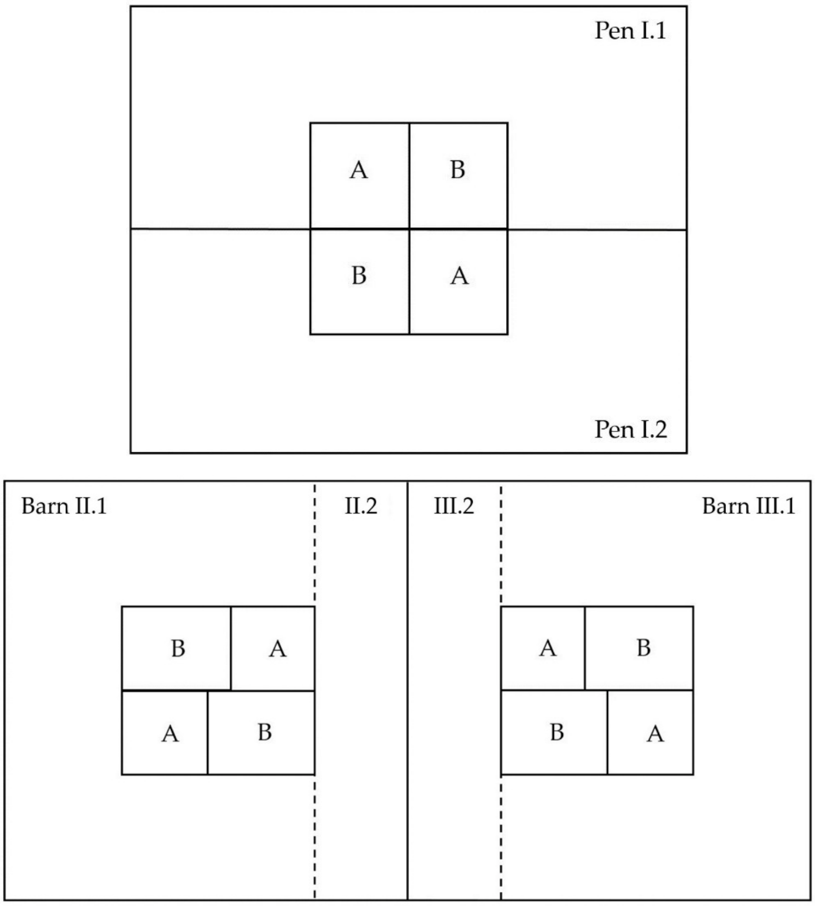

Figure 2.2 Above: Outline of Barn I with its two pens (I.1 and I.2) and two feeding areas (A and B) per pen. Below: Outline of barn II and III, each subdivided in a bigger (II.1; III.1) and a smaller (II.2; III.2) area and four feeding areas (A and B) per barn.

2.4.1.3 Animals

In Barn I, the 655 piglets came from a farm in Brandenburg, Germany and were crossbred products of a Danzucht and Bundes Hybrid Zucht Program (BHZP; German Federal Hybrid Breeding Program). The animals all came from one litter group. The males were castrated as suckling pigs and their average body weight at the time of housing was 25 kg. The animals were randomized into two pens so that two identical groups were formed by size and weight. Randomization was ensured by the fact that the two pens were not separated from each other by the otherwise closed connecting doors before data collection and examinations began. Dividing the animals into two pens for maximum comparability was controlled and could be confirmed by the almost identical mean body mass of the animals in the groups.

In Barn II and III, 700 piglets with the same genetics as used in Barn I were housed in for the experimental group and the control group, respectively. The fattening period of the control group started at the beginning of November 2018, while the period of the experimental group started four weeks later. Due to the large number of piglets needed for both groups, it was not possible to house in both groups at the same time. The average body weight at the beginning was about 40 kg for the control group and 25 kg for the experimental group.

2.4.2 Feeding

2.4.2.1 Feeding Groups

The experimental groups were divided into four feeding groups. This was done by means of ultrasound examination (see Section 2.4.2.2) of each animal (Ø bodyweight 50 kg; standard deviation ± 6.42 kg). The groups were divided according to the parameters of body weight and the ratio between back fat thickness and the diameter of *Musculus longissimus dorsi*. Based on the weighing data, all animals were subdivided into "light" (Pen I.1) and "heavy" (Pen I.2) with roughly equal proportions. In addition, all animals were categorized as "fat" and "lean" based on the ultrasound data and the calculated back fat/muscle ratio (see Figure 2.1). The categorization was carried out for both the light and heavy animals, so that one group of light animals with a low back fat/muscle ratio ("light lean (LL)") and a second group of light animals with a high back fat/muscle ratio ("light fat (LF)") originated. The heavy animals were grouped as "heavy lean (HL)" and "heavy fat (HF)", respectively. The division of the animals in the subgroups and the associated feeding areas was ensured by the recognition of the individual transponder ear tags and the sorting gates. The gender was initially not taken into account in the division.

2.4.2.2 Ultrasound Examination

The ultrasound examination was performed with the LOGIQ®V2 device (GE Healthcare, Little Chalfont, UK). The measurement was made in the exit gate after the feed intake of the animals. The measuring point was chosen at the side of the spine at the height of the last rib on the left side of the body. This measuring point was based on the P2 measuring point (Hesse, 2003). In younger animals, 6–8 cm of the greatest possible muscle thickness running laterally along the back line cannot be detected (Susenbeth, 1995) and so the point was adapted to the body mass and body condition of the growing animals. In order to be able to judge the same point with each measurement, a prominent bone point was used that was anatomically visible on the ultrasound images of the 655 evaluated pigs (Figure 2.3).

The back fat and muscle thickness was determined on all animals in the compartments. The measurement was performed on the *longissimus dorsi* muscle and recorded the back fat thickness, which consists of the skin, the first layer of fat (*subcutis*), and the second layer of fat (interfacial fat layer) as well as the connective tissue, which is located above the *longissimus dorsi* muscle and the muscle thickness of said muscle (Figure 2.4) (Müller & Polten, 2004).

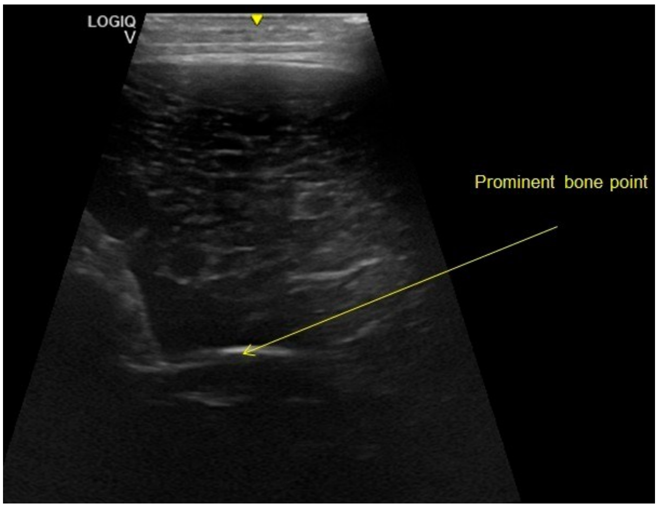

Figure 2.3 Ultrasound image taken in these examinations in order to illustrate the prominent bone point (photo: ©Reckels, University of Veterinary Medicine, Hanover).

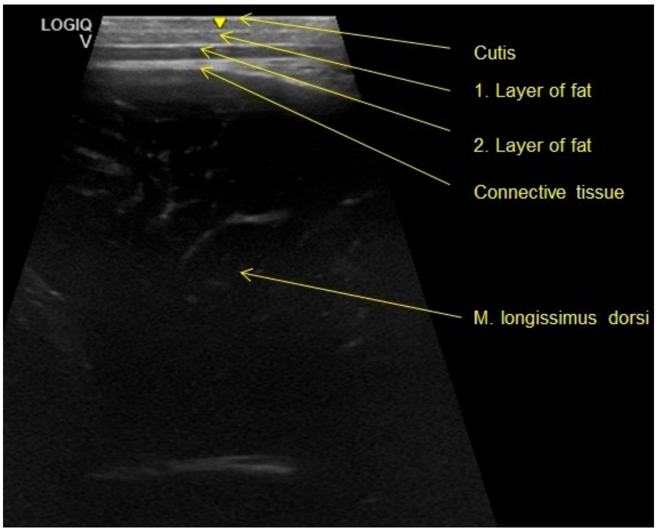

Figure 2.4 Ultrasound image taken in these examinations in order to illustrate the layers mentioned (photo: ©Reckels, University of Veterinary Medicine, Hanover).

2.4.2.3 Feeding Technology and Feeding Components

The fattening pigs on the farm are fed exclusively with a liquid feeding system (®Hölscher + Leuschner GmbH and Co. KG, Emsbüren, Germany). The liquid feed for the fattening pigs was composed of six different components (complete feed, supplementary feed, and feed material) in different percentage proportions. Due to the storage on the test farm, however, it was only possible to use five different components at the same time. The complete feed, "CF1", as well as the supplementary feed, "SF1", "SF2", and "Soybean oil", were purchased from a German feed company and were used as the sole component and part of the compound feed. Corn-Cob-Mix (CCM) and Triticale whole-plant silage (WPS) were used as the farm's own components. The diets were designed according to the demand of the animals and components were used according to the ingredients. Table 2.1 shows the chemical compositions of the used components.

The water supply was additionally provided by an open drinking trough and 30 drinking nipples per barn. In addition, the animals were granted access to roughage through a suspended hay rack. However, since the hay was laced, the hay bales had to be renewed once a week, and the roughage could not be seen as a feed but as additional enrichment material.

Table 2.1 Chemical composition of "CF1", "SF1", "SF2", and "Soybean oil", according to the declaration (88% dry matter content; DM). Triticale WPS and the Corn-Cob-Mix (CCM) were analyzed in the Institute for Animal Nutrition Hanover (88% DM) (Visscher et al., 2018).

Ingredients	**CF1 (%)**	**SF1 (%)**	**SF2 (%)**	**Soybean Oil (%)**	**Triticale-WPS (%)**	**CCM (%)**
Crude protein	16.00	25.00	21.50	0.00	7.10	9.12
Crude fat	3.50	3.50	3.00	97.00	1.76	4.11
Crude fiber	4.50	7.00	7.00	0.00	20.50	1.28
Crude ash	4.50	9.00	7.50	0.00	4.51	1.35
Starch	37.84	22.52	21.47	0.00	23.44	60.54
Sugar	4.36	6.04	5.17	0.00	1.33	11.00
Lysine	1.10	2.20	1.40	0.00	0.21	0.25
Methionine	0.32	0.35	0.40	0.00	0.07	0.20
Calcium	0.65	1.60	1.00	0.00	0.27	0.06
Phosphorus	0.45	0.60	0.65	0.00	0.20	0.31
Acid detergent fiber (ADF)	6.34	9.24	10.32	0.00	27.02	2.88
Metabolic energy (MJ kg^{-1})	13.40	11.90	11.60	35.88	6.09	16.00

2.4.2.4 Feeding Scheme and Diets

The feed was offered to all feeding groups *ad libitum* throughout the fattening period. The composition of the diets was adapted two times in the course of the fattening period in order to meet the demands of energy and nutrient requirements (GfE, 2006) (see Table S1 and Table S2). The sorting gates automatically determined the average body mass of the feeding group and individually graded the animals. Based on this subdivision, individual animals were sorted out into the appropriate feeding area. All feeding compositions were designed on an equal amount of energy and nitrogen, yet the amount of crude fiber significantly differed. The diets offered to the four different groups were changed every six days. The average daily feed intake per animal was calculated by the installed feeding technique. Table 2.2 shows the diets for an average bodyweight of 70 kg in the experimental groups.

Table 2.2 Components given in Barn I and II to experimental groups fed at an average body weight of 70 kg.

Components	CF1 (%)	SF1 (%)	SF2 (%)	Soybean Oil (%)	Triticale-WPS (%)	CCM (%)
Diet 1:	0.0	0.0	52.5	0.0	2.5	45.0
Diet 2:	0.0	8.0	41.0	1.0	5.0	45.0
Diet 3:	0.0	18.8	27.1	1.6	7.5	45.0
Diet 4:	0.0	29.3	13.1	2.6	10.0	45.0

Table 2.3 shows the diets for an average bodyweight of 70 kg of the control group.

Table 2.3 Components given in Barn III to control group fed at an average bodyweight of 70 kg. Diet 5 was for the 50% lighter animals. Diet 6 was for the 50% of the heavier animals.

Components	CF1 (%)	SF1 (%)	SF2 (%)	Soybean Oil (%)	Triticale-WPS (%)	CCM (%)
Diet 5:	85.0	0.0	0.0	0.0	0.0	15.0
Diet 6:	90.0	0.0	0.0	0.0	0.0	10.0

Table 2.4 shows the nutrient contents of all diets in Barns I–III. The basis for the calculation were the values from Table 2.1. The Triticale WPS and the CCM were analyzed at the Institute for Animal Nutrition in Hanover (Visscher et al., 2018).

Table 2.4 Calculated energy and nutrient contents per kg of dry matter in all diets for Barns I-III.

		Diet 1	**Diet 2**	**Diet 3**	**Diet 4**	**Diet 5**	**Diet 6**
ME	MJ kg DM	14.62	14.63	14.55	14.54	14.87	14.80
Ash	g/kg DM	43.15	44.85	47.80	50.38	44.85	46.55
Crude protein	g/kg DM	167.83	167.59	167.87	168.12	168.65	172.79
Crude fat	g/kg DM	37.18	47.05	53.33	63.21	27.97	27.14
Starch	g/kg DM	437.53	438.08	440.24	441.45	531.77	521.76
Sugar	g/kg DM	35.04	34.96	35.63	36.03	38.10	39.90
Crude fiber	g/kg DM	54.47	58.42	62.87	67.03	44.64	45.91
Lysin	g/kg DM	9.89	9.94	9.99	10.00	12.18	12.39

Diets 1–4 are compound diets, which were tested in the experimental groups. Diets 5 and 6 are the composed diets of the control group. An overview of the components used is shown in Tables 2.2 and 2.3.

2.4.3 Emission Measurement Techniques

2.4.3.1 Gas Sampling and Emission Calculation

The ammonia concentrations were measured for the control group and both experimental groups inside and outside the barns. For the measurement photoacoustic-infrared-spectroscopy (PAS) was used. Barn I was equipped with a Multi-Gas-Monitor Innova 1314 and a Multipoint-Sampler 1309 (LumaSense Technologies A/S, Ballerup, Denmark), while Barn II and III were equipped with a Multi-Gas-Monitor Innova 1412i and a Multipoint-Sampler 1409. The measurement was carried out using the methodology as described by (Austermann, 2016; Schmithausen et al., 2016). The measurement of fresh and exhaust air was done continuously for the control group and experimental groups, respectively. In each barn, one air sampling point outside and inside were installed. The sample points for fresh air were installed at the air inlets at the eaves. The sample points for exhaust air were installed below an exhaust fan inside every barn.

The emissions (E_{Gas}) were calculated using the following equation:

$$E_{Gas} = V * (C_{in} - C_{out})$$

where V is the hourly ventilation rate ($m^3 h^{-1}$) based on the average of 12 values per hour and C_{in} and C_{out} are the hourly gas concentrations (gm^3) inside and outside the barns based on 15–18 values per hour. The average daily emissions were calculated and expressed as g d^{-1} per livestock unit (LU; equal to 500 kg body weight).

2.4.3.2 Ventilation Rate, Temperature, and Relative Humidity

The ventilation rate was estimated using measuring fans (Reventa GmbH, Horstmar, Germany). The measuring fans were calibrated by the manufacturer. Below each exhaust fan in each exhaust chimney, a measuring fan was installed. The measurement data were recorded by Almemo 2590 data loggers (Ahlborn Mess- und Regelungstechnik GmbH, Holzkirchen, Germany) every five minutes.

At every measuring point for gas concentration in the exhaust air, the temperature and relative humidity were recorded with data loggers Testo 174 H (Testo SE and Co. KGaA, Lenzkirch, Germany) every five minutes. One Testo data logger was installed outside to record external climatic conditions.

2.4.3.3 Emission Data Analysis

For analysis of the emission situation, the fattening periods were divided into sections. For each group (Barn I = experimental group summer; Barn II = experimental group winter; Barn III = control group) 10 measuring days were evaluated during the middle of the fattening period (average weight section 75–85 kg) and during the final part of fattening period (average weight section 105–115 kg), respectively. Additionally, a period of 30 measuring days from the middle to the final of the fattening period (average weight section 70–110 kg) was analyzed. Each measuring day was based on n = 415 and n = 350 (for Barn I and II/III) single values for gas concentration. For ventilation rates, temperature, and humidity measurements, n = 288 values per day were analyzed.

2.4.4 Evaluation of Floor Pollution

To investigate whether the crude fiber supplemented diet influenced floor contamination, an evaluation for the experimental group during summer in Barn I was conducted and modified according to Austermann (2016) and Ebertz et al. (2019). The floor pollution of a control group in Barn III was evaluated. For each barn, the total surface area was determined. Despite the presence of different types of slatted floors, the total void percentage in the two barns did not significantly differ from each other (10.8% Barn I; 9.6% Barn III), so that comparability was possible.

The surface area was subdivided into score areas according to different floor elements. Due to the different types of slatted floor, the score areas differed in size. The percentage of each score area was calculated as a percentage of the total surface area, so that the total percentage of pollution could be calculated by the end. Each score area was individually evaluated. This evaluation concerned the pollution of surface areas (0 = clean and dry; 1 = wet; 2 = polluted; 3 = wet and polluted; 4 = muddy) and occlusion of slats (0 = 0% – 25% blocked; 1 = 26% – 50% blocked; 2 = 51% – 75% blocked; 3 = 76% – 100% blocked). For the experimental group, a total of six evaluations were carried out (30, 50, 65, 85, 100, and 120 kg average body weight). Due to external circumstances, only four evaluations could be carried out in the control group (30, 40, 65, and 85 kg average body weight). In all cases, the evaluation was done by the same person at a three-week interval. This enabled an evaluation of floor contamination that was as evenly distributed as possible over the entire fattening period for both groups.

2.4.5 Statistical Analysis

The statistical analysis was done using IBM SPSS Statistics 24 and the statistical software package from SAS, Version 7.1 (SAS Inst., Cary, NC, USA). All measured data were analyzed descriptively by sample size, mean values, confidence interval, standard deviation, minimum, and maximum (environmental data). For the environmental data, the Kolmogorov–Smirnov test was used to test for normal distribution. If normal distribution was present, a simple variance analysis was used to determine significance. Otherwise the Kruskal–Wallis test was used. All charts were created with Microsoft (MS) Office Excel 2016. The group comparisons were performed by one-way analysis of variance (ANOVA) for independent samples. The sum of the mean daily feed intake per animal was compared in four different groups (HF/HL/LF/LL), which were constantly divided, under the different diets. The mean values were compared with each other. In general, the Ryan-Einot-Gabriel-Welsch multiple-range test (REGWQ) was used for multiple pairwise means comparisons between the four groups. All statements of statistical significance were based on $p < 0.05$.

2.5 Results

2.5.1 Animal based Data during the Experiment

2.5.1.1 Body Composition during Group Building

Table 2.5 shows the body mass (kg), gender, back fat thickness (cm), diameter of the *Musculus longissimus dorsi* (cm), and the ratio of the back fat and muscle of the fattening pigs at the grouping time. Significant differences can be seen for "body mass" between the "light (LL/FF)" and the heavy (HL/HF)" groups (Table 2.5). Additionally, there is a significant difference between the heavy group (HL to HF). At the parameter of back fat thickness, there are significant differences between all four groups. The muscle diameter is nearly equal in the heavy groups (HF/HL) but there are significances between the animals of LF and LL and both heavy groups. Taking the ratio between back fat and muscle, there are significant differences between the "fat" groups (HF/LF) and the "lean" groups (HL/LL).

Table 2.5 Body composition and gender of the animals at the grouping time in Barn I.

Group	**Ø**	**HF** (n = 163)	**HL** (n = 165)	**LF** (n = 163)	**LL** (n = 164)
Body mass (kg)	49.82 ± 6.42	$54.32^{a} \pm 4.97$	$52.5^{b} \pm 5.38$	$46.09^{c} \pm 5.20$	$45.21^{c} \pm 4.58$
Male (%)	49.01	59.51	41.21	56.44	39.02
Female (%)	50.99	49.49	58.79	43.56	60.98
Backfat (cm)	0.69 ± 0.13	$0.80^{a} \pm 0.11$	$0.63^{c} \pm 0.09$	$0.72^{b} \pm 0.11$	$0.57^{d} \pm 0.09$
Muscle (cm)	3.50 ± 0.40	$3.60^{a} \pm 0.37$	$3.66^{a} \pm 0.37$	$3.31^{c} \pm 0.37$	$3.41^{b} \pm 0.40$
Backfat/Muscle	0.20 ± 0.03	$0.22^{a} \pm 0.02$	$0.17^{b} \pm 0.02$	$0.28^{a} \pm 0.02$	$0.17^{b} \pm 0.02$

^{a,b,c,d} averages differ significantly within a line ($p < 0.05$).

2.5.1.2 Feed Intake

Table 2.6 shows the average feed intake of four different diets for four different groups per animal and day. Every diet was fed for 18 days in total.

Comparing diet 2 and diet 4, there are significant differences in daily feed intake in the LF and LL group. For the feed intake of the HL group, there are significant differences between diet 1 and all other diets. In the HF group, there are no significant differences but a tendency of reduction can be seen in the comparison of diet 1 and 4. Differences can also be seen between the feeding groups with regard to feed intake; lean animals tend to have a lower feed intake than fat animals for almost all diets.

Table 2.6 Daily feed intake (in kg 88% DM) with a calculated body weight of 100 kg per animal in the four groups and diets.

	Ø	**HF (n = 163)**	**HL (n = 165)**	**LF (n = 163)**	**LL (n = 164)**
Diet 1	3.61 ± 0.65	$3.65^{A} \pm 0.67$	$3.88^{A} \pm 0.93$	$3.74^{AB} \pm 0.77$	$3.18^{AB} \pm 0.79$
Diet 2	3.51 ± 0.50	$3.15^{A} \pm 0.70$	$3.14^{B} \pm 0.62$	$4.29^{A} \pm 0.61$	$3.44^{A} \pm 0.99$
Diet 3	3.31 ± 0.44	$3.60^{A} \pm 0.32$	$2.75^{B} \pm 0.70$	$3.89^{AB} \pm 0.80$	$3.00^{AB} \pm 0.52$
Diet 4	3.20 ± 0.42	$3.25^{A} \pm 0.71$	$3.20^{B} \pm 0.69$	$3.62^{B} \pm 0.71$	$2.71^{B} \pm 0.44$

$^{A, B}$ averages differ significantly within a column ($p < 0.05$).

2.5.2 Environmental Aspects

2.5.2.1 Climatic Conditions

Table 2.7 shows the average of ventilation rates per livestock unit; internal and external temperatures; and internal and external relative humidity measured during the different weight sections for the control and experimental groups, respectively.

Compared to CD, significant differences could be determined for both CFD_W and CFD_S with regard to climatic conditions. However, due to the different seasons during the experiments, the differences between CD and CFD_S are more pronounced, especially for ventilation rate and external temperature. A comparative analysis of the data is only possible to a limited extent. Nevertheless, for completeness, the results of CFD_S are presented in order to be able to compare and discuss them with results reported in other studies. For the weight section, 70–110 kg, the measured external temperature in CFD_W was 2.5 °C higher than in CD. In comparison, the average external temperature in CFD_S was 15.5 °C higher than in CD. According to the measured external temperatures, the ventilation rate per LU for CFD_S was, on average, 303.4 units higher than in CFD_W and CD. In contrast, CD and CFD_W only differed by 21.5 $m^3 h^{-1} LU^{-1}$. Due to the considerably higher ventilation rate during CFD_S, the internal temperature was 3.5 °C higher than in CD. For CD and CFD_W, a difference in mean internal temperature of only 0.6 °C was noticed. The relative humidity inside during CFD_S was 12 units below those measured during CD. For CD and CFD_W, the difference was −5.5 units. Relative humidity measured outside during CFD$_S$ was around 26.5 units. During CFD$_W$ it was eight units lower than during CD. The results for the separate evaluation of middle- and end-part of the fattening period can be seen in Table 2.7.

Table 2.7 Climatic conditions during control and experimental feeding. Mean ± standard deviation.

Diet	Body weight (kg)	Ventilation rate (m^3 h^{-1} LU^{-1})	Temperature inside (°C)	Temperature outside (°C)	Relative humidity inside (%)	Relative humidity outside (%)
CD	75–85	193.4 ^{A} ± 23.0	20.5 ^{A} ± 0.5	6.4 ^{A} ± 2.0	75.9 ^{A} ± 5.0	89.9 ^{A} ± 9.1
	105–115	177.3 ^{D} ± 28.8	18.7 ^{D} ± 0.9	2.4 ^{D} ± 2.4	80.5 ^{D} ± 6.3	91.4 ^{D} ± 8.4
	70–110	183.2 ^{G} ± 34.3	19.8 ^{G} ± 1.2	4.7 ^{G} ± 3.8	77.2 ^{G} ± 5.9	89.4 ^{G} ± 10.1
CFD$_W$	75–85	193.2 ^{B} ± 59.5	19.5 ^{B} ± 0.8	6.4 ^{A} ± 3.6	71.5 ^{B} ± 6.5	79.7 ^{B} ± 14.5
	105–115	231.5 ^{E} ± 121.1	18.9 ^{D} ± 0.8	8.2 ^{E} ± 3.7	70.5 ^{E} ± 5.8	81.3 ^{E} ± 14.0
	70–110	204.7 ^{H} ± 62.2	19.2 ^{G} ± 0.9	7.2 ^{H} ± 3.3	71.7 ^{H} ± 6.1	81.4 ^{H} ± 14.0
CFD$_S$	75–85	509.3 ^{C} ± 156.5	20.6 ^{C} ± 2.2	16.1 ^{B} ± 4.7	66.7 ^{C} ± 10.4	67.9 ^{C} ± 19.3
	105–115	457.6 ^{F} ± 33.8	24.1 ^{E} ± 4.1	21.9 ^{F} ± 6.6	60.7 ^{F} ± 12.0	55.1 ^{F} ± 19.2
	70–110	497.4 ^{I} ± 96.4	23.3 ^{H} ± 3.9	20.2 ^{I} ± 6.4	65.2 ^{I} ± 12.2	62.9 ^{I} ± 21.5

CD: Control diet; CFD$_W$: Crude fiber diet (winter); CFD$_S$: Crude fiber diet (summer); LU: Livestock unit, equal to 500 kg body weight. $^{A;B;C}$ values differ significantly in weight section 75–85 kg within a column ($p < 0.05$). $^{D;E;F}$ values differ significantly in weight section 105–115 kg within a column ($p < 0.05$). $^{G;H;I}$ values differ significantly in weight section 70–110 kg within a column ($p < 0.05$).

2.5.2.2 NH_3 Concentration and Emissions

Figure 2.5 shows the average ammonia emissions in g per day and LU for the three selected weight sections per animal group.

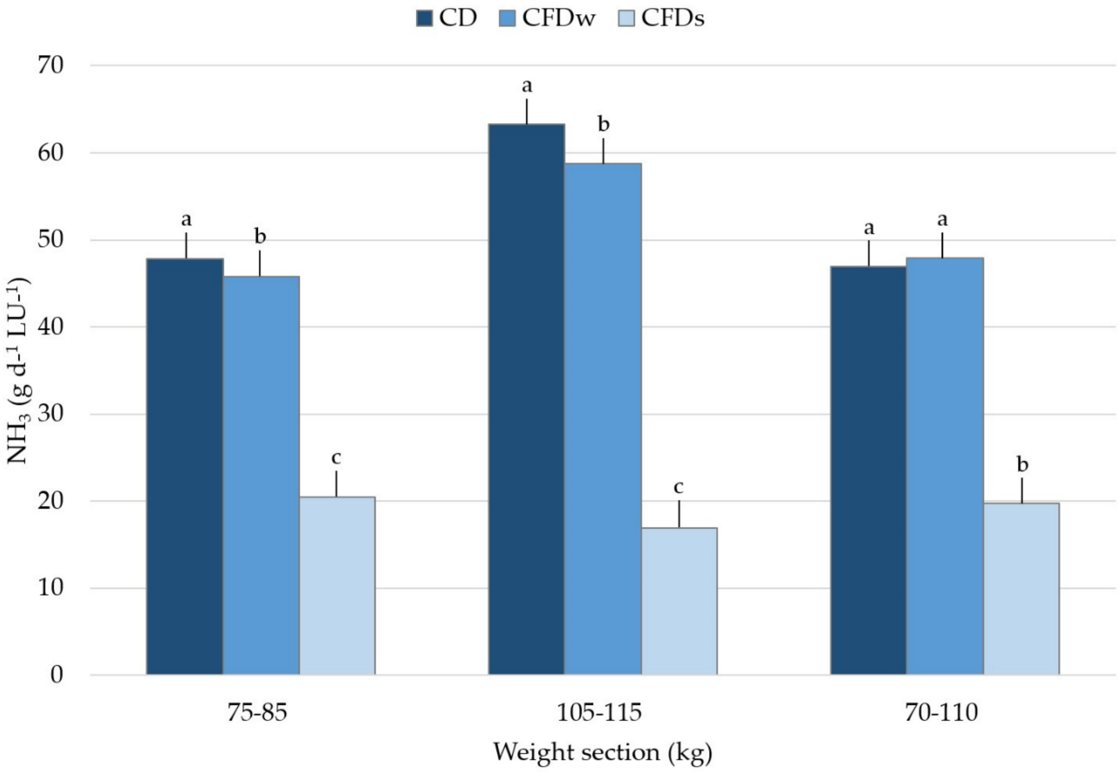

Figure 2.5 Ammonia emissions per day and livestock unit as influenced by the diet (CD = control diet; CFD$_W$ = crude fiber diet winter; CFD$_S$ = crude fiber diet summer) according to the weight section. Weight section 75–85 kg and 105–115 kg had an average of 10 days. Weight section 70–110 kg had an average of 30 days. a, b, and c significantly differ from each other.

For the 75–85 kg weight section, emissions for CD, CFD$_W$, and CFD$_S$ were 47.8 ± 8.4, 45.8 ± 10.5, and 20.4 ± 5.5 g d^{-1} LU^{-1}, for the 105–115 kg weight section, 63.3 ± 20.2, 58.7 ± 25.1, and 16.9 ± 10.8 g d^{-1} LU^{-1}; and for the 70–110 kg weight section 47.0 ± 9.9, 48.0 ± 9.9, and 19.8 ± 9.0 g d^{-1} LU^{-1}. For all three weight sections, the ammonia emissions for CFD$_S$ significantly differed from the CD and CFD$_W$ ($p < 0.05$). During winter, increased crude fiber content in the diet resulted in 4.2% and 7.3% less ammonia emissions for weight sections 75–85 kg and 105–115 kg compared to CD. Both differences are significant ($p < 0.05$). Nevertheless, for the weight section 70–110 kg, the average ammonia emissions were 2.1% higher in CFD$_W$ than in CD, which is not a significant difference ($p > 0.05$). The ammonia emissions were 55.5%, 71.2%, and 58.8% lower (weight sections 75–85, 105–115, and 70–110 kg) in CFD$_S$ compared to CFD$_W$.

The ammonia concentrations measured in the exhaust air for weight section 75–85 kg were 6.8% higher for CFD_W than for CD. In contrast, the concentrations in the last part of the fattening period (105–115 kg) were 21.8% lower for CFD_W than for CD. During both sections of the fattening period, the differences were significant ($p < 0.05$). On average, the ammonia concentrations of the weight section 70–110 kg were reduced by 1.5% for CFD_W compared to CD, which was not significant. The ammonia concentrations of CFD_S were significantly lower than those of CD (37.4%, 52.0%, and 37.1% for weight section 75–85 kg, 105–115 kg, and 70–110 kg). The results are shown in Figure 2.6.

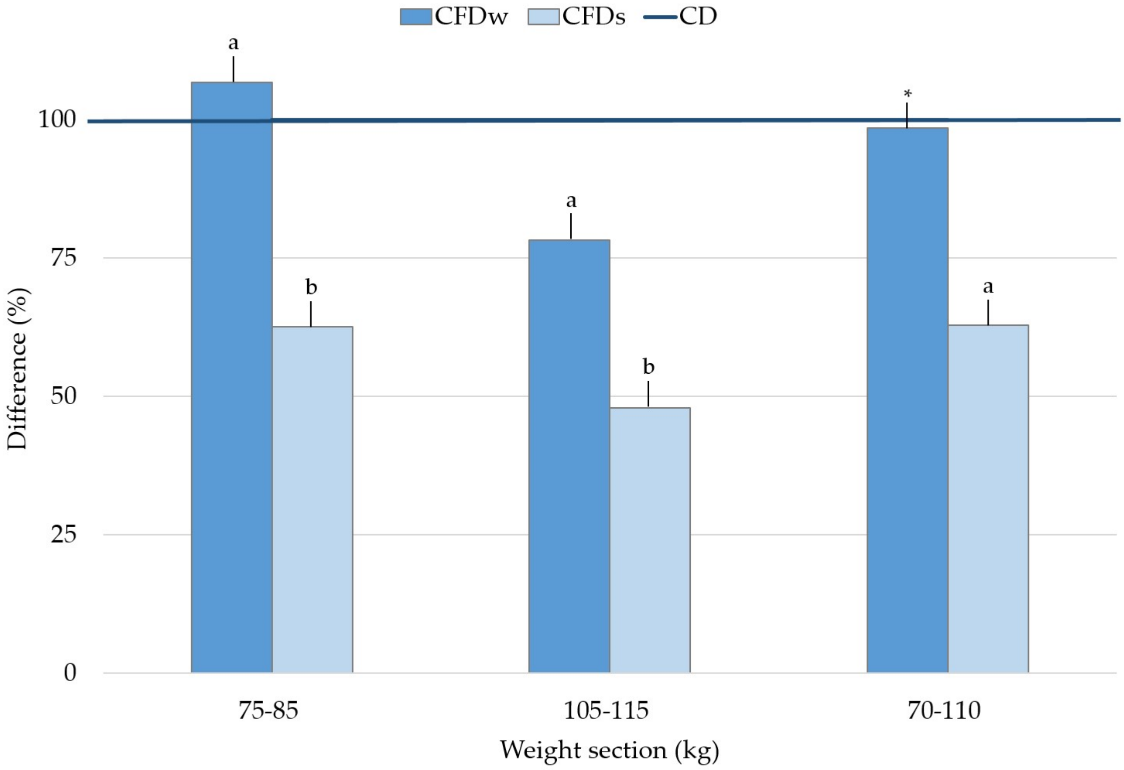

Figure 2.6 Percentual difference of mean ammonia concentrations measured in the exhaust air for CFD_W and CFD_S in relation to CD (defined as 100%). a and b significantly differ from CD; * no significant difference from CD.

2.5.2.3 *Pollution of Surface Area*

In general, the formation of functional areas by the animals could be reconstructed during the evaluation of surface pollution. The feeding areas and areas next to them could be described as “dry and clean”. These were used as lying and activity areas. In contrast, the areas near the outer walls of the barns were used for excreting feces and mostly described as “polluted” (see Figure S1).

For the assessment of surface contamination, the results of four days of evaluation per animal group were compared (the first four evaluation days were from the average body weight section 30–85 kg). On average, the clean surface area was 47% ± 7.4%; the polluted surface area was 53% ± 5.2% in the control group. In the experimental group, the amount of clean surface area was 41% ± 8.6% and 44% ± 7.6%. For the polluted surface area, it was 59% ± 8.5% and 56% ± 7.2% (Pen I.1 and I.2). A contaminated area of 0.4 m^2 per animal could be determined for CD and CFD, respectively. No significant difference was observed between the groups ($p > 0.05$). Figure 2.7A shows the mean percentage of surface area within the five evaluation categories. No significant differences could be found between the groups for the different categories ($p > 0.05$).

The results of the slat occlusion evaluation are suitable for the results of surface contamination in all three groups. On average, the number of slats blocked 0%–25% did not significantly differ within the groups (53% ± 7.4%, 53% ± 9.4%, and 58% ± 2.8% for control, CFD I.1 and CFD I.2; $p > 0.05$). The number of slats blocked 26%–50% was significantly higher in CFD I.1 (26% ± 3.4% compared to 11% ± 8.8% for control and 14% ± 6.0% for CFD I.2). For all other categories, no significant difference was found. The detailed amounts of slat occlusion are shown in Figure 2.7B.

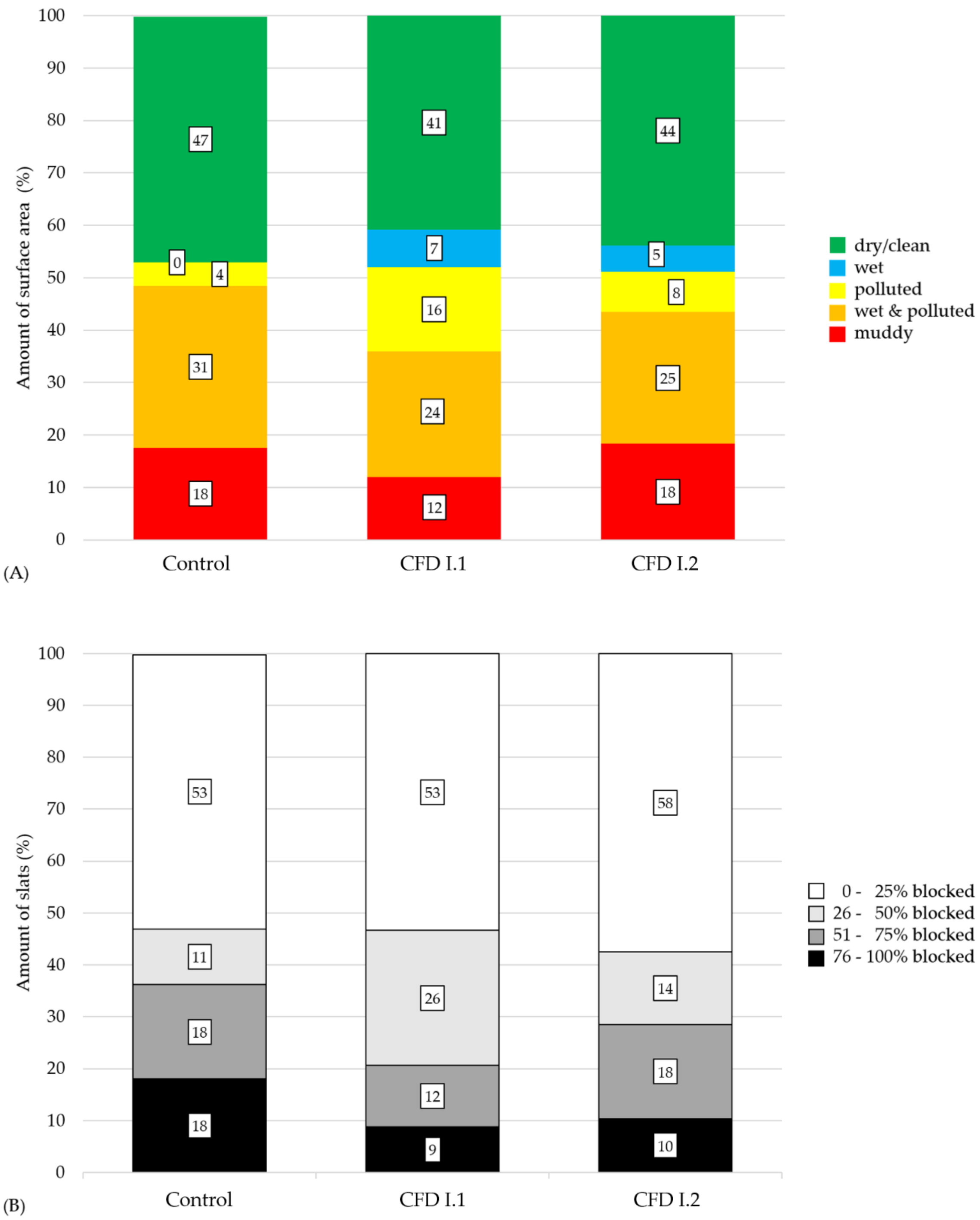

Figure 2.7 Mean amount of polluted surface area (A) and occluded slats (B) in % for the control and the experimental group (pen I.1 and I.2). Figure follows Ebertz et al. (2019).

2.6 Discussion

2.6.1 Heterogeneity of Animals and Classification according to Genetic Performance Potential

Although all animals up to 50 kg were kept and fattened under the same conditions, there is a clear heterogeneity in the whole group. A significant difference was the body weight (HF/HL to LF/LL) between the heavy and light animals. In order to ensure an energy and protein adapted diet and avoid oversupply, the heavy animals must be separated from the light animals and fed differently. The composition of the mass growth of a fattening pig changes in the course of its development. With a body mass of 60–70 kg, the protein content of the body mass decreases, and the fat content continues to increase (Hollmichel & Quanz, 2016; Schinckel & Einstein, 1995). In addition, the composition of biomass is determined by genetics and gender. According to Kirchgeßner (2014), genetic protein uptake has a significantly higher influence on the protein approach than the different protein and energy supply. These sources were confirmed by the experiment. Table 2.5 shows that approximately 60% of lean animals (HL/LL) were female. Conversely, about 60% of the fatter animals (HF/LF) were castrated boars.

This potential is reflected in the fat-muscle ratio. The different animal species can be significantly separated by recording the fat-muscle ratio (HF/LF to HL/LL). However, fattening pigs with a high feed intake capacity and a low genetic performance potential automatically absorb more energy and protein, which they cannot use efficiently. As a result, they develop more fatty tissue and excrete more nitrogen (Canh et al., 1998). Therefore, the starting point for resource-efficient feeding is the classification of fattening pigs into four different subgroups according to their presumed genetic performance potential (HF/HL/LF/LL) (Figure 2.1).

2.6.2 Influence of a Feed rich in Crude Fiber on Daily Feed Intake Capacity

The aim of the study was to classify the pigs according to their suspected genetic potential and see whether they react differently to the increased crude fiber content in relation to their daily feed intake. Resource efficiency can only be guaranteed if fattening pigs are fed according to their genetic protein accretion potential and oversupply is prevented. One hypothesis was to control feed intake by using a structured crude fiber source. Looking at the average daily feed intake of the animals, the daily feed intake for all four groups (HF/HL/LF/LL) had an increased use of Triticale-WPS and ultimately decreased. The difference of the average daily feed intake in the "heavy-lean" animals (HL) differed significantly between the diet with the lowest crude fiber content (diet 1) and the diet with the highest crude fiber content (diet 4). In both groups of light animals (LF/LL), a significant difference between the second and the fourth diet was seen.

However, in all four groups, there is a clear tendency to see a decrease in daily feed intake with increased use of crude fiber. The saturation of pigs is basically divided into mechanical and chemical saturation (Sanders, 2016). Mechanical saturation is caused by the filling of the stomach. Stretch receptors transmit a signal via vagus fibers to the hypothalamus, with a neural network regulating saturation (Cummings & Overduin, 2007; Jeroch et al., 1999). With regard to the saturation effect, WPSs are important as a source of crude fiber. Due to the high proportion of acidic detergent fibers (ADF) and hemicellulose (Kamphues et al., 2014), as well as the high proportion of bacterially fermentable substances (Lindemayer et al., 2009), WPS contributes to saturation. Another important contribution is the high-water retention capacity of feedstuffs containing crude fibers (De Leeuw et al., 2008; Leterme et al., 1998; Schafzahl, 2016), which supports mechanical saturation. Heinritz et al. (2016) have shown that, feed rich in crude fiber has a significant influence on an animal's microbiome. It can therefore be assumed that the proportion of Lactobacilli and Bifidobacteria has increased due to an increased fiber content. There is evidence that SCFAs produced by the microbiota interact with entero-endocrine host cells (e.g. L-cells) by modulating the G-protein coupled receptor signal (GPR41, GPR43), which affects the production of glucose homeostasis modulators such as peptide YY (PYY) and glucagon-like peptide (GLP)-1 (Kaji et al., 2014). Tyrosine (PYY) and glucagon-like peptide-1 (GLP-1) from entero-endocrine cells. Both hormones influence saturation via an effect in the brain and on the "ileal brake". The presented results support these results.

2.6.3 Environmental Aspects

For CFD_W, significantly lower ammonia emissions were observed for weight sections 75–85 kg and 105–115 kg, compared to CD. No significant difference was found for weight section 70–110 kg between CD and CFD_W. The highest difference between CD and CFD_W was found for the final weight section. As mentioned above, the protein requirement of fattening pigs decreases at the end of the fattening period (Jeroch et al., 1999). At the same time, there is an increase in feed intake (Kamphues et al., 2014). Fattening pigs with a high capacity of feed intake excrete more nitrogen, as they cannot efficiently utilize all of the absorbed protein (Canh et al., 1998). This is particularly noticeable at the end of a fattening period. Consequently, in the presented feeding, the greatest saving potential for ammonia emissions was the last part of the fattening period. The presented results of ammonia emissions support this theory. As presented, feed intake decreases with increasing crude fiber content in the diet. At the same time, an increased fiber content supports bacterial growth in the animals' intestinal tract. As a result, more nitrogen can be incorporated in bacterial protein, so that less nitrogen is excreted with urine. This can reduce ammonia emissions (Canh et al., 1998; Jeroch et al., 1999). In the presented study, avoiding luxury consumption and increased nitrogen fixation in the intestine may have led to a reduction in ammonia emissions. However, the last point was not investigated and can only be assumed.

The ammonia emissions determined for CD and CFD_W are comparable to those described by other authors. Gallmann (2003) reviewed ammonia emissions of 41–160 g d^{-1} LU^{-1} while Philippe et al. (2011) reported an average value of 68.5 g $d^{-1}LU^{-1}$. Demmers et al. (2003) reported an average value of 51 g d^{-1} LU^{-1} during the winter period. Compared with the reported values in the literature, the measured ammonia emissions in this study are at a lower level.

For the experimental period during summer, significantly lower ammonia emissions were observed for all weight sections compared to CD and CFD_W. The presented values are markedly lower than described in the literature. Various studies have reported on the correlation between ventilation rates, exhaust air concentrations, and emission rates from animal houses (Aarnink, 1997; Oldenburg, 1989; Venzlaff et al., 2010). For an approximately constant room temperature in the animal area, higher ventilation rates are measured in summer because of higher external temperatures. Due to a higher air exchange rate, ammonia emissions increase in summer months (Austermann, 2016; Gallmann, 2003). However, concentrations decrease inside due to a dilution effect (Jungbluth et al., 2017).

Other authors reported contrary results. Palkovicova et al. (2012) demonstrated higher ammonia emissions in winter than in summer. Gallmann (2003) also referred to various authors who were able to determine higher emission rates at lower temperatures. For CFD_S, an increase of the ammonia emissions could not be found in this study, despite significantly higher ventilation rates. In accordance with the named authors, lower ammonia concentrations were measured for CFD_S compared with CD and CFD_W. As shown in Section 2.4.3.1, the emission rates are calculated by the difference of fresh- and exhaust air concentrations. Due to the position of Barn I on the farm, the fresh air was already contaminated with higher ammonia concentrations than measured for Barn II and III. The fact that significantly lower exhaust air concentrations were measured in Barn I during CFD_S suggests that less ammonia must have been released in the barn under experimental conditions. Therefore, lower emissions could be explained by this, although higher ventilation rates were measured. Philippe et al. (2015a) achieved 50% reduction in ammonia emissions compared to a control group by use of crude fiber in fattening pigs. Other authors reached reductions of 30%–40% under laboratory conditions (Jarret et al., 2012; O'Shea et al., 2009). The average emissions in weight section 70–110 kg were approximately identical in CD and CFD_W. Reduction of ammonia emissions during CFD_S correspond to those of the mentioned studies. However, a comparison of the summer and winter periods is only conditionally possible due to the different seasons and different barns. The fact that emissions during CFD_S were lower than values reported in other studies suggests that the crude fiber supplemented feeding had a reducing effect on ammonia emissions. Since the study was carried out on a farm under practical conditions, this factor must be taken into account. In comparison to Philippe et al. (2015a), this study investigated large group housing with differences in husbandry and management. This may have influenced the results and may have led to a lower reduction in ammonia emissions. It must be noted that the different diets were offered simultaneously in the different feeding areas. No precise conclusion can be made about the potential of ammonia reduction for the different crude fiber contents in the diet.

About 44% of ammonia emissions from fattening pig barns originate from polluted surface area (Janssen & Krause, 1987). Polluted surface area and ammonia emissions are directly related (Aarnink, 1997). As shown by Massé et al. (2003), increased crude fiber content in the diet can lead to an increase in fecal mass and a higher viscosity of manure. Both factors can result in an increased contamination of the surface area. In the presented study, no significant differences in surface contamination and occlusion of slats could be found between CD and CFD. On average, the amount of "clean and dry" surface area was around 44% for both the control and experimental group. Moreover, the amounts of "polluted" area in the different categories are comparable. More than half of the slats were not occluded by excrements for CD and CFD, respectively. As shown by the results, feed intake decreases by increasing crude fiber content in the diet. The fact that there was no significant difference in surface contamination could be explained by avoiding luxury consumption. Thus, it would be possible that the effects described by Massé et al. (2003) are balanced with those of reduced feed intake. The results suggest that the increased use of crude fiber has no negative impact on floor cleanliness or ammonia emissions. Further, with regard to animal welfare, this is a positive factor, since negative effects e.g., on claw health due to increased pollution (Austermann, 2016; Ebertz et al., 2019) cannot be assumed. For the same aspect, it is also positive that clear functional areas could be identified during the evaluation. It corresponds to the natural behavior of pigs (Aarnink, 1997). This behavior is supported by the use of the presented feeding technology and the large group housing. The influence of feeding rich in crude fiber on the behavior of the animals was not subject of these studies. This aspect could be considered in subsequent studies in order to enable an evaluation of the improvement of animal welfare.

2.7 Conclusions

In summary, it can be said that the use of WPSs with a high crude fiber content increases the feeling of satiety and has an influence on feed intake. Different “types” of pigs showed differences in their feed intake capacity, especially the control of feed intake for more fat-prone animals, which was herein confirmed via WPSs. With this knowledge, a further development of the presented resource-efficient feeding concept is desirable to feed fattening pigs individually and according to their nutrient requirements. This will enable a reduction of luxury consumption and help save important resources. The next step is to take into account the new knowledge of the whole plant silage in terms of feed intake and to adapt the feed ingredients to each species, taking into account their average feed intake. Ammonia emissions were not negatively affected in this study. During the winter period, no deterioration in ammonia emissions compared to the control was observed. Ammonia emissions could be reduced in some sections. In summer, significantly lower ammonia emissions were found in the experimental group (also in comparison with values reported in other studies). Thus, a positive conclusion can be drawn in this regard. Moreover, no deterioration of floor cleanliness could be determined due to increased crude fiber content in the diets. This can be seen as a positive aspect, regarding the ammonia release as well as animal welfare. More research and investigations on this topic are currently being conducted. These will be necessary for a final overall evaluation of the resource-efficient feeding concept.

Supplementary Materials: The following are available online at http://www.mdpi.com/2076-2615/10/3/497/s1, Table S1: Components given in Barn I to experimental groups; fed at an average bodyweight of 50 kg, Table S2: Components given in Barn I to experimental groups; fed at an average bodyweight of 70 & 90 kg, Figure S1: Average Evaluation of score areas in Barn I and III and Illustration of the different functional areas.

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3 Study 2

Impact on Ammonia Emissions under a Resource Efficient Feeding Concept in Fattening Pigs based on Performance Groups and Crude Fiber supplemented Diets.

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The study presented in this chapter (Study 2) followed the research presented in Study 1 and provided further results regarding ammonia emissions and their reduction through the investigated feeding concept also presented in Study 1. The study was submitted as a contribution to the 5th International Conference of the International Commission of Agricultural and Biosystems Engineering (CIGR) from May 11-14, 2021. Results have been presented oral on the conference and were published in the conference proceedings afterwards.

3.1 Abstract

In fattening pig husbandry new feeding concepts offer great potential to reduce nitrogen inputs in the environment. Fattening pigs differ individual in their nutritional needs and feed intake capacity. Classification into performance groups enables to feed the animals efficiently and to avoid luxury consumption. In the study the impact on ammonia emissions under a new feeding concept based on performance groups and crude fiber supplemented diets was investigated. For the study 610 pigs were classified into four performance groups based on body weight and the ratio of backfat and back muscle thickness determined by ultrasound examinations. Using sorting gates and four different feeding areas, each group was fed with a specific diet differing in crude fiber content. Ammonia emissions were measured continuously in the experimental and a control barn. In the experimental barn ammonia emissions were reduced by 40% compared to the control barn. During 50-110 kg mean ammonia emissions were 7.68 g animal^{-1} d^{-1} and 12.67 g animal^{-1} d^{-1} (experimental and control group). Also for the individual fattening period sections (pre-fattening, mid-fattening, finishing) ammonia emissions were significant lower in the experimental barn. The largest difference of 44% was observed during the finishing period. Resource efficient feeding is desirable from an environmental and economic aspect. Furthermore, animal welfare can be improved by crude fiber supplementation. Especially in view of climate change, livestock husbandry has to be adapted to new requirements. The study shows that the tested feeding concept enables the connection of environmental protection, animal welfare and economic efficiency.

Keywords: Feeding technology, feeding groups, ammonia reduction, sustainability, roughage-based diet

3.2 Introduction

In recent years, agricultural livestock husbandry has been characterized by constant change. Animal welfare, as well as climate and environmental protection, are more and more in the focus of social debate regarding modern agriculture. Not least due to the increasingly stringent animal welfare and environmental protection requirements, an adjustment of agricultural animal husbandry is mandatory (BMEL, 2017). As the most important producer in the meat industry, pig farming plays an important role not only in Germany, but also in the European Union (EU) (DBV e.V., 2019). In total, 95% of the annual ammonia (NH_3) emissions are due to agriculture. In Germany, pig farming is the second largest source of NH_3-emissions in the agricultural livestock husbandry (UBA, 2020). By causing acidification and eutrophication, ammonia contributes to lasting damage to the environment (Steinfeld et al., 2006). Furthermore, it is harmful to the health of humans and animals (Drummond et al., 1980; Ryer-Powder, 1991). New feeding concepts for fattening pigs have great potential to reduce NH_3-emissions from fattening pig husbandry. The initial substance for the formation of ammonia is nitrogen, which is primarily absorbed via dietary protein. Excess nitrogen which is not utilised by the animals, is excreted as urea with faeces and urine and thus released to the environment (Aarnink, 1997). An oversupply of protein and thus nitrogen to the animals must therefore be avoided to prevent an excess input of nitrogen into the environment. In phase feeding systems currently used in fattening pigs, the diet is generated according to the average requirement of the whole group (KTBL, 2011). However, fattening pigs differ in their individual nutrient requirements and fattening performance potential (Jeroch et al., 1999). Consequently, individual animals are undersupplied or oversupplied and not fed efficiently (KTBL, 2011). This must be avoided, both in terms of animal welfare and in terms of resource efficiency and economic aspects.

In the presented study, a new resource-efficient feeding system for fattening pigs was investigated. As described by Lengling et al. (2020) and Reckels et al. (2020) fattening pigs can be classified into performance groups based on differences in their backfat and backmuscle thickness. By using sorting gates and spatially separated feeding areas, the animals should be fed to the exact nutritional requirements of individual performance groups. Based on daily measurements by the sorting gate, a constant adaption of the diets should be made possible. Lengling et al. (2020) were able to show that animals with different fattening performance potential differ in their feed intake capacity and that this correlates negatively with the crude fiber content in the diet. Based on those results, in this study it was investigated whether animals with a high feed intake capacity can be controlled in their feed intake via an increased crude fiber content in the diet and if this affects NH_3-emissions positively by reducing them. The results presented in this paper are limited exclusively to the investigations of NH_3-emissions. The investigations should contribute to a comprehensive evaluation of the new feeding system and thus enable a more resource-efficient feeding in fattening pig husbandry.

3.3 Material and Methods

3.3.1 Animals and Housing

The study was carried out from May to August 2020 on a pig fattening farm in Germany. Two barns, which were designed for large group housing, were available for the study. Barn I was used to measure NH_3-emissions under experimental conditions, while barn II was used as control.

Barn I was subdivided into two compartments (I.1 and I.2) by half-height partition walls, and had a total surface area of 556 m^2 and a capacity of up to 656 animals, so 278 m^2 and 328 animals per compartment. For the experimental group, 610 fattening pigs (cross-breed products of the Genesus F1 sow (Yorkshire x Landrace) and Canadian Duroc boar) with an average body weight of 25.8 kg were housed in. There was a usable surface area of approx. 0.9 m^2 per animal. On day three after housing, each pig was equipped with a Radio-Frequency-Identification (RFID) ear tag for individual identification. Barn II had a total surface area of 585 m^2 and a capacity of up to 700 animals. For the control group, 670 fattening pigs, with the same genetic and average body weight as for barn I, were housed in. The usable surface area was approx. 0.9 m^2 per animal, respectively. Each barn was equipped with two sorting gates (one per compartment in barn I) of the company Hölscher + Leuschner (Hölscher + Leuschner GmbH and Co. KG, Emsbüren, Germany) which connected the activity areas from two spatially separated feeding areas (feeding area “A” and “B”). Both barns were force ventilated with fresh air supply along the eaves and decentralized over floor extraction by means of exhaust fans. An outline of barn I and II is given in Fig. 3.1.

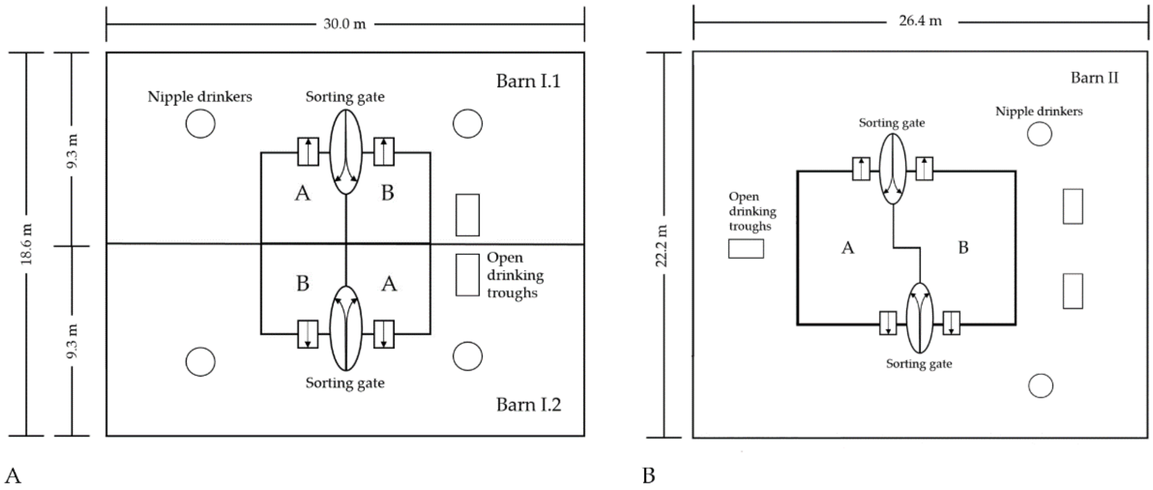

Figure 3.1 Outline of the experimental and control barn. Figure A: Barn I with its two compartments I.1. and I.2. Each compartment was equipped with two feeding areas (A and B, respectively), which could be reached by the animals of each compartment via a sorting gate and left via an exit door. Figure B: Barn II with one compartment. Barn II was equipped with two feeding areas (A and B, respectively), which could be reached by the animals via two sorting gates and left via two exit doors.

3.3.2 Sorting Gate

The sorting gate connects the lying and activity area with the two separated feeding areas in each barn. When the animals want to reach the feeding area they have to pass through the sorting gate (Jungbluth et al., 2017). For this the pig has to enter the sorting gate via an electronically controlled entrance door. Using a scale at the bottom of the sorting gate the body weight of the animal is determined. Additionally, by means of 3D-camera technology the body weight can be measured optically. The data are stored and processed on a connected computer system. Due to the individual RFID ear tags and an ear tag recognition inside the sorting gate, the data can be assigned individual to each animal. According the group affiliation and the measured body condition data, the animal is guided in one of the two feeding areas via one of two exit doors. After feed intake the animals can leave the feeding area via an one-way exit door. Due to the fact that the pigs pass the sorting gate several times a day, the body condition data are recorded continuously during the whole fattening period. Thus the diets can be adapted to the nutritional requirements based on the daily measurements (KTBL, 2011).

3.3.3 Feeding

3.3.3.1 Feeding Groups

In barn I animals were divided into two groups according their body weight which was determined via the sorting gate. Group 1 consisted of the 50% heaviest animals, while group 2 consisted of the 50% lightest animals. Each group was further divided into two feeding groups according the ratio of backfat thickness and diameter of back muscle (*Musculus longissimus dorsi*) in "fat" and "lean". The ratio was determined using ultrasound examinations as described by Reckels et al. (2020) and Lengling et al. (2020). So, for group 1 there have been the feeding groups "heavy lean" (HL) and "heavy fat" (HF) and for group 2 the feeding groups "light lean" (LL) and "light fat" (LF). In barn II the control group was only differentiated into heavy and light animals, without spatially separation of the animals.

3.3.3.2 Feeding technology

All animals in all groups were fed *ad libitum* with a liquid feeding system (Hölscher + Leuschner GmbH & Co. KG., Emsbüren, Germany) throughout the fattening period. The four performance groups in barn I were fed a constant amount of crude fiber in the diet over the entire fattening period. The crude fiber content of the four diets were 2.5, 5.0, 7.5 and 10.0% in dry matter (DM). The HF and LF groups received the diets with the highest crude fiber content (HF 10.0%; LF 7.5%), while the lean groups received the lower crude fiber content (HL 5.0%; LL 2.5%). A triticale whole plant silage (WPS) was used as source of crude fiber. The diets differed only in their crude fiber content, while protein and energy content were almost the same in all diets (protein content approx. 155 g per kg DM; energy content approx. 12.5 MJ metabolizable energy (ME) per kg DM). The control group in barn II received a conventional fattening diet, consisting of Corn-Cob-Mix (CCM) and two different supplementary feeds, without any additional crude fiber.

3.3.4 Emission Measurement

For the investigation of NH_3-emissions, concentrations of ammonia were measured continuously inside and outside barn I and II using Photoacoustic-Infrared-Spectroscopy (PAS). The measurements were carried out as described by Lengling et al. (2020) and Schmithausen et al. (2016). Fresh air from outside and exhaust air from inside the barns were sampled and analysed using a Multi-Gas-Monitor and a Multipoint-Sampler

(LumaSense Technologies A/S, Ballerup, Denmark) in each barn, respectively. For calculation of the NH_3-emissions the ventilation rates were determined using calibrated measuring fans (Reventa GmbH, Horstmar, Germany) inside the exhaust chimneys inside the barns as described by Lengling et al. (2020) respectively. Based on ammonia concentrations inside and outside the barns and the measured ventilation rates emissions were calculated using following equation:

$$E_{Gas} = V * (C_{in} - C_{out}) \tag{1}$$

with V the ventilation rate ($m^3\ h^{-1}$) and C_{in} and C_{out} the ammonia concentrations ($g\ m^3$) inside and outside the barns. Temperature and relative humidity inside and outside the barns were measured respectively using Testo data loggers (Testo SE and Co. KGaA, Lenzkirch, Germany) (Lengling et al., 2020).

3.4 Results

For data analysis and comparison of experimental and control group results are presented as mean values for different weight sections of pre-fattening (50-60 kg), mid-fattening (60-90 kg) and finishing period (90-110 kg) as well as weight section 50-110 kg representing the total fattening period. A weight section of 10 kg body mass gain corresponds to n = 7 measurement days. As presented in Fig. 3.2, NH_3-emissions were significant lower in the experimental group compared to the control group during all weight sections. On average NH_3-emissions were 7.68 g $animal^{-1}$ d^{-1} in experimental group and 12.67 g $animal^{-1}$ d^{-1} in control group. This corresponds to a reduction of 39.4%. Highest difference could be found during finishing period with 9.61 g $animal^{-1}$ d^{-1} and 17.19 g $animal^{-1}$ d^{-1} in experimental and control group respectively. This corresponds to a reduction of 44.1%. Ammonia emissions increased in course of fattening period in both barns about approx. two and a half times.

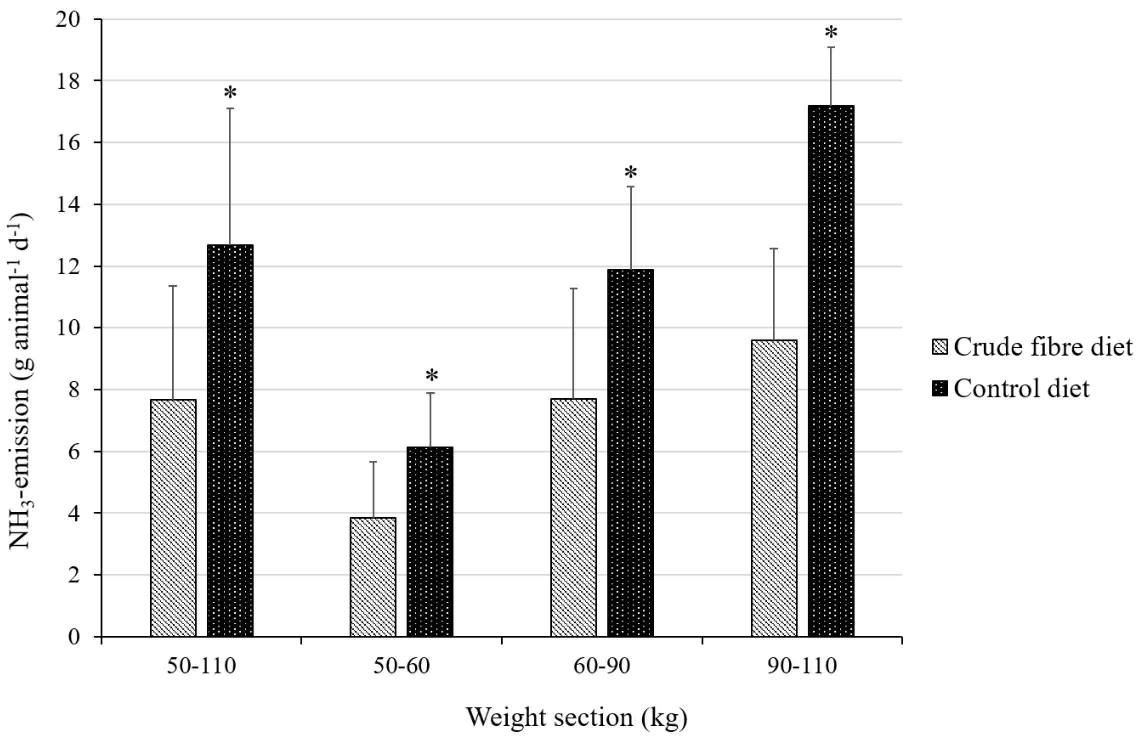

Figure 3.2 Mean NH$_3$-emissions (g animal^{-1} d^{-1}) and standard deviation during different weight sections (pre-fattening 50-60 kg , mid-fattening 60-90 kg, and finishing period 90-110 kg) for the experimental group with crude fiber supplemented diet and control group with control diet. * indicate significant differences between experimental and control group within the same weight section ($p < 0.05$).

Figure 3.3 shows the mean NH$_3$-concentrations (ppm) measured inside barn I and II during the different weight sections. On average concentrations were 20.1% lower inside barn I (experimental group) compared to barn II (control group). Again the highest difference could be found during finishing period with on average 8.53 ppm and 13.25 ppm in barn I and barn II respectively.

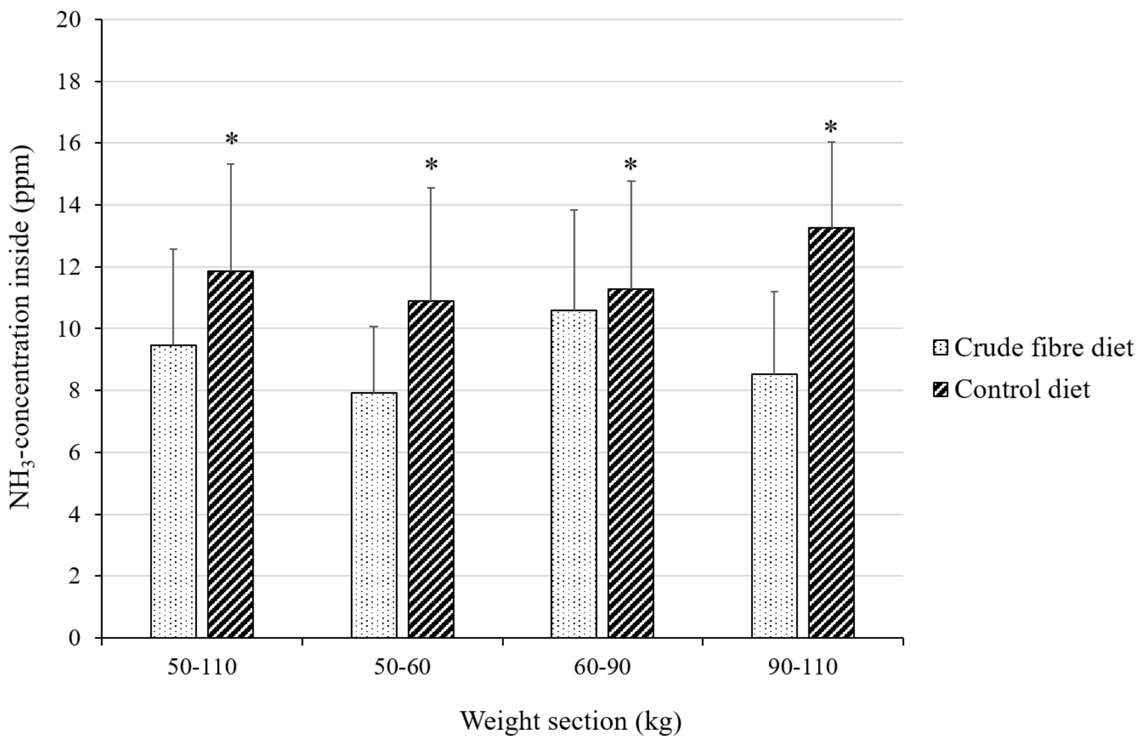

Figure 3.3 Mean NH_3-concentrations (ppm) and standard deviation measured inside the barns during different weight sections (pre-fattening 50-60 kg, mid-fattening 60-90 kg, and finishing period 90-110 kg) for the experimental group with crude fiber supplemented diet and control group with control diet. * indicate significant differences between experimental and control group within the same weight section ($p < 0.05$).

3.5 Discussion

In the presented study it was investigated whether NH_3-emissions can be reduced by dividing fattening pigs into performance groups according their body composition and by using crude fiber supplemented diets to control the animals feed intake. Results showed that there were significant lower ammonia emissions for the experimental group compared to the control group. Other studies received comparable reductions in ammonia emissions by using crude fiber supplemented diets (Jarret et al., 2012; Philippe et al., 2015). In the study, fast-growing animals received the highest crude fiber concentration in the diet. This was intended to control the feed intake of animals with a particularly high feed intake capacity in order to avoid luxury consumption and to prevent excessive nitrogen intake. The results support the hypothesis that the investigated feeding system results in less nitrogen and consequently ammonia being released into the environment. In the course of the fattening period, the physiological feed intake capacity of the animals increases. At the same time, the animals' protein requirement decreases (Jeroch et al., 1999). This suggests that control of feed intake and the associated ammonia reduction is therefore most effective in the finishing period of fattening. The presented results confirm this. The maximum concentration for ammonia in pig houses permitted in Germany is 20 ppm (TierSchNutztV, 2006). Concentrations exceeding this value can lead to damage of e.g. the respiratory tract of the animals (Drummond et al., 1980). With regard to animal welfare and a good air quality inside the barns necessary for this, recommendations of 10 ppm ammonia in a pig barn are made (Boehringer Ingelheim, 2016). In experimental groups as well as in the control group the limit of 20 ppm could be kept. However, ammonia concentrations were significant lower in the experimental group. Furthermore, on average the recommendation value of 10 ppm could be kept in every fattening section, while higher values were determined in the control group. This suggests that the feeding system investigated leads to less ammonia in the air inside the barn and thus made a positive contribution to animal welfare.

3.6 Conclusion

In summary animals with high feed intake capacity can be controlled in their feed intake by using crude fiber supplemented diets and thus avoid luxury consumption. Based on the results presented in this study it can be conclude that NH_3-emissions can be reduced significantly by using the investigated new feeding concept. Beside the positive effect on the environment, a reduction of ammonia concentrations inside the barns can contribute to animal welfare. New feeding systems like the one investigated in this study are necessary to meet the increasing demands for environmental protection and animal husbandry. The study shows that the investigated feeding system offers a possibility to combine environmental protection and animal welfare in modern agriculture. However, further studies are necessary to provide a comprehensive evaluation of the system with all relevant aspects and to be able to apply the system in practice.

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4 Study 3

Feasibility Study on the Use of Infrared Thermography to Classify Fattening Pigs into Feeding Groups according their Body Composition

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4.1 Abstract

Fattening pig husbandry and associated negative environmental impacts due to nitrogen inputs by ammonia emissions are current issues of social discussion. New resource-efficient feeding systems offer great potential to reduce excess nutrient inputs into the environment. Using ultrasound measurements, fattening pigs can be divided into performance groups based on their backfat/muscle ratio to feed them according to their nutritional needs. Ultrasound measurements are not suitable for practical use, so alternatives have to be found. As a non-invasive, contactless method, infrared thermography offers many advantages. This study investigated whether infrared thermography can be used to differentiate between “fat” and “lean” animals. Two evaluation methods with different measurement spot sizes were compared. During a fattening period, 980 pigs were examined three times with an infrared camera. Both methods showed significant differences. Body surface temperature was influenced by factors like measurement spot size and soiling of the animals. Body surface temperature decreased (−5.5 °C), while backfat thickness increased (+0.7 cm) in the course of the fattening period. Significant correlations ($R > |0.5|$; $p < 0.001$) between both parameters were found. Differentiation between “fat” and “lean” animals, based on temperature data, was not possible. Nevertheless, the application of thermography should be investigated further with the aim of resource-efficient feeding. The results of this feasibility study can serve as a basis for this.

Keywords: body surface temperature; performance groups; pig husbandry; sorting gate; infrared images; thermal isolation; resource-efficient feeding

4.2 Introduction

In Germany, 95% of ammonia emissions originate from agriculture. Pig husbandry takes the second largest proportion (UBA, 2020). The increasing spatial concentration of pig farms (Statistisches Bundesamt, 2020), and increasingly restrictive regulations regarding nitrogen inputs into the environment (DüV, 2017), make it necessary to find new possibilities to reduce nitrogen input and ammonia emissions. New feeding strategies offer great potential, especially in pig husbandry. Since only about 30% of ingested protein is utilized efficiently by the animal, and most of the nitrogen is excreted, it is urgently necessary to feed the animals according to their nutritional needs (Aarnink, 1997). The prevention of luxury consumption of animals with a high feed intake capacity is desirable from an environmental and economic aspect. With conventional phase feeding systems, the diets are based on the average requirements of the whole animal group.

Animals with feed intake capacity and nutritional needs above or below average are consequently not fed efficiently (KTBL, 2011). In their study, Reckels et al. (2020) showed that fattening pigs can be divided into performance groups according to their individual body compositions. Those were determined by the ratio of backfat thickness and diameter of *Musculus longissimus dorsi* using ultrasound examinations. Furthermore, Lengling et al. (2020) were able to demonstrate that feed intake of fattening pigs can be controlled by the crude fiber content of the diet, as both parameters correlate negatively. In terms of resource-efficiency and based on the results of Reckels et al. (2020) and Lengling et al. (2020), feeding according to individual performance groups is desirable. However, ultrasound examinations are not suitable for practical use. New technologies have to be developed, which automates the classification of the animals into performance groups.

Sorting gates have already been used for several years to differentiate animals according to their bodyweight (Cielejewski et al., 2005). They can be used in large group housing systems of gestating sows (Ebertz, 2020) and fattening pigs, respectively. By the sorting gate, the lying area is separated from two different feeding areas. If the animals want to enter the feeding area, they have to pass the sorting gate. Using optical and mechanical weight determination, the animals' bodyweight is recorded several times a day. According to those data, the animal is given access to feeding area A, or feeding area B, where different diets can be offered (KTBL, 2011).

Infrared thermography (IRT) enables the measurement of heat radiation from objects or organisms. The IRT is being used increasingly in animal husbandry and veterinary medicine. As a non-invasive method, which can be repeated as often as required, it offers many advantages (Shekhawat, 2016). In reproductive medicine, IRT is used in sows to make conclusions about diseases like the mastitis-metritis-agalactia complex (Traulsen et al., 2010). Changes in metabolism, that are due to a change in feed intake, or feed composition can be detected with IRT, respectively (Loughmiller et al., 2005). Several studies investigated the possibility of early detection of febrile animals, due to a change in body surface temperature (Gerß, 2014; Loughmiller et al., 2001).

The different thermal conductivity of fat and muscle tissue has already been investigated in many studies (Cohen, 1977; Lipkin & Hardy, 1954). Henriques and Moritz (1947) reported thermal conductivity values of 11×10^{-4} (cal cm^{-1} s^{-1} $°C^{-1}$) for porcine muscle tissue, while for porcine fat tissue, they reported 3.8×10^{-4} (cal cm^{-1} s^{-1} $°C^{-1}$) (Henriques & Moritz, 1947). Similar results have been presented by Breuer (1924). Fat tissue shows significantly lower thermal conductivity than muscle tissue, which is related to the different water content (Giering et al., 1995).

In the present study, it was examined, for the first time, whether infrared thermography is suitable to divide fattening pigs into performance groups. Firstly, it was hypothesized that different backfat thicknesses lead to differences in body surface temperature of the animals, as fat tissue acts as a thermal isolator (Schmidt et al., 2013). Those differences should be visualized by infrared images and enable them to distinguish between fat and lean animals. Secondly, it was assumed that the infrared images would lead to a comparable grouping as obtained with the ultrasound examinations described by Reckels et al. (2020) and Lengling et al. (2020). Furthermore, two different evaluation methods for the infrared images were compared to determine which method could be more suitable. This feasibility study should contribute to a new resource-efficient feeding concept. A technical extension of established sorting gate systems with an infrared camera could enable new options in feeding and animal health management.

4.3 Materials and Methods

4.3.1 Animals and Housing

The study was carried out from August to December 2019 on a pig fattening farm in Lower Saxony, Germany. For the trial, 980 fattening pigs with an average bodyweight of 25.8 kg were housed in. The males were castrated as suckling pigs, and all animals were cross-breed products of the Genesus F1 sow (Yorkshire x Landrace) and a Canadian Duroc boar. Each pig was equipped with a Radio-Frequency-Identification (RFID) ear tag on day three after housing, which enabled individual identification.

The barn was designed for large group housing and subdivided into three compartments with a total surface area of 841 m^2. Since the prescribed area per animal has to be at least 0.75 m^2 (TierSchNutztV, 2006), the barn had a total capacity of 1121 animals. Due to the fact that only 980 pigs were housed in, there was a usable surface area of 0.85 m^2 per animal. Activity and lying areas were spatially separated from two feeding areas (feeding area "A" and "B") per compartment. A sorting gate of the company Hölscher + Leuschner (®Hölscher + Leuschner GmbH and Co. KG, Emsbüren, Germany) in each compartment, connected the different areas. The barn was force ventilated. Fresh air was continuously supplied along the eaves, while exhaust air was decentralized extracted over the floor by means of three exhaust fans with a diameter of 1090 mm. Approximately 60% of the barn were equipped with a concrete slatted floor with a void percentage of 15%. The remaining 40% were equipped with a structured plastic slatted floor (Comfi-Floor, Hölscher + Leuschner GmbH and Co. KG, Emsbüren, Germany) with a reduced void percentage of 3.8%. Figure 4.1 gives an outline of the barn.

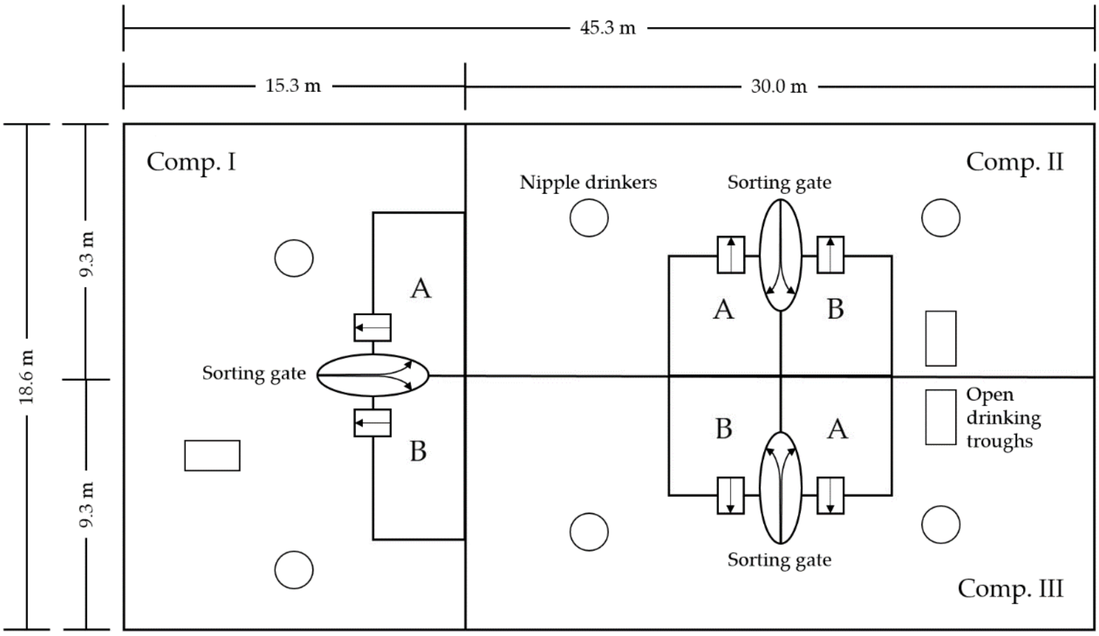

Figure 4.1 Outline of the experimental barn with its three compartments (Comp. I–III). Each compartment was equipped with two feeding areas (A and B, respectively), which could be reached by the animals of each compartment via a sorting gate and left via an exit door.

4.3.2 Feeding

4.3.2.1 Feeding Groups

The animals were divided into three groups with two feeding groups, each according to their body composition. The grouping was done with an average bodyweight of the animals of 50 kg. Bodyweight was determined by all animals using a weighbridge inside the sorting gate. Additionally, the ratio between backfat thickness and the diameter of

Musculus longissimus dorsi was measured by using ultrasound examinations, as described by Reckels et al. (2020) and Lengling et al. (2020). Group 1 in compartment I contained 330 randomly selected animals and represented an average group. The remaining 650 animals were firstly divided into group 2 (compartment II) and group 3 (compartment III), according to their bodyweight. Group 2 contained approximately the 50% heaviest (*n* =328) and group 3 approximately the 50% lightest (*n* = 322) animals. Each group was further divided into two feeding groups. In group 1, the feeding groups consisted of the approximately 50% heaviest and 50% lightest animals. Since groups 2 and 3 have already been separated according to the bodyweight, those groups were subdivided related to the ratio between backfat thickness and diameter of *Musculus longissimus dorsi* in "fat" (≥0.19) and "lean" (<0.19). Thus, for group 2, the subgroups were "heavy lean (HL)" and "heavy fat (HF)"; and for group 3, the subgroups were "light lean (LL)" and "light fat (LF)" (Lengling et al., 2020; Reckels et al., 2020). Table 4.1 gives an overview of the feeding groups.

Table 4.1 Classification of animals into feeding groups.

Compartment	Group	Feeding group	Number of animals
I	1	Light	166
		Heavy	164
II	2	Heavy lean	164
		Heavy fat	164
III	3	Light lean	161
		Light fat	161

4.3.2.2 Feeding Technology

Due to the two spatially separated feeding areas in each compartment, it was possible to feed each feeding group with an individual diet. The animals had to pass the sorting gate to change from lying area to the feeding areas. The sorting gate consists of an entrance door and two exit doors, each leading to one of the two feeding areas. By means of the RFID ear tag recognition, each animal could be identified when entering the gate. Using a weighbridge and three-dimensional (3D) camera-technology, the animal's individual weight and body condition data were recorded mechanical and optical every time it passed the sorting gate. Optical weight is calculated by measuring the height, width, and length of the animal with the assistance of special software (optiSORT, Hölscher + Leuschner GmbH and Co. KG, Emsbüren, Germany). Cielejewski et al. (2005) verified the correlation between optical and mechanical weight determination. Depending on the data, the animals were directed to either feeding area “A”, or feeding area “B”. The animals were fed with a liquid feeding system of the company Hölscher + Leuschner (®Hölscher + Leuschner GmbH and Co. KG, Emsbüren, Germany) *ad libitum* for the entire fattening period. The liquid feed for the fattening pigs was composed of different components. Corn-Cob-Mix (CCM) and Triticale whole-plant-silage (WPS) were used as the farm’s own components. Two different supplementary feed and soybean oil were purchased from a German feed company. Detailed chemical composition of the feeding components is given in Table S1 in the Supplementary Materials (see Table S1: Chemical composition of supplementary feed “SF1”, and “SF2”, as well as “Soybean Oil”, according to the declaration (88% dry matter content; DM). Triticale whole-plant-silage (WPS) and the Corn-Cob-Mix (CCM) were analyzed in the Institute for Animal Nutrition Hanover (88% DM)). The diets of the feeding groups only differed in their crude fiber contents. Thus, the “fat” animals were given a higher crude fiber content in order to limit feed intake and avoid luxury consumption. The two animal groups in compartment I received the same diets as the “lean” animal groups in compartment II and III. As a crude fiber component, the WPS was used. All diets had an equal amount of energy and nitrogen. Water was provided by open drinking troughs and nipple drinkers, additionally to the water provided with the liquid feeding.

4.3.3 Infrared Thermography

Thermographic measurements were carried out on three dates during the fattening period (fattening day 32, 61, and 109) with 1828 examined animals in total. At day 32 and 109, all animals in the barn were examined (average bodyweight 53.1 ± 9.0 kg and 109.6 ± 8.8 kg). Because the first amount had already been marketed for slaughtering, there were fewer animals on day 109. At day 61 (average bodyweight 72.5 ± 8.6 kg), only the animals from group 1 were investigated, which is related to the parallel ultrasound examinations to which the thermographic measurements were adjusted. In addition to the thermographic measurements for each animal, the ear tag number, a reference temperature, and parameters of body composition were recorded.

The infrared thermography was performed with a VarioCAM (InFraTec GmbH, Dresden, Germany). The camera covered a spectral range from 7.5 to 14 µm and a temperature range from −40 to 1200 °C. The measurement accuracy was ± 2%. The infrared images of the animals were taken in the sorting gate of compartment I. The animals were successively moved into the sorting gate for the measurements. It was tried to handle the animals as calm as possible to avoid an increased stress level. Since the animals were used to enter and remain in the sorting gate, this was not a new situation for them. No fixation techniques to the animals were necessary inside the sorting gate. In order to ensure that all images are taken in the same distance and angle, the infrared camera was fixed to the sorting gate using a bracket. The camera was, thus, located at a total height of 1.81 m above the floor of the gate. The emission level was set at a constant of 0.98, as described for pigskin by Gerß (2014). The measuring angle was approximately vertical to the measuring object. Due to the permanently mounted technology of the sorting gate, a completely vertical angle was not possible. The camera was operated manually for each image, and the images were saved automatically. By the individual ear tags, the images could be exactly assigned to the animals. In total, 529 animals could be identified, which were investigated on days 32 and 109, while 156 animals were assigned to the measurements on all three measurement days. Ultrasound measurements, as described by Reckels et al. (2020) and Lengling et al. (2020), were performed on the animals at the same time. Feeding and ultrasound data will be reported in detail elsewhere and were only used in times of a high variance to evaluate the infrared thermography for classification.

4.3.3.1 Evaluation of Thermograms

Two methods were used for the evaluation of the thermograms. A comparison of those was made in order to determine, which method is more suitable for the research question. Figure 4.2 shows the evaluation methods used on the basis of a thermogram.

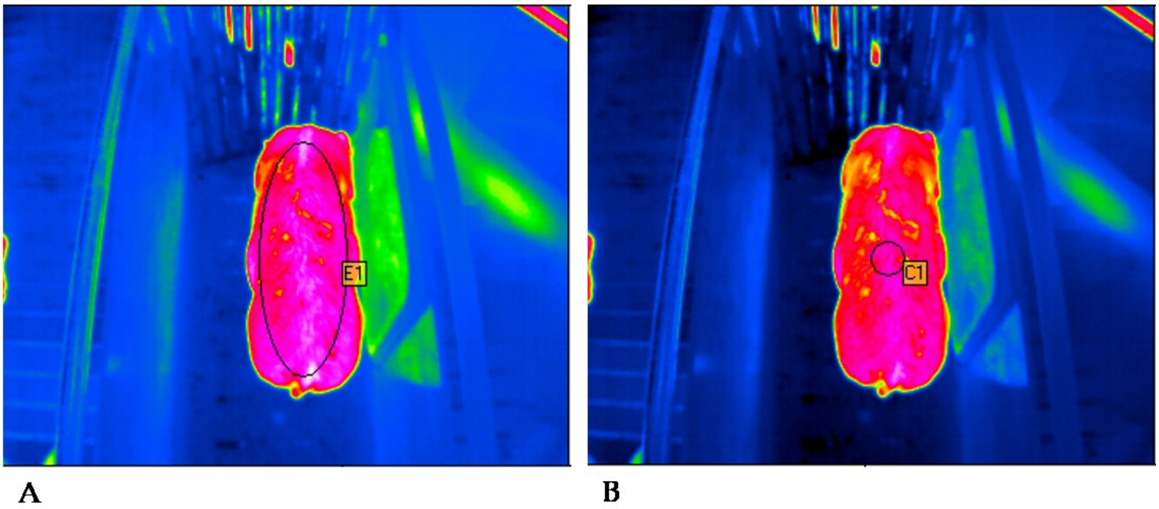

Figure 4.2 Comparison of the two evaluation methods. (A) First method (ME, maximal ellipse) with an elliptical measurement spot placed over the maximum possible area of the pig's body. (B) Second method (SC, standardized circle) with a standard circular measurement spot at the height of the last rib of the animal (©Alfert).

The evaluation of the thermograms was done with IRBIS® Software (InFraTec GmbH, Dresden, Germany). The evaluation methods differed in the size of the measuring spot. For the first method, the spot was adapted to the size of each animal individually. Therefore, it had an elliptical geometry in order to cover the maximal possible area of the animal's body (method 1 = maximal ellipse = ME). For the second method, the measurement spot was standardized (method 2 = standardized circle = SC). A circle with a radius of 3.5 cm and a base area of 38.5 cm^2 was used. The measurement spot was placed in the same position as the ultrasound measurements at the height of the last rib.

Animals were excluded from data analysis, due to an increased degree of soiled skin. Whenever contamination was detected within the measuring spot, an animal was classified as soiled (Figure 4.3).

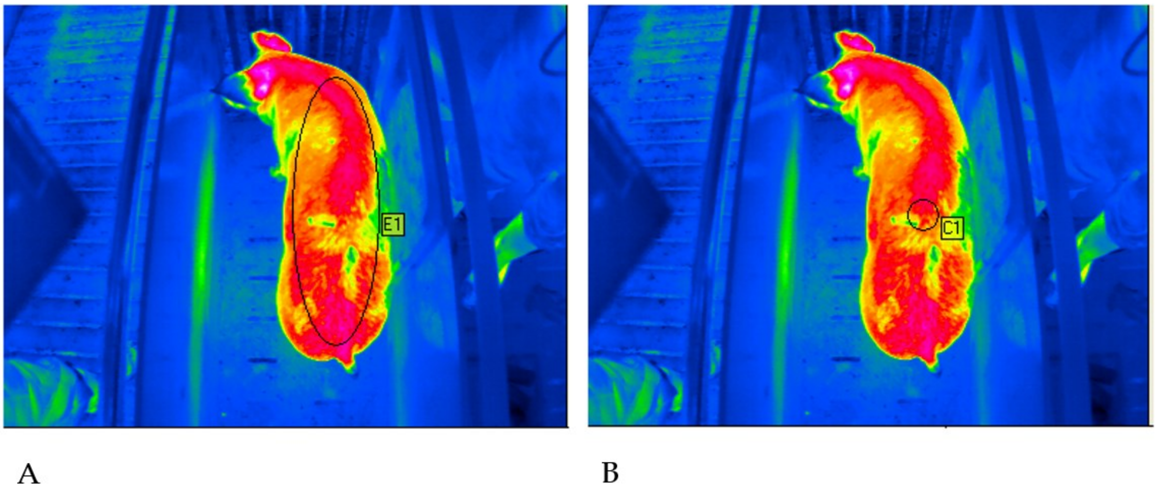

Figure 4.3 Thermogram of a fattening pig with visible soiling within the measurement spots. (A) Evaluation method ME (maximal ellipse). (B) Evaluation method SC (standardized circle) (©Alfert).

Consequently, animals which were classified as soiled in SC, automatically were classified as soiled in ME, respectively. Table 4.2 summarizes the number of investigated and excluded animals on the three measurement days.

Table 4.2 The number of investigated and soiled animals (% of investigated animals) of the three measurement days (MD) (fattening day 32, 61, and 109) and in total for the entire period.

MD	Investigated animals	Soiled animals (%)		Non-Soiled animals (%)
		SC	ME&SC*	
1	933	7.3	23.1	76.9
2	289	20.8	25.6	74.4
3	606	9.9	26.1	73.9
Total	1828	10.3	24.5	75.5

*ME = maximal ellipse; SC = standardized circle; Animals which were classified as soiled in SC consequently were classified as soiled in ME.

4.3.3.2 *Reference Temperature and Climatic Conditions*

In order to take a reference value of the temperature of each animal, an infrared thermometer IR-1001A (Voltcraft, Hirschau, Germany) was used. Reference temperature was taken to obtain a comparative value to the temperature data received with the thermograms. It also represents the body surface temperature and was not used to represent the body core temperature of the animals. The measurement accuracy of the thermometer was ± 1.5% for a temperature range of -20 to 200 °C. The reference temperature was measured on the skin surface of the pigs, at the height of the last rib, respectively. The emission level was also 0.98. The distance to the measuring point was 30 cm. With a ratio of measuring distance and measuring spot size of 50:1, the measuring spot size was 0.6 cm^2. Due to the limited space in the sorting gate and the intention to keep the animals as short and unstressed as possible for the measurements, a rectal or orbital temperature measurement as a reference value was not feasible.

Climatic parameters, like temperature and relative humidity, can influence IRT measurements (Clark & Cena, 1977; Röhlinger et al., 1979). For this reason, these data were recorded during the fattening period with data loggers Testo 174 H (Testo SE and Co. KGaA, Lenzkirch, Germany) continuously every five minutes.

4.3.4 Statistical Analysis

The infrared images were evaluated descriptively by minimum, mean, and maximum with the IRBIS® Software (InFraTec GmBH, Dresden, Germany). All charts were created with Microsoft (MS) Office Excel (Microsoft® Office Professional Plus 2013). Statistical analysis was done with SAS 9.4 (SAS, 2016). Results are presented as mean values ± standard error (SE). Body composition and reference temperature data of the animals, which were identified on all three measurement days, were analyzed by a General Linear Model with measurement days as a fixed effect. Body surface temperature data were analyzed by the Mixed Model with soiling status, evaluation method, and measurement day, as well as their interactions as fixed effects and individual pig as a random effect. The post-hoc Tukey multiple comparison tests were performed to determine statistically significant differences. Correlations were performed according to Pearson with $R > |0.3|$ as weak, $R > |0.5|$ as mean, and $R > |0.8|$ as strong correlation. All statements of statistical significance were based on $p \leq 0.05$.

4.4 Results

4.4.1 Comparison of Evaluation Methods

For comparison of the two evaluation methods, measured temperature minima, mean, and maxima, were evaluated. For all temperature measurements, significant differences were found between method ME and SC. In general, body surface temperature determined with ME was lower than with SC. The highest difference was found for the temperature minimum. For ME, the mean of temperature minima for all three measurement days was 28.06 °C ± 0.13, whereas for SC, it was 31.91 °C ± 0.07. The mean of mean temperature values for all measurement days were 33.07 °C ± 0.06 and 33.44 °C ± 0.07 (ME and SC), respectively, while the mean of maxima were 34.92 °C ± 0.05 and 34.32 °C ± 0.05 (ME and SC). Method ME consequently showed a temperature range between mean minimum and maximum temperature of 6.86 °C, while SC had a temperature range of 2.41 °C. A significant difference between ME and SC could be found for all three measurement dates, respectively.

In order to investigate the influence of contamination on the temperature data, body surface temperature of soiled and non-soiled animals was compared. In general, the body surface temperature of the soiled animals was lower than of the non-soiled animals. These results were found for ME and SC, respectively. For example, for ME, the mean temperature of the soiled animals was 32.81 °C, while the non-soiled animals showed a mean temperature of 34.19 °C (on measurement day 1; $p < 0.01$). For method SC, similar significant differences between the soiled and non-soiled animals were found. Temperature decreased from measurement day 1 to 3, independent of soiling status or evaluation method. Table 4.3 shows the results in detail.

For both methods, the temperature maximum showed the lowest variance. In contrast, the temperature minimum showed a higher variance, especially for ME, and was more influenced by animal soiling than mean and maximum temperature values. Figure 4.4 shows the cumulative distribution of all measured temperature values for minimum, mean, and maximum for method ME and SC, respectively.

Table 4.3 Body surface temperature (mean ± SE (n)) of soiled and non-soiled fattening pigs determined by evaluation method ME (maximal ellipse) and SC (standardized circle) on three measurement days (MD).

MD	Body surface temperature (°C)	Evaluation Method			
		ME		SC	
		Soiled‡	Non-Soiled	Soiled‡	Non-Soiled
1	Min	28.87 ± 0.11 (215) ^{A}	30.82 ± 0.07 (639) $^{A, *}$	30.12 ± 0.19 (68) $^{A, \#}$	33.34 ± 0.04 (787) $^{A, *, \#}$
	Mean	32.81 ± 0.07 (215) ^{A}	34.19 ± 0.04 (639) $^{A, *}$	32.67 ± 0.14 (68) ^{A}	34.66 ± 0.06 (787) $^{A, *, \#}$
	Max	35.01 ± 0.06 (215) ^{A}	35.65 ± 0.03 (639) $^{A, *}$	34.18 ± 0.13 (68) $^{A, \#}$	35.33 ± 0.03 (787) $^{A, *, \#}$
2	Min	26.70 ± 0.18 (74) ^{B}	26.88 ± 0.12 (129) ^{B}	30.57 ± 0.16 (60) $^{A, \#}$	32.16 ± 0.13 (145) $^{B, *, \#}$
	Mean	31.66 ± 0.09 (74) ^{B}	32.95 ± 0.13 (129) $^{B, *}$	32.45 ± 0.13 (60) ^{A}	33.63 ± 0.12 (145) $^{B, *, \#}$
	Max	34.74 ± 0.11 (74) ^{A}	35.07 ± 0.14 (129) ^{B}	33.60 ± 0.13 (60) $^{B, \#}$	34.49 ± 0.12 (145) $^{B, *, \#}$
3	Min	21.05 ± 0.20 (158) ^{C}	21.93 ± 0.16 (263) $^{C, *}$	24.76 ± 0.33 (60) $^{B, \#}$	28.74 ± 0.13 (366) $^{C, *, \#}$
	Mean	28.23 ± 0.13 (158) ^{C}	30.43 ± 0.09 (263) $^{C, *}$	28.44 ± 0.28 (60) ^{B}	30.75 ± 0.09 (366) $^{C, *}$
	Max	31.94 ± 0.12 (158) ^{B}	33.10 ± 0.06 (263) $^{C, *}$	30.60 ± 0.24 (60) $^{C, \#}$	32.10 ± 0.07 (366) $^{C, *, \#}$

$^{A, B, C}$ different letters indicate differences ($p < 0.01$) among the measurement days 1–3 within the same soiling status and evaluation method. * stars indicate differences ($p < 0.01$) between the soiled and non-soiled groups within the same measurement day and evaluation method. $^{\#}$ hash keys indicate differences ($p < 0.01$) between evaluation method ME and SC within the same soiling status and the same measurement day. ‡ soiling rating refers to the total visible top view of the pig independent of the evaluation method.

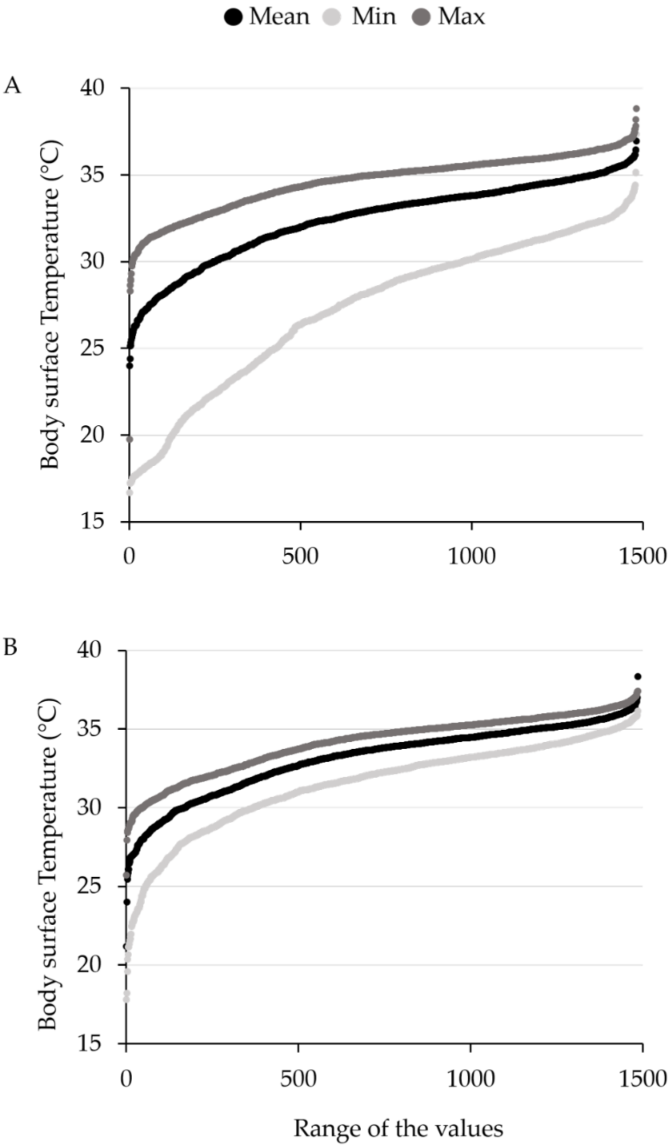

Figure 4.4 Cumulative distribution of all measured values for minimum, mean, and maximum body surface temperature (°C) for evaluation method ME (A) and SC (B).

The two evaluation methods showed significant differences ($p < 0.05$) with regard to evaluable thermograms of the animals. For ME, 30.2% of the thermograms were classified as soiled, while for SC, only 12.6% were excluded, due to contamination. Thus, less than half as many thermograms were excluded, due to contamination in SC compared to ME.

For both evaluation methods, strong, significant correlations with the reference temperature could be observed for all temperature parameters with $r \geq 0.8$ and $p \leq 0.001$.

Due to a technical defect, no climate data were available for measurement 1. During measurement 2, a higher relative humidity was measured in compartment I. Further significant differences could not be determined for indoor temperature and relative humidity between the compartments on measurements 2 and 3 ($p > 0.05$).

4.4.2 Body Composition and Body Surface Temperature

Table 4.4 summarizes the results of body composition and reference temperature measurements of the animals, which were identified on all three measurement days ($n = 156$). As those animals, all belong to group 1, and this was an average group of all animals in the barn, this data can be seen as representative for all animals.

Table 4.4 Body composition and reference temperature data of the animals which were identified on all three measurement days (n = 156).

Parameter	MD	Mean	SE	Minimum	Maximum
Body weight (kg)	1	57.58 ^{A}	1.334	39.40	70.40
	2	69.99 ^{B}	0.752	42.60	89.70
	3	110.93 ^{C}	0.841	91.40	160.60
Backfat (cm)	1	0.63 ^{A}	0.012	0.43	0.97
	2	0.85 ^{B}	0.017	0.37	1.56
	3	1.34 ^{C}	0.022	0.83	1.98
Muscle (cm)	1	3.37 ^{A}	0.044	2.65	4.52
	2	4.14 ^{B}	0.040	3.36	5.52
	3	4.97 ^{C}	0.040	3.95	6.15
Backfat/ Muscle	1	0.19 ^{A}	0.003	0.12	0.27
	2	0.21 ^{B}	0.004	0.07	0.37
	3	0.27 ^{C}	0.005	0.17	0.42
Reference Temp. (°C)	1	36.72 ^{A}	0.121	34.10	38.80
	2	36.23 ^{B}	0.162	32.50	39.80
	3	31.15 ^{C}	0.171	25.50	36.50

$^{A, B, C}$ different letters indicate significant differences ($p < 0.05$) between the measurement days within the same parameter. MD: measurement day; SE: standard error.

During the fattening period, the body composition of the animals changed, and the effects of those on the temperature data were observed. From measurements 1 to 3, a gain in bodyweight of 53.35 kg per pig and a mean reduction of reference temperature of 5.57 °C was observed. Thus, the reference temperature decreased from 36.72 °C (measurement 1) to 31.15 °C (measurement 3). Backfat/muscle ratio increased during fattening period from 0.19 ± 0.03 to 0.27 ± 0.05.

Data analysis showed significant correlations between all measurement parameters (temperature values, as well as body condition parameters) for all measurements on all three measurement days (Figure 4.5.).

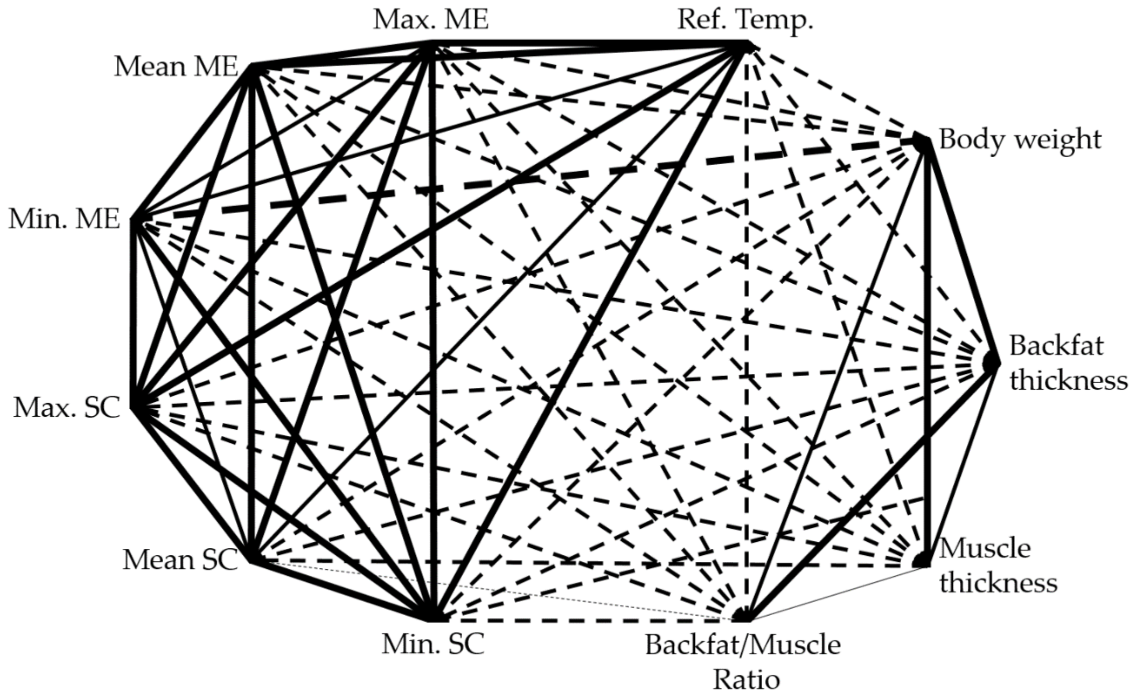

Figure 4.5 A significant correlation ($p < 0.0001$) for all measurements on all three measurement days between body surface temperature measured with ME and SC, reference temperature, and body condition parameters like bodyweight, backfat thickness, muscle thickness, and backfat/muscle ratio. Continuous lines indicate positive correlations, and dotted lines indicate negative correlations. The thicker the connecting line, the stronger the correlation, with $R > |0.3|$ as weak, $R > |0.5|$ as mean and $R > |0.8|$ as strong correlation.

One of the research questions was whether there is a visible correlation between the backfat thickness and the body surface temperature. Reference temperature and body surface temperature determined by the thermograms decreased with increasing body condition values, respectively. Figure 4.6 shows the correlation between body surface temperature and backfat thickness, according to the two evaluation methods, and differentiated between the soiled and non-soiled animals for all measurement days. All figures show a negative trend. Similar correlation values were found for both methods and all temperature parameters.

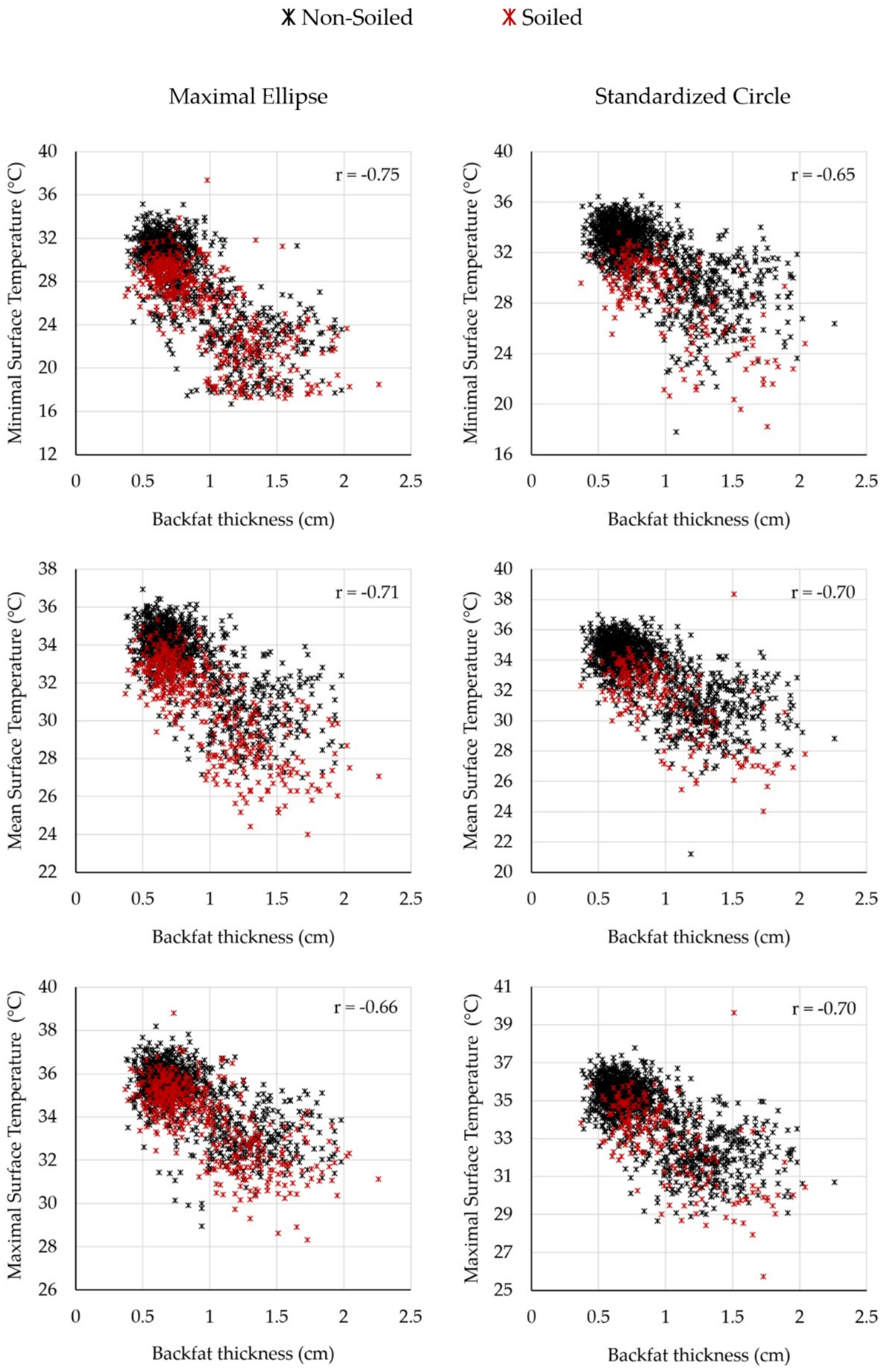

Figure 4.6 Correlation between body surface temperature (°C) and backfat thickness (cm) for soiled and non-soiled animals with n = 1457 in total. Left column: evaluation method ME; right column: evaluation method SC ($p < 0.001$).

4.4.3 Comparison of Body Surface Temperature and Feeding Group

Body condition values and body surface temperatures determined by thermography were compared for the different compartments and each feeding group. On measurement 1, no significant differences were found for body surface temperature values, neither between the compartments nor between the feeding groups within the compartments ($p > 0.05$). Nevertheless, a significant interaction for temperature maximum determined with ME could be found ($p = 0.05$). Except for bodyweight (heavy animals 67.8 kg; light animals 51.6 kg; $p < 0.05$), no significant differences were found between the heavy and the light animals in compartment I. Body condition values differed significantly between compartment II and III ($p < 0.05$). The backfat thickness and backfat/muscle ratio also differed significantly between the feeding groups within the same compartment. A noteworthy interaction was determined for backfat thickness, respectively. Table 4.5 shows the mean values and standard error for compartment II and III of measurement 1, according to the feeding groups.

During measurement 2, only the animals in compartment I were investigated. No significant difference between the two feeding groups could be observed either ($p > 0.05$). On average, the body surface temperature of the light animals was 32.81 °C ± 0.30 and 33.64 °C ± 0.30 (method ME and SC). For the heavy animals mean temperature was 33.10 °C ± 0.23 and 33.61 °C ± 0.22 (method ME and SC).

On measurement 3, the body surface temperature of the animals in compartment I differed significantly from those in compartment II and III ($p < 0.05$). On average, the body surface temperature was lower in the compartment I compared with the other two compartments. Except for bodyweight (heavy animals 113.3 kg; light animals 106.4 kg; $p < 0.05$), no significant differences were found between the heavy and the light animals in compartment I. Comparing compartment II and III, significant differences were found between the feeding groups for backfat, muscle, and backfat/muscle ratio ($p < 0.05$). Bodyweight differed significantly between those two compartments, but not between the feeding groups within the compartments. For body surface temperature, no significant differences were found, neither between the compartments II and III, nor between the feeding groups within the compartments ($p > 0.05$). However, as shown for measurement 1, a significant interaction for temperature maximum in ME could be determined for measurement 3, respectively ($p = 0.05$). Table 4.6 shows the mean values and standard error for compartment II and III of measurement 3, according to the feeding groups.

Table 4.5 Body condition values and body surface temperatures (mean ± SE (n)) for compartment II and III on measurement day 1, according to the feeding groups.

	Comp. II		**Comp. III**		**p-values (ANOVA)**		
	Heavy/Lean	**Heavy/Fat**	**Light/Lean**	**Light/Fat**	**Comp.**	**Feeding group**	**Comp. × Feeding group**
Backfat (cm)	0.646 ± 0.007 (154) ^{a}	0.817 ± 0.009 (150) ^{a,*}	0.554 ± 0.007 (154) ^{b}	0.691 ± 0.008 (154) ^{b,*}	0.001	0.001	0.03
Muscle (cm)	3.83 ± 0.03 (154) ^{a}	3.73 ± 0.03 (150) ^{a}	3.42 ± 0.03 (154) ^{b}	3.32 ± 0.03 (154) ^{b}	0.001	0.002	n.s.
Backfat/Muscle	0.169 ± 0.001 (154) ^{a}	0.219 ± 0.002 (150) ^{a,*}	0.162 ± 0.001 (154) ^{b}	0.208 ± 0.002 (154) ^{b,*}	0.001	0.001	0.14
Body weight (kg)	56.76 ± 0.41(147) ^{a}	57.15 ± 0.47 (142) ^{a}	44.98 ± 0.28 (146) ^{b}	45.91 ± 0.28 (149) ^{b}	0.001	0.07	n.s.
Reference Temp. (°C)	36.99 ± 0.11 (146)	36.85 ± 0.10 (145)	36.97 ± 0.11 (145)	37.09 ± 0.10 (148)	n.s.	n.s.	n.s.
Min. Temp. ME (°C)	30.47 ± 0.16 (142)	30.46 ± 0.15 (139)	30.13 ± 0.19 (136)	30.37 ± 0.16 (142)	n.s.	n.s.	n.s.
Mean. Temp. ME (°C)	33.89 ± 0.10 (142)	33.75 ± 0.99 (139)	33.91 ± 0.09 (136)	33.97 ± 0.08 (142)	n.s.	n.s.	n.s.
Max. Temp. ME (°C)	35.53 ± 0.07 (142)	35.35 ± 0.07 (139)	35.46 ± 0.07 (136)	35.55 ± 0.07 (142)	n.s.	n.s.	0.05
Min. Temp. SC (°C)	33.08 ± 0.15 (143)	33.05 ± 0.13 (138)	33.11 ± 0.12 (136)	33.11 ± 0.12 (142)	n.s.	n.s.	n.s.
Mean Temp. SC (°C)	34.45 ± 0.09 (143)	34.30 ± 0.10 (138)	34.65 ± 0.24 (136)	34.54 ± 0.09 (142)	n.s.	n.s.	n.s.
Max. Temp. SC (°C)	35.25 ± 0.08 (143)	35.11 ± 0.08 (138)	35.23 ± 0.07 (136)	35.31 ± 0.07 (142)	n.s.	n.s.	n.s.

$^{a, b}$ different letters indicate significant differences ($p < 0.05$) between compartments within the same feeding group. * indicate significant differences ($p < 0.05$) between feeding groups within the same compartment.

Table 4.6 Body condition values and body surface temperatures (mean ± SE (n)) for compartment II and III on measurement day 3, according to the feeding groups.

	Comp. II		**Comp. III**		**p-values (ANOVA)**		
	Heavy/Lean	**Heavy/Fat**	**Light/Lean**	**Light/Fat**	**Comp.**	**Feeding group**	**Comp. × Feeding group**
Backfat (cm)	1.33 ± 0.03 (76)	1.42 ± 0.03 (69) *	1.28 ± 0.02 (107)	1.37 ± 0.03 (106) *	0.07	0.002	n.s.
Muscle (cm)	5.05 ± 0.07 (52)	4.88 ± 0.08 (41) *	5.12 ± 0.05 (75)	4.93 ± 0.06 (71) *	n.s.	0.01	n.s.
Backfat/Muscle	0.252 ± 0.007 (52)	0.288 ± 0.007 (41) *	0.241 ± 0.005 (75)	0.274 ± 0.008 (71) *	0.09	0.001	n.s.
Body weight (kg)	113.6 ± 0.7 (78) ^{a}	113.7 ± 0.9 (70) ^{a}	106.2 ± 0.7 (110) ^{b}	107.1 ± 0.8 (107) ^{b}	0.001	n.s.	n.s.
Reference Temp. (°C)	33.63 ± 0.23 (65)	32.98 ± 0.26 (58)	32.86 ± 0.21 (86)	33.22 ± 0.24 (77)	n.s.	n.s.	0.06
Min. Temp. ME (°C)	23.16 ± 0.19 (57)	22.60 ± 0.25 (51)	22.73 ± 0.23 (74)	22.97 ± 0.23 (63)	n.s.	n.s.	0.08
Mean. Temp. ME (°C)	30.51 ± 0.19 (57)	30.18 ± 0.20 (51)	30.17 ± 0.19 (74)	30.46 ± 0.19 (63)	n.s.	n.s.	n.s.
Max. Temp. ME (°C)	33.13 ± 0.13 (57)	32.79 ± 0.16 (51)	32.95 ± 0.13 (74)	33.18 ± 0.14 (63)	n.s.	n.s.	0.05
Min. Temp. SC (°C)	29.70 ± 0.27 (57)	29.31 ± 0.26 (51)	29.15 ± 0.22 (75)	29.53 ± 0.25 (63)	n.s.	n.s.	n.s.
Mean Temp. SC (°C)	31.31 ± 0.19 (57)	31.10 ± 0.24 (51)	30.99 ± 0.17 (75)	31.03 ± 0.25 (63)	n.s.	n.s.	n.s.
Max. Temp. SC (°C)	32.37 ± 0.16 (57)	32.24 ± 0.23 (51)	32.14 ± 0.16 (75)	32.28 ± 0.17 (63)	n.s.	n.s.	n.s.

^{a,b} different letters indicate significant differences ($p < 0.05$) between compartments within the same feeding group. * indicate significant differences ($p < 0.05$) between feeding groups within the same compartment.

4.5 Discussion

As a non-invasive method, the infrared thermography offers many possibilities for temperature measurement, especially in livestock husbandry and veterinary medicine. Until now, IRT has not been used commonly in fattening pig husbandry. Technical and environmental parameters influencing the measured values must be identified and taken into account for practical use (Meola, 2012). For an automated and standardized application of IRT in practice, a suitable and reliable evaluation method is essential. Few authors describe the different possibilities of evaluating thermal images and the advantages and disadvantages of those (Glas, 2008; Menzel, 2014; Schaefer, 2004). Therefore, two evaluation methods were compared in this study. The two methods differed significantly from each other for all measured parameters. In her study, Glas (2008) also used different evaluation methods. Using a polygon measuring tool, the maximum area of the object is investigated. Therefore, the individual limits of each object are manually circumvented. Due to the large dataset used in this study, this was not practical. Instead, an elliptical shape was used, which described the pigs' corpus almost completely.

For the second method, a standardized, circular measuring spot at the level of the last rib was used. In her study, Glas (2008) also uses a standardized measuring spot as second method. In method SC, the difference between the minimum and maximum temperature was reduced compared to method ME. The percentage of animals classified as soiled was significantly lower in method SC, than in method ME, respectively.

In this study, the reference temperature was measured using an infrared thermometer. On average, the two methods did not differ significantly in their deviation to the reference temperature. Both methods showed a strong correlation for all temperature parameters with the reference temperature. Schmidt et al. (2013) also showed a correlation between infrared thermometer and IRT. In general, the measured reference temperature was higher than the maximum temperature determined with IRT. Consequently, the temperature maximum showed the smallest deviation from the reference temperature compared to minimum and mean values. This indicates, that the body surface temperature of fattening pigs can be described most accurately by the temperature maximum of the thermal images. The largest difference between the two evaluation methods was shown for temperature minimum. Due to the physiological limits of heat tolerance (3–6 °C) and cold tolerance (15–25 °C) of pigs (Bianca, 1976), the temperature maximum shows less variation compared to the temperature minimum. Factors like moisture, soiling, hair growth, or airflow can influence the temperature minimum, which makes it more sensitive to disturbances (Clark & Cena, 1977; Röhlinger et al., 1979; Schaefer et al., 2004). This fact also implies, that the temperature maximum is the most suitable parameter for measuring the body surface temperature. This can be confirmed by Traulsen et al. (2010). In their study, temperature maximum measured with IRT showed the best correlation to rectal temperature. Other studies show strong correlations between the rectal temperature and body surface temperature, respectively (Loughmiller et al., 2001; Spiegel, 2016). It should be considered, that rectal temperature measurement is an invasive and stressful process for the animals, which may lead to an increase, and thus, confounding of the body temperature (Zhang et al., 2019). With regard to animal welfare and economic aspects, stressful situations for the animals should be avoided, even though rectal measurement still constitutes the golden standard for measurement of the body core temperature. Considering the aim of an automated and continuous temperature measurement in the daily practice of fattening pig husbandry, contactless measurements with an infrared thermometer are preferable for this purpose.

As shown by Reckels et al. (2020) and Lengling et al. (2020), fattening pigs can be divided into performance groups according to their backfat/muscle ratio. In this study, it was investigated, for the first time, whether such a division based on body surface temperature is possible. As fat tissue acts as a thermal isolator (Schnurrbusch, 2004), it was investigated, whether there is a correlation between backfat thickness and body surface temperature. By infrared thermography, a reduction of body surface temperature could be observed in the course of the fattening period. Backfat thickness increased over the same period, respectively. Significant correlations between both parameters were shown. Thus, the hypothesis could be verified. However, it should be noted that the body surface temperature can be influenced by external factors. Hair intensity and contamination of the skin (e.g., moisture, feed residues) reduce the surface temperature (Clark & Cena, 1977). Both factors increase towards the end of the fattening period and could be related to temperature reduction. As shown, the body surface temperature of soiled animals was significantly lower compared to non-soiled animals. Since the body surface temperature decreases with increasing age of the animals, and at the same time, soiling increases, this fact must be taken into account. By using the temperature maximum for determining body surface temperature, the influence of soiling can be minimized. Direct air circulation can reduce body surface temperature (Jiang et al., 2005). Since the animals were examined inside the sorting gate, direct airflow can be almost completely excluded. The ambient temperature can also influence body surface temperature. This factor should be minimized by comparable internal temperatures between the compartments and the continuous control of it. Within the same compartment, it can be assumed that the ambient temperature has the same effect on all measurements, and consequently, a potential measurement error is balanced. During the study, ambient temperature was measured continuously, and no significant differences were found between the compartments. Nevertheless, cold ambient temperatures influence body surface temperature less than warm ambient temperatures. For this reason, the tested method is more suitable for cold ambient temperatures to visualize differences in body surface temperature, due to different fat layers. This factor must be taken into account when applying the method. In future studies, it has to be investigated how ambient temperature can be included in the evaluation or how its influence can be minimized.

The second hypothesis of this study was that classification into performance groups (based on infrared thermography) is possible, and would be comparable to the classification done with ultrasound examinations (Lengling et al., 2020; Reckels et al., 2020). In the literature, no comparable investigations are described. No significant differences in body surface temperature between the groups could be found. Only group 1 in compartment I differed significantly from the other groups on measurement 3. However, even within the compartment, no differences could be detected between the two feeding groups, “light” and “heavy”. Since ultrasound measurements showed significant differences in the backfat/muscle ratio between “fat” and “lean” animals, the results suggest that differences in fat tissue do not affect thermal isolation, and thus, body surface temperature to the same extent. The differences in backfat- and muscle thickness between “fat” and “lean” animals lie within a range of a few millimeters (Reckels et al., 2020). It is possible that such small differences are not sufficient to produce a significant difference in surface temperature even if they can be detected with ultrasound examinations. The reason why the temperatures in group 1 on measurement 3 were significantly lower compared to the other groups cannot be answered conclusively. The fact that there were no differences between the subgroups “heavy” and “light” within group 1 suggests, that external factors influenced the temperature evaluation. During the measurements, the conditions were tried to keep as standardized as possible to minimize disturbing factors. Nevertheless, there are some factors, like stress, which are difficult to determine and control. This could have influenced the results. Berry et al. (2003) recommend a detailed recording of the present measurement conditions. However, inside a barn of pig husbandry, it might be difficult to control all disturbing factors.

4.6 Conclusions

Based on the results, method SC seems to be less susceptible to temperature variations and more resistant to factors, such as contamination. Additionally, the evaluation with a standardized measuring spot is less work-intensive, and thus, time-saving. However, it has to be clarified how representative a standardized measuring spot is in comparison to the whole measured object. Under this aspect, ME seems to be more suitable to represent the body surface temperature of the animal. Temperature maximum seems to be the most reliable parameter for the determination of body surface temperature, as it shows the lowest variance and the lowest difference to the measured reference temperature. Furthermore, the temperature maximum showed less influence by soiling than temperature mean and minimum. In conclusion, the combination of ME and temperature maximum can be considered the most reliable method. Nevertheless, the results should be confirmed by further studies.

In the present feasibility study, a correlation between body condition and surface temperature could be shown. However, a classification of different performance groups using infrared thermography was not possible. Nevertheless, as a non-invasive method, infrared thermography offers many advantages. A combination of the sorting gates with a thermal imaging camera would enable continuous data acquisition. Daily temperature profiles of the animals could be recorded, as the animals pass the sorting gate several times a day. Correlations between body development and body temperature could, thus, be visualized in more detail. The possibility of using infrared thermography for the described purpose cannot be excluded. With the aim of resource-efficient feeding, this technique should be investigated in further studies.

Supplementary Materials: The following are available online at http://www.mdpi.com/1424-8220/20/18/5221/s1, Table S1: Chemical composition of supplementary feed “SF1”, and “SF2”, as well as “Soybean Oil”, according to the declaration (88% dry matter content; DM). Triticale whole-plant-silage (WPS) and the Corn-Cob-Mix (CCM) were analyzed in the Institute for Animal Nutrition Hanover (88% DM).

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5 General Discussion and Conclusion

5.1 Discussion

This thesis deals with the development and investigation of a new resource-efficient feeding system for fattening pigs focussing on technical and environmental aspects. In this chapter, the results achieved in the presented studies will be discussed in a comprehensive manner and integrated into the scientific context. Furthermore, the aspect of animal welfare will be related to the presented system. Finally, an evaluation of the investigated feeding system will be made and recommendations for practical use and possibly further, subsequent research questions will be given.

As outlined in the introduction, an adaptation of agricultural animal husbandry is necessary in order to take into account the growing demands with regard to animal welfare and environmental protection. In many areas of agriculture, there are already many different strategies to improve animal welfare or to reduce the environmental impact of agriculture (BLE, 2019; Baumgarten et al., 2018; LfL, 2018). However, these two points are often in conflict with each other, as an improvement of one leads to worsening of the other (BMEL, 2017).

For a long time, animals were only protected because of economic and not due to ethical aspects (Hornauer et al., 2020). Animals kept for meat production have a shorter period of use and consequently a shorter life expectancy than animals whose products are obtained, such as laying hens or dairy cows, or animals used for breeding (Bundesinformationszentrum Landwirtschaft, 2021). Nevertheless, animal welfare and animal health are no less important for fattening pigs. Only healthy animals in a good husbandry can develop optimally and healthily during the short, intensive period of use (LfL, 2006). As the largest part of meat production in Germany and the European Union (Deutscher Bauernverband e.V., 2019), pig fattening occupies a particular position here. In order to improve animal welfare, increasing efforts are being made to adapt the housing environment to the physiological behavior of the pigs. The design of the pens and the use of enrichment materials play a significant role in this context (BLE, 2019). Since, on the other hand, pig farming is responsible for a large proportion of ammonia emissions (UBA, 2020), in consequence great potential for reduction strategies is seen here (Döhler et al., 2010).

Protein supply is essential for the production of high quality pigs for slaughtering (Jeroch et al., 1999). The nitrogen absorbed via the feeding protein is the initial substance for the formation of ammonia in the environment (Aarnink, 1997). In the past, there have therefore been many efforts to reduce the formation of ammonia by adapting the diets. While universal fattening was common practice a few years ago, today there are feeding concepts with multiphase feeding, nitrogen-reduced diets and specific amino acid supplementation (DLG e.V., 2019; Kamphues et al., 2014; KTBL, 2012). Many studies were able to prove with their investigations that a reduction of ammonia emissions is possible through the mentioned feeding concepts (Arogo et al., 2006; Canh et al., 1998; Hansen et al., 2014; Philippe et al., 2011). A supply according to nutritional needs contributes just as much to animal welfare and animal health as feed quality, feed components and form of feeding (BLE, 2019). Only animals that are fed ideally are able to grow optimally, maintain their body functions and have an intact immune system to defend against pathogens and consequently remain healthy (Jeroch et al., 1999). As shown in study 1, individual differences in body condition and growth performance of fat and muscle tissue already exist at the beginning of fattening, despite the same body weight of the animals. Also Miller et al. (1991) and Kirchgessner (2014) describe existing differences in nutrient requirements and growth potential depending on factors such as gender or genetic variation. In contrast to the universal fattening system used in the past, phase or multiphase feeding meets the changing needs of the animals better during the fattening period (KTBL, 2012). However, differences in the individual needs of individual animals are not taken into account sufficiently, as the average needs of the group are used in the composition of the diet. This results in over- or undersupply of some animals. Oversupply is to be avoided in terms of environmental protection and resource conservation, as it leads to excess nutrients, especially nitrogen, being released into the environment. Undersupply is not in line with animal welfare and is contraindicated for the preservation of animal health. As the results from study 1 show, the investigated feeding system is suitable for taking this discrepancy in supply into account.

Study 1 of this thesis showed, as Jack et al. (2010) and Jeroch et al. (1999) described before, that animals differ in their feed intake capacity. Animals that were classified as "fat" already at the beginning of fattening showed the highest feed intake, while "lean" animals consumed less feed. If the entire group of animals is fed uniformly, this can lead to the animals growing apart. Large and heavy animals rank higher than small and lean animals within the animal group (Schrader et al., 2009). The animals lower in rank can be suppressed from the feeding trough, so that their nutrient intake is additionally restricted (Hoy, 2009). Animals with a high feed intake eat continuously above their needs. This luxury consumption increases steadily in the course of fattening, as the nutrient requirement decreases while the feed intake capacity increases at the same time (Jeroch et al., 1999). Those points become even more important the more heterogeneous an animal group is, because then a large part of the animals deviates from the "average". The investigated feeding system enables the individual differences in the animals' needs to be taken into account. It could be shown that a differentiation with regard to the performance potential and the demand is generally possible. This can be considered in feeding by dividing the animals into performance groups using sorting gates and digital body condition determination.

It is not common to keep fattening pigs in separate gender groups. There are individual exceptions in the housing of uncastrated boars. Castrated males are usually kept in mixed groups with females (Zaludik, 2002). The advantages of mixed gender groups, e.g. stable social structure and reduced fighting (LfULG, 2014), are countered by disadvantages in terms of optimal nutritional supply. Here, the different needs of male and female animals are not met, respectively (Zaludik, 2002). Even in the investigations carried out within the framework of this thesis, no gender specific feeding was carried out. The groups were heterogeneously mixed. However, an identification of the gender is possible via the individual RFID ear tags, so that the sex can be recognised by means of the sorting gate. In further studies, gender-specific performance groups could be divided in order to investigate whether this has a further influence on resource efficiency and whether the animals could be fed even more optimally.

One working hypotheses for the investigations was that ammonia emissions can be reduced by increasing the use of fiber in the diet and by feeding the animals according to performance groups. The hypothesis was confirmed in studies 1 and 2. Regardless of the season, ammonia emissions could be reduced in the experimental periods, whereby the reduction was greater in summer than in winter. Various authors describe the effect of increased emissions in summer due to higher ventilation rates (Aarnink, 1997; Oldenburg, 1989; Venzlaff et al., 2010). Also, in the conducted studies, the ventilation rates were significantly higher in summer than in winter. Nevertheless, the ammonia concentrations could be reduced to such an extent that there was no increase in emissions compared to winter. In the experimental periods, the legally prescribed limit of 20 ppm ammonia inside pig barns (TierSchNutztV, 2006) could be kept at all times. Especially in winter, keeping the limits is often a problem, as there is less ventilation due to cold temperatures (Groot Koerkamp et al., 1998; Jungbluth et al., 2017). Due to the negative health effects of high ammonia concentrations as described before (see chapter 1.1.1), the results are not only positive from an ecological point of view, but also in terms of animal welfare.

The greatest reduction in ammonia concentrations and emissions could be achieved in the last third of the fattening period, regardless of the season. In this phase, ammonia concentrations in the barn are normally highest (Aarnink, 1997; Oldenburg, 1989). On the one hand, the contamination of surfaces, which cause up to 40% of ammonia emissions in the barn (Janssen & Krause, 1987), increases over the course of fattening (Austermann, 2016). On the other hand, the feed intake of the animals increases while the protein requirement decreases (Jeroch et al., 1999). Especially in winter, for the reasons mentioned above, this is often a problem. The results from studies 1 and 2 indicate that the investigated feeding method can prevent the problem of high ammonia concentrations in the barn, especially in the final fattening phase. By using fiber, the animals with a high feed intake capacity are specifically inhibited in their feed intake. This effect is particularly noticeable at the end of fattening when the feed intake capacity increases physiologically but the protein requirement decreases.

Many studies and investigations describe the possibility of reducing ammonia emissions through the use of fiber (see also chapter 1). For example, Philippe et al. (2015) achieved a reduction in ammonia emissions of 48% while Jarret et al. (2012) were able to reduce ammonia emissions by 31% by increasing the amount of crude fiber in the diet. Based on the results from study 1 and 2, it can be concluded that the increased use of fiber led to a reduction in ammonia emissions also in these studies. As described by Canh et al. (1997) and Jarret et al. (2011) increased intake of fiber leads to an increased proliferation of bacteria in the large intestine and thus to an increased binding of nitrogen in the form of bacterial protein. This shifts the excretion of nitrogen from urine to feces, which means that less urea can be converted into ammonia in the environment (BLE, 2919). For the presented studies, it cannot be said whether the reduction was solely due to the regulation of feed intake but also due to changed nitrogen fixation in the large intestine. In this context, it would be interesting in further studies to determine to what extent the nitrogen fixation in the intestine can be influenced by the different fiber contents within different performance groups.

Fiber is of particular importance with regard to animal welfare. As a natural material, with its structure and physiological properties it can be used as a suitable enrichment material for pigs (Hoy, 2009). If the amount of crude fiber in the diet is increased, an extension of the feeding time can be achieved (Kallabis, 2012). As described in section 1.1.2.4, under natural conditions pigs spend a large part of their time foraging and eating. This distinct exploration behavior is only inadequately or even barely satisfied by feeding conventional, often finely ground and energy-rich diets. In addition, the rationed feed presentation with two feedings per day is often practised (Schrader et al., 2009). It could also be shown that animals which received an increased amount of fiber in the diet were calmer in their behavior compared to a control group and that the occurrence of behavioral anomalies could be reduced (Bergeron et al., 2000; Brouns et al., 1994; Danielsen & Vestergaard, 2001; Lee & Close, 1987). Fiber contributes to a better saturation of the animals due to its structure and swelling capacity (Jeroch et al., 1999; Leeuw et al., 2008). Furthermore, it has a positive effect on the intestinal microbiome by promoting bacterial growth (Heinritz et al., 2016). The bacterial flora in the intestine plays a significant role in the animals' immune system and is therefore important for the defense against pathogenic agents (Jeroch et al., 1999). Studies 1 and 2 were able to demonstrate that the use of fiber in feeding according to performance groups is possible in order to supply the animals better according to their needs and to avoid luxury consumption. Considering the other positive effects of fiber mentioned, especially with regard to animal welfare, it can be assumed that the investigated feeding system not only has a positive effect on the ammonia emissions, but also on animal welfare. Based on the already described negative health effects of increased ammonia concentrations, it can be assumed that a reduction of ammonia concentrations in the barn has a positive effect on the lung health of the animals. The animals in the experimental groups were less frequently diagnosed with pneumonia and/or pleurisy at the slaughterhouse. This indicates a positive effect on the lung health of the animals due to the investigated feeding system, but could not be definitively confirmed, here. In the presented studies, no ethological investigations were carried out. Primarily, it should be investigated whether the idea of the system can generally be implemented. For a comprehensive evaluation of the feeding system, the focus must therefore be placed more on the aspects of animal welfare and animal health in further studies. Behavioral analyses, evaluation of feeding times or assessments of the health status of the animals are possible research topics which must be further investigated to fill the remaining knowledge gaps regarding the new feeding system.

In the presented studies, the influence of fiber supplemented feeding on ammonia emissions, as well as the pollution of surface areas, were investigated. In addition to ammonia emissions, methane emissions from agriculture play an important role in the topic of environmental impact. As GHG which affects the climate, methane contributes significantly to global warming. In Germany, 62% of total methane emissions originate from agriculture (UBA., 2021). Methane is produced during the anaerobic decomposition of organic substances. Whereas in ruminants the largest amount arises from enteric fermentation in the pre-stomach system, the largest amount of methane emissions in pig farming arises from the storage of excrements inside the barn under the slats (Dammgen, 2009; Monteny 2001; UBA., 2021). The use of fiber in pig farming is positive for increasing animal welfare and animal health for the reasons described above (compare chapter 1.1.3.3). However, as with many other aspects, there is a conflict of objectives between increasing animal welfare and environmental protection. Various studies have found an increase in methane emissions through the use of higher fiber contents in pig diets. For example, Philippe et al. (2015) describe an increase in methane emissions from 27.2 to 37.9 g LU^{-1} day^{-1} following the use of increased crude fiber content in the diet of fattening pigs. Jarret et al. (2011) and Seradj et al. (2018) found increased methane emissions in their studies, respectively. This is due to the increased input of organic substances (fiber residues in the diet; increased fecal volume; increased amount of microorganisms) into the barn and the slurry pit (BLE, 2019). In the studies conducted within the context of this work, methane emissions could only be insufficiently assessed due to technical circumstances. An adequate evaluation was therefore not possible, so that no statements can be made about methane emissions. Due to the described environmental relevance of methane, it is necessary to consider and evaluate this important aspect in further studies for a complete evaluation of the presented feeding system. The advantages of an increased use of fiber have already been explained. Likewise, ammonia emissions could be reduced in the studies presented. A potential increase in methane emissions could be counteracted with other emission-reducing interventions. Shin et al. (2019), for example, were able to significantly reduce methane emissions by acidifying liquid manure. Other possibilities to mitigate methane emissions include covering the liquid manure storage or fermenting organic residues in biogas plants. The conflicting objectives described above make it difficult to develop a holistic approach that addresses the aspects of animal welfare, environmental protection and consumer protection in equal proportions. Compromise solutions and the combination of several approaches and processes are therefore generally necessary (BMEL, 2017).

Several studies describe the influence of increased amount of fiber in the diet on the fecal quality and quantity of pigs (Canh et al., 1998; Ebertz et al. 2020; Massé et al., 2003). Thus, an increased fecal volume is attributed on the one hand to the increased water binding capacity of fiber. Furthermore, it is attributed to an increased proportion of undigested fiber components in the feces (Massé et al., 2003). In their studies on *ad libitum* silage feeding in sows, Ebertz et al. (2020) observed, on the one hand, an increased amount of feces and, on the other hand, an increased soiling of the pen surface. They concluded that there is a direct relation between increased feces and increased surface contamination. Furthermore, they described that the feces is more difficult for the animals to push through the slatted floor due to changed consistency, which also results in increased surface soiling and increased occlusion of the slats (Ebertz et al., 2020). The cleanness of the pens has an influence on animal welfare and animal health (Hutson et al., 1993; Wiedmann et al., 2011), as well as on the ammonia emissions generated in the barn (Aarnink, 1997; Austermann, 2016).

The investigated feeding system is designed for use in large group housing systems of fattening pigs. In a large group, structuring the pen and creating functional areas is much more possible for the animals than in pens of small group housing systems (KTBL, 2011). Especially a clear, spatial separation of the feces area is only possible to a limited extent in pens for small groups. Thus, an increased degree of soiling of the pen can result in an increased degree of soiling of the animals (Ebertz et al., 2020). Due to the described aversion of pigs to their own excrement (compare chapter 1.1.2.4), this should be prevented for reasons of animal welfare and to promote their natural behavior. Furthermore, permanent contact with excrements and thus moisture can lead to claw diseases (von Borell & Huesmann, 2009). The microbial exposure, and thus the infection rate with, for example, salmonella, are increased as well (Roesner et al., 2014). The surface contamination evaluations carried out as part of study 1 showed that the increased use of fiber did not result in increased contamination of the surfaces. Thus, the results do not agree with the findings of Ebertz et al. (2020). When comparing the studies, it should be noted that fattening pigs in large groups were examined here, whereas Ebertz et al. (2020) examined sows kept in small groups. The spatial structuring in the large group and the larger surface area may have result in less excrements per surface area unit, so that it could be better passed through the slats. The used fiber source (triticale whole plant silage vs.

maize silage) may also have had an influence, as these differ in nutritional characteristics (Kamphues et al., 2014).

Nevertheless, there are opportunities to counteract possible increased pollution due to higher crude fiber contents in diet. For example, regular flushing of surfaces could improve floor cleanliness. However, increased water consumption and thus increased volumes of liquid manure to be stored have to be taken into account. As a new approach in pig farming, Ebertz et al. (2019) investigated the use of a robot scraper in group-housing of sows. Thus, the floor cleanliness could be significantly improved. Especially in large group housing, as used in the investigated feeding system, such automated cleaning technologies could be used to counteract the risk of an increased degree of contamination. However, until now, these technologies have mainly been used in cattle farming (Ebertz et al., 2019). Due to the already described positive effects of a better barn cleanliness, science and industry should consider new solutions for pig farming.

Based on the evaluations of the surface area in study 1, the functional areas created by the animals could be clearly traced and differentiated. While the fecal areas were mainly located along the outer walls, the inner surface areas of the pen and the feeding areas were predominantly clean and dry, and were used by the animals as lying/activity areas. As described in the introduction (see chapter 1.1.2.4) this corresponds to the physiological behavior of pigs. When constructing barns, the aspect of pen structuring to increase animal welfare should not be disregarded (BLE, 2019). It can be assumed that the tested feeding system, beside other already described factors, contributes to increasing animal welfare through its technical and structural implementation in the barn (large group; spatial separation of different areas). In addition to the positive effects on animal welfare, large group housing with sorting gate also has economic advantages compared to other housing methods (KTBL, 2011). Savings in investment costs of 9% compared to small group housing are described. There are also savings in working hours due to automation, e.g. when selecting using the sorting gate. The savings in working time outweigh the additional work required due to more intensive animal control and maintenance work on the sorting gate, so that the total labor time is lower compared to small group housing (KTBL, 2011).

The results of studies 1 and 2 showed that there are individual differences in the feed intake capacity and nutritional requirements of the individual animals and that feeding according to performance groups is desirable for the previously described reasons. For implementation in the agricultural practice, a technically sufficient method is still lacking that makes it possible to non-invasively measure the back fat and back muscle thickness of the animals and thus automatically divide them into performance groups. The ultrasound examinations used for this purpose in studies 1 and 2 can be used in the trials, but are not suitable for permanent practical use, as each animal has to be examined manually. In addition, the ultrasound sensor must be in contact with the animal in order to perform the measurement. In daily practice, this procedure causes stress for the animals, which should be avoided for reasons of animal welfare (FAWC, 1979). Study 3 therefore dealt with the possible use of infrared thermography to classify animals into performance groups. The idea of the study was that animals of different body condition differ in their body surface temperature due to the different thermal conductivity of fat and muscle tissue (Cohen, 1977; Lipkin & Hardy, 1954). These differences should be made visible by thermal imaging. As a non-invasive method, thermography would be particularly advantageous for use in practice. Thermography is already being used in other areas of animal husbandry and in veterinary medicine. In ruminant medicine, for example, it is used to detect inflammation of the claws or mastitis (Röhlinger et al., 1979). Inflammations in particular can be detected at an early stage due to temperature changes (Baumgärtner & Gruber, 2015) and can thus be treated prematurely. There have also been studies in pig husbandry and medicine on the detection of inflammation based on thermal images. Traulsen et al. (2010), for example, describe the possibility of identifying the mastitis-metritis-agalactia complex in sows. Other studies deal with the hot spot detection of e.g. tail lesions in fattening pigs (Teixeira et al., 2020).

For the application with the intention described in study 3, there are no comparable studies in the literature. It was therefore not possible to rely on already proven methods when carrying out the experiments. Since the study was carried out with the intention of being able to combine thermography measurements with the sorting gate in the future, the animals were investigated with the infrared camera from above, inside the sorting gate. The same localization on the animal body was also chosen to enable comparability with the ultrasound examinations. Various parts of the pig's body have already been examined thermographically to show the body temperature (Boileau, 2018). It cannot be excluded that a classification of the performance groups is possible by measurable differences in body condition on other locations. This would have to be investigated further in future studies, as it was not possible to classify groups on the basis of the measurements taken on the backs of the animals in study 3.

There are also different methods for evaluating the thermograms (Glas, 2008). For this reason, two methods were compared in study 3. It remains to be assessed whether the body surface temperature is better determined on the basis of the largest possible area on the animal, which is thus more representative of the entire animal. Or whether a standardized measuring spot is used, which is less susceptible to interferences due to its smaller size, but less representative for the whole animal.

In the study presented, thermal images were taken manually on three measurement days during the fattening period. A permanent combination of a thermal imaging camera with the sorting gate would enable continuous data collection. As the animals pass through the gate several times a day to reach the feeding area, daily profiles of the body surface temperature of the pigs could be created. Changes in temperature could then be better detected. Possibly, continuous data collection could be used in future studies to identify even more precise correlations between body surface temperature and body condition, as shown in study 3. A permanent recording of body temperature could also be used in other contexts and offer advantages. For example, visible temperature changes could be used to detect diseases or injuries of the animals at an early stage. One possible application would be to detect tail biting (Teixeira et al., 2020) at an early stage so that intervention can be taken in time. The data could also allow conclusions to be drawn about the stable climate and, for example, detect hyperthermia as indicator for heat stress in the animals (Ricci et al., 2019). As the investigations in study 3 showed, the thermal images can also be used to detect and evaluate the soiling of the animals. In this way, the degree of soiling of the animals could be used to draw conclusions about the cleanliness of the barn, which in turn would provide important information about the barn climate and animal welfare. Thermography in combination with a sorting gate has great potential with regard to animal health monitoring. The described possible applications could thus all contribute to an increase in animal welfare. However, as the presented study and other studies (Glas, 2008; Röhlinger et al., 1979; Schaefer et al., 2004) have shown, there are many external influencing factors that need to be considered and recorded. In future studies, these parameters and the potential applications need to be further investigated in order to make this technique practicable for permanent application in the barn.

5.2 Final Conclusion

In conclusion, based on the research and knowledge presented in this thesis, it can be stated that the investigated feeding system offers a new approach of feeding fattening pigs, which allows to consider and compensate the existing discrepancy in the supply of fattening pigs. As the results showed, differences in the nutritional needs and development of the animals can be taken into account more effectively through the assessment of body condition parameters, the use of performance groups and an increased use of fiber in the diet.

As previously discussed, the feeding concept has the potential to have a positive impact on the environment, economy and animal welfare. The positive effects on the environment, due to ammonia reduction, and economy, e.g. due to savings in feed, has already been demonstrated by the studies described. However, there are missing data concerning further environmentally relevant effects, e.g. methane emissions. Agricultural science must investigate these environmental effects and, if necessary, develop new approaches to counteract potential negative effects of the new feeding system.

In contrast to the environmental aspects, only few conclusions could be drawn regarding the positive influence on animal welfare, e.g. through the use of fiber. Also, comprehensive studies on animal health in context with the new feeding system are still lacking. Agricultural sciences and veterinary medicine have the responsibility to close these knowledge gaps in future studies in order to be able to evaluate the feeding concept with regard to these important aspects.

The investigations showed that the principle of body condition based performance groups is desirable. However, a technically mature possibility to apply the system in practice is still missing. An automated classification of the animals into the appropriate groups is not feasible right now. The agricultural industry must work on a technical solution here as soon as possible in order to be able to exploit the demonstrated potential of the feeding system.

A possible use of IRT in combination with the sorting gate technology was investigated in this thesis. Even if the desired results could not be achieved, IRT offers great potential for monitoring animal health. Further research should also be conducted in this area in the future from both, veterinary and agronomic perspectives, to further expand the use of IRT in fattening pig husbandry.

A major deficit in existing fattening pig husbandry and feeding systems is the lack of a closed-loop system with information feedback. While individual animal identification has long been mandatory in cattle farming, fattening pigs are not individually identified, due to economic reasons. But only if the information collected, for example on health status or body condition, can also be assigned to the animals, it is possible to control success and use the information with maximum efficiency. A rethinking must take place here, so that not only the additional costs, for example through RFID ear tags, are considered, but also the advantages of information acquisition and the resulting savings potential. Besides information on body condition and development, e.g. animal activity and feed intake behavior within the large group, which is otherwise difficult to monitor, could also be recorded. In addition to the current techniques for animal identification through transponders, new technologies could also be considered here, for example, the individual recognition of animals through camera systems, face recognition or similar.

However, modern agriculture without technical support systems is hardly possible nowadays and has become necessary in many areas in order to achieve the high demands placed on agriculture. Nevertheless, research and agricultural industry should work to improve existing technical systems. Only through research and further development it will be possible to find solutions for the existing conflicts of interests in agriculture and to combine the interests of animal welfare, environmental protection and economy in livestock husbandry.

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