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Review article

Impact of forage feeding and grazing on behavior, health, and performance of pigs

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HIGHLIGHTS

- Forages are underestimated feed materials for pigs.
- Forages can contribute to pig nutrition and welfare.
- Pasture husbandry affects production parameters.

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ABSTRACT

Current pig production systems rely on compound feeds with high densities of energy and nutrients to optimize production performance. Several challenges are associated with those feeding practices, which are mainly based on processed cereals, grain legumes, and oil seeds. Compound feeds are often presented in forms that can inhibit natural feeding behavior and impede gut health, both having negative effects on pig welfare. Furthermore, feeding pigs with products, which could also be used directly for human nutrition, is criticized to increase the competition with food in terms of available calories, proteins and arable land. Human-inedible forages and pasture play a marginal role in the nutrition of pigs, and are mainly found in organic production systems. However, there are studies indicating that feeding forages can improve animal welfare and contribute to the nutrition of pigs. The aim of this review article is to summarize the effects of forage feeding and grazing from available studies on pig behavior, animal welfare, production performance, product quality, and the environment and shed light on the possible contribution of forages and pasture to the nutrient supply in the nutrition of pigs.

1. Introduction

Pigs have evolved as opportunistic omnivores with a preference for foraging (Andresen and Redbo, 1999). For instance, feral pigs on Hawaii exhibit a broad dietary niche including C4 grasses (Peyton et al., 2024) and Molnár et al. (2024) described pigs as 'Gourmet omnivore', whose diet also includes herbs, weeds, grasses, leaves and twigs. The digestion of pigs is adapted to their omnivorous diet, allowing them to efficiently utilize both plant and animal-based feeds. Among them, forages can provide a valuable contribution to the nutrition of pigs and help to promote the pigs' natural behavioral repertoire (Studnitz et al., 2007), gastric health (Friman et al., 2024) and intestinal health (reviewed by Wenk, 2001).

In modern pig production systems, growth rate and feed efficiency are most important for farmers. Accordingly, fibrous feedstuffs with lower digestibility and high labor input, like forages, have not been favored. On the contrary, grinding and pelleting of feedstuffs are common procedures to enhance feed intake and increase digestibility. However, decreasing particle size has been associated with gastric lesions and ulcerations (Vukmirović et al., 2017). Furthermore, these processed feedstuffs and restrictive feeding strategies do not promote natural rooting or foraging behavior. The inability to perform this behavior can lead to stereotypical and aggressive behavior as reviewed by Hoorweg et al. (2022). Providing fibrous feedstuffs, on the other hand, has been shown to positively affect pigs' behavior (Holinger et al., 2018a), improve intestinal health and prevent the development of gastric ulcers (Friman et al., 2024; Holinger et al., 2018a, b).

The integration of catch crop biomass in pig nutrition is inherently

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linked to crop rotation strategies. Cultivating catch crops – especially small-grained legumes – is beneficial from the perspective of agronomy and environment, improving biodiversity (Karlsson et al., 2022), increasing soil humus content and water retention capacity and reducing the reliance on mineral fertilizer (Zira et al., 2023). At the same time, these crops generate substantial amounts of green biomass in form of legume forages and pasture, which may further contribute to the amino acid supply of pigs (Edwards, 2003; Kyntäjä et al., 2014). Thus, this non-human-edible biomass can be integrated into pig diets, serve as a nutritionally valuable diet component and replace human-edible components effectively decreasing feed-food-competition, which is an increasingly discussed topic in animal nutrition science (Pexas et al., 2023; Pinotti et al., 2025; Schader et al., 2015; Vlaicu et al., 2024). To gain deeper insight and assess the current state of research on forage and pasture feeding in pig nutrition a comprehensive literature review was conducted. This included evaluating the effects of forage feeding on pig behavior and gut health, summarizing relevant legal frameworks for Switzerland, the USA, the EU and Germany, specifically, compiling available data on nutrients in forages, and discussing the effects of forage feeding on growth, reproduction, product quality and the environment.

In this review the term “forage” is defined as vegetative material in a fresh, dried, or ensiled state; it includes the leaves, stems, and stalks of plants.

2. Forages and pig welfare

The World Organisation for Animal Health defines animal welfare as “the physical and mental state of an animal in relation to the conditions in which it lives and dies” and states that animals under human control should be free from hunger, malnutrition and thirst, fear and distress, heat stress or physical discomfort, pain as well as injury and disease and free to express normal patterns of behavior (WOAH 2025). Animal welfare, thus, includes behavioral and health aspects. Several aspects of pig welfare can be affected by forages: e.g., feeding motivation, behavioral expression, digestive physiology and emotional states.

Forage feeding and grazing can influence pig behavior and gut health in particular and, thus, contribute to pig welfare.

2.1. Behavioral aspects of forage feeding and grazing

Pigs perform rooting, i.e., exploration and foraging, as innate behavior for many reasons: searching for food, looking for bedding materials, finding a place to lie down or simple curiosity about their living area (European Commission, 2016). The exploration will persist until a more intense need occurs and the importance of the exploration behavior increases under restrictive feeding as reviewed by Studnitz et al. (2007). When the pigs’ needs, including the need for exploration, are not fulfilled, adverse behavior, e.g., tail biting, can result. The risk to develop adverse behavior can be considerably reduced, though, by supplying appropriate enrichment materials. Forages are generally considered as proper enrichment materials for pigs, as they are chewable, odorous, deformable and destructible. They have been associated with prolonged exploratory behavior compared to objects such as chains or tires (Bracke et al., 2006; Scott et al., 2009; Van de Weerd et al., 2003; Van de Weerd and Day, 2009). With regards to edibility and chewability (in addition to investigation and manipulation as well as feed safety qualities), the European Commission (2016) classified straw and silage as optimal enrichment materials.

The provision of forages is observed to increase activity behavior as well as exploratory behavior (Holinger et al., 2018a; Høøk Presto et al., 2009). Holinger et al. (2018a) reported that growing pigs provided with grass silage showed a higher probability of engaging themselves with the silage or straw litter than pigs provided only with straw. This was validated by results of a study by Machner et al. (2025), who compared the effects of straw and whole plant vetch silage as forage on the behavior of growing pigs. Presto Åkerfeldt et al. (2018) found that the extrusion of clover-grass silage reduced feed sorting and promoted a more uniform intake. This was confirmed by Friman et al. (2021), in whose study the extruded feed was consumed entirely. In contrast, coarse feed structures (e.g., chopped material or intact silage) can lead to pronounced feed sorting behavior by the animals (Wallenbeck et al., 2014). The production type of forages as well as the feeding management can, thus, have a considerable effect on their acceptance.

A study conducted by Tozawa et al. (2016) showed that an outdoor pasture led to increased foraging behavior compared to indoor housing or a concrete floor outdoor run and that the provision of fresh grass or a soil floor in the outdoor run also have the ability to increase foraging behavior. Moreover, the provision of forages leads to a decrease of aggressive behavior, like fighting among two or more pigs (Høøk Presto et al., 2009). This effect occurs independently of the type of forage, which was confirmed by Holinger et al. (2018b), Friman et al. (2024) and Machner et al. (2025), who reported that neither aggressive behavior nor skin lesions were influenced by the type of forage provided.

Another starting point for research into the use of forage feeding to sows is its role in preventing obesity through restrictive feeding, which may otherwise lead to insufficient satiety and the development of stereotypical behavior. According to Becker et al. (2003) grass, grass silage, hay, and corn silage ensure mechanical saturation by gut filling of gestating sows. Aubé et al. (2019) observed that sows choose forage with low contents of neutral detergent fiber (NDF) as well as high contents of crude protein (CP) and non-structural carbohydrates. The sows were more prone to eating fresh forage than hay and preferred leguminous plants over grasses and timothy grass over tall fescue. Makalani et al. (2025) observed a significant reduction of stereotypic behavior, like manipulating pen fixtures or sham chewing, in sows, which have been pregnant for 45 to 85 days and were fed a diet with 20 % DM replaced by red clover silage and Ebertz et al. (2020) reported that gestating sows fed whole crop maize silage were quieter and more occupied than sows fed a restricted dry feed. In indoor husbandry systems, forage inclusion can thus be used to serve the demand for rooting material and increase satiation, and can thereby effectively decrease adverse behaviors.

Outdoor systems are commonly considered beneficial for pig welfare, as they allow pigs to express their natural exploratory behavior. Outdoor pig production is often seen as especially animal-friendly. Challenges regarding production and animal welfare in pasture-based systems have been reviewed comprehensively by Pietrosemoli and Tang (2020) and Delsart et al. (2020), who reported risks for animal health from extreme temperatures, contact with wildlife, pathogens and parasites, predators and malnutrition. Exposure to sun without protection can additionally pose a risk of sun burn (Buijs et al., 2025). Amarie et al. (preprint 2024) reported that the choice of breed can be relevant in the context of pasture husbandry. Overall, the complexity of management processes can increase health risks in these systems. However, with good management, pasture-based pig husbandry systems have been shown to improve animal health. All-year outdoor-systems displayed several advantages regarding different health parameters, e.g., respiratory or digestive diseases, compared to indoor, or part-outdoor husbandry systems in a study of Leeb et al. (2019). Buijs et al. (2025) observed generally good health in grassland and agroforestry systems, which, nevertheless, cannot be attributed to forage intake alone but depends on multiple criteria. The use of pasture for grazing and foraging by pigs is affected by the supplemented feed, the quality and composition of the sward, the weather, the age of the pigs, the diurnal rhythm as well as the stocking density. In general, pigs on pasture show more activity and foraging behavior and less sniffing, nibbling, pushing and tail manipulations than pigs held indoor (Høøk Presto et al. 2008). This might be attributed to the larger space, the possibility to conduct rooting behavior or the pasture composition. Iberian pigs in the Dehesa spent 61.3 ± 1.3 % and 71.2 ± 2.3 % of the observation time foraging, including grazing, which corresponds to more than 54 % of their daylight hours (Rodríguez-Estévez et al., 2009). Rivero et al. (2013)

observed in an experiment with European wild boar, that the animals spent 42.4 % of their time grazing, with 62 % of this activity occurring in the first three hours after giving access to the pasture. The pasture consumption and grazing behavior did not differ between continuous and rotational grazing systems over a five-day period. However, adjusting the grazing period to this observed grazing pattern might enhance feed intake from pasture and affect sward quality. Andresen and Redbo (1999) observed that growing pigs have a priority for grazing, when clover-grass of good quality is available.

Pasture consumption can be influenced by the amount of supplementary feed provided. In gestating sows, more rooting was observed when the compound feed fulfilled 90 % of INRAE (French National Research Institute for Agriculture, Food and Environment) recommended energy intake, while more grazing and activity behavior was observed, when the compound feed fulfilled only 40 % of INRAE recommended energy intake (Aubé et al., 2021a). These findings suggest that sows increased foraging activity to compensate for an energy deficit (Aubé et al., 2021b). This was also observed by Stern and Andresen (2003), who reported that pigs supplied with 80 % of the recommended feed allowance for indoor housed pigs showed generally more rooting and grazing behavior than fully fed pigs. Although Andresen and Redbo (1999) found no effect of the CP content of the in the feed on foraging behavior, it can be inferred from the study of Horsted et al. (2012), in which growing pigs were provided with 10 % more compound feed than recommended that pigs show negligible grazing activity (0.5 %) when their nutritional requirements are fully met by concentrate feeding. Consequently, it is difficult to determine, if the grazing and rooting behavior occurs to satisfy natural behavioral needs or if it is caused by hunger and frustration, when animals are not satiated and require further nutrients.

Temperature and humidity also affect the rooting behavior of pigs. At lower temperatures foraging behavior increases (reviewed by Olczak et al., 2015), whereas hot weather shifts behavioral priorities towards drinking and can reduce foraging/eating (Rodríguez-Estévez et al., 2009; Andresen and Redbo, 1999). Moreover, Andresen and Redbo (1999) observed that increased stocking density reduces eating behavior. The authors attributed this effect primarily to a reduced availability of fresh herbage per animal at higher stocking densities, which limited grazing opportunities and thereby influenced overall feed intake patterns.

In summary, the extent to which forages are consumed and grazing is performed is affected by several factors including climate and the amount of compound feed provided. Nevertheless, the inclusion of forages in the diet or the use of pasture in pig husbandry improve the possibility for pigs to express normal behavioral patterns and, thus, contribute strongly to animal welfare. This effect might be strengthened by a positive effect on gut health.

2.2. Effects of forage feeding on gut health

Gastric ulceration affecting the non-glandular gastric mucosa is a common problem in the swine industry, with economic losses due to sudden deaths and decreases in growth performance (Ayles et al., 1996; Dunlop et al., 2021; reviewed by Krepelková et al., 2024). Cybulski et al. (2021a) reported that the occurrence and negative welfare effect of gastric ulcers in sows may be underestimated. Diet has long been identified as one key factor influencing stomach health and ulceration (Gamble et al., 1967). A recent polish study investigated 32′264 stomachs of finishing pigs after slaughter in an abattoir of which 71.9 % were found to have gastric lesions and 54.9 % had ulcers (Cybulski et al., 2021b). The authors concluded that feed protein level and pelleting increased the risk for stomach diseases, whereas fiber-rich wheat bran was associated with a decreased risk for stomach ulcers. A prevalence for pars esophageal ulcers of 35.5 % has been reported for nursery pigs fed commercial diets (Peralvo-Vidal et al., 2021). The fraction of very fine particles (<0.4 mm) has been shown to play an important role in the onset of ulceration and an upper limit of fine particles seems necessary (Grosse Liesner et al., 2009). A study with finely and coarsely ground feed in meal and pelleted form demonstrated the effects of particle size on the intragastric milieu with higher pH-values in the non-glandular gastric area with coarsely ground feed in unpelleted form and lower pH and lower DM content with finely ground feed (Mößeler et al., 2010). These observations confirmed results obtained by Regina et al. (1999) and Ange et al. (2000), who assumed that more fluid digesta, resulting from finely ground feed, can allow the reflux of irritants from the distal stomach to damage the pars esophageal region. Fibrous feeds, on the other hand, have a high water-holding capacity that slows down the passage rate in the stomach (Friman et al., 2024). A protective effect of solid gastric content has been observed when the gastric content solid phase percentage was higher than 52.6 % (Peralvo-Vidal et al., 2021).

Studies investigating effects of forage feeding with larger particles in the range of several mm to several cm on pH gradients in the stomach of pigs are missing. But forage (pasture) feeding was shown to reduce the development of gastric ulcers (Gamble et al., 1967), even under conditions of chronic stress when the risk for gastric ulcers is higher (Holinger et al. 2018a). However, no beneficial effects were seen when the forage was milled and mixed with commercial feed and fed as a pellet (Friman et al., 2024), indicating the importance of particle size. Straw ingestion has also been shown to improve stomach health by increasing DM content and enhancing the structure of the stomach content (Jensen et al., 2017). Furthermore, it was reported that the inclusion of sugar beet pulp in the diet of growing pigs reduced the development of gastric ulcers (Badaras et al., 2022; Grimm and Julliand, 2021; Laitat et al., 2015).

Dietary fiber can promote gut peristaltic and reduce the risk of digestive problems such as constipation as reviewed by Wenk (2001). There is an increasing number of studies focusing on the effects of dietary fiber on the hindgut microbiome, but only few studies used forages as a fiber source. Especially in early life, gut health can be regulated by including fiber sources like alfalfa (Mu et al., 2017). Increasing the levels of dietary fiber has been associated with an increase of bacteria with cellulolytic and hemicellulolytic activities in growing pigs (Metzler and Mosenthin, 2008) and studies revealed an increase of potentially beneficial bacteria in the large intestine, as shown in weaning piglets (Chen et al., 2013), suckling piglets (Zhang et al., 2016) and finishing pigs (Niu et al., 2022). Feeding whole plant corn silage (WPCS) was shown to increase fecal microbial diversity, with possible beneficial health effects by decreasing potential pathogenic bacteria (Yin et al., 2024). Beneficial effects are associated with butyrate producing bacteria present in the colon, as shown with the inclusion of limited amounts of alfalfa (1.3 %) or pure cellulose (1 %) in diets for suckling piglets (Mu et al. 2017). Grass silage was observed to reduce the occurrence of Clostridium perfringens in the feces of pregnant sows (Schubbert et al. 2010). In addition, certain fiber sources in the diet of piglets have been shown to improve the intestinal barrier function by up-regulation of tight junction protein (zonula occludens 1; ZO-1) and Toll-like receptor 2 (TLR2) gene mRNA levels (Chen et al., 2013). Although more research is needed to investigate the effects of particle size and fiber source on the gut microbiome and gut health, the reviewed literature indicates a positive effect on gut health of intact fiber sources, i.e., forage and pasture.

2.3. Legal framework concerning forages in pig husbandry

Forages are feedstuffs listed in the European feed materials register (2025) and the German Positive List for Straight Feeding Stuffs (DLG, 2023) and underlie all regulations for maintaining feed security. In the European Union (EU), according to Council Directive 98/58/EC (EC, 1998) on the protection of animals kept for farming purposes animals need to be provided with “a wholesome diet which is appropriate to their age and species and which is fed to them in sufficient quantity to maintain them in good health and satisfy their nutritional needs”. Furthermore, Sather et al. (1997) and Council Directive 2008/120/EC

(2008) lays down minimum standards for the protection of pigs and requires pigs to be provided permanently with “a sufficient quantity of material to enable proper investigation and manipulation activities, such as straw, hay, wood, sawdust, mushroom compost, peat or a mixture of such, which does not compromise the health of the animals“. The German Animal Welfare Livestock Farming Ordinance (TierSchNutztV, 2001) states that organic, fiber-rich foraging material must be available in a sufficient quantity for pigs at all times. In Switzerland, similar information can be found in the legal framework addressing pig husbandry and feeding. The Animal Welfare Act (AniWA, 2005) requires that the well-being of animals is supported, meaning that the “bodily functions and […] behaviour [of the animals] are not disturbed and excessive demands are not made on their capacity to adapt” (AniWA, Art. 3 and 4). In the Swiss Animal Protection Ordinance (AniPO, 2008; Section 3: Pigs, Article 44) it is stated concretely that “Pigs must have access at all times to straw, roughage or other equivalent foraging material”. Contrary to that, pigs are not mentioned in the Animal Welfare Act of the United States (1966) and no federal laws regulating farm animal husbandry regarding farm animal welfare are in use. Nonetheless, some states have their own husbandry and welfare regulations and some private agreements are in use.

Additional regulations apply for organic pig husbandry. In the US, the National Organic Program (NOP, Title7 Part 205), which is administered by the United States Department of Agriculture (USDA, 2000), sets specific requirements for organic animal husbandry and requires that organically kept swine must be provided with rooting material. In organic farming in the EU and in Switzerland, it is also mandatory to provide pigs with forage. The forage must be derived from organic production, i.e., without GMO, mineral and synthetic fertilizers, and pesticides (Regulation EC 2018/848 and implementation regulations; Swiss Organic Farming Ordinance by the Swiss Federal Council, 2025; NOP of the USDA, 2000). Privately organized organic farming associations can set even stricter requirements.

The use of pasture is strictly regulated due to the need to prevent epidemics transmitted by wildlife. The German pig husbandry hygiene regulation (SchHaltHygV, 1999) regulates that animals, litter and feed must not have contact with wildlife, especially wild boars. However, in organic production systems in Europe, pigs, like all livestock, “shall have permanent access to open air areas that allow the animals to exercise, preferably pasture, whenever weather and seasonal conditions and the state of the ground allow” (2018/848 EU, Annex ll, Part 2, General requirements, 1.7.3; EC, 2018).

Overall, no comprehensive legal framework regarding the use of forages including pasture in the nutrition of pigs exists. Although some regulations in the considered countries already deliberate the pigs’ needs for rooting material and environmental enrichment and point out the superiority of forages, the implementation on the farms is not completed to date. Taking into account the nutritional value of forages for pigs, implementing their use might get more interesting for farmers.

3. Nutritional value of forages used in pig feeding

Although forages can be fed without further processing, i.e., as freshly cut material or by grazing on pasture, in most areas fresh forages are only available during parts of the year. To ensure a year-round supply, the feed has to be preserved after harvest, which can affect its feed value. The main preservation methods include wilting and drying in the field for hay production, hot air drying and pelleting, as well as ensiling through lactic acid fermentation. The studies evaluated in the present review article conducted feeding trials with fresh or preserved whole plants of alfalfa, clover-grass mixtures, vetches and whole-plant corn silage. Other forage species such as white or red clover, chicory, dandelion or arable forage mixtures were reported in individual studies but were not available in sufficient detail for structured comparison. Table 1summarizes the nutritional composition of overground biomass from legumes and grasses and displays the in vivo apparent total tract digestibility (ATTD) of the forages in studies conducted with indigestible markers. The presentation of nutrient values focuses on dry matter (DM), crude protein (CP), crude fiber (CF), lysine and methionine, as these parameters are most consistently reported and relevant for comparability across forage types.

Concentrations of CP in fresh alfalfa of the reviewed studies ranged from 197 to 299 g/kg DM, with lysine levels between 7.6 and 18.0 g/kg DM and CF contents between 217–313 g/kg DM (Blume et al., 2021; Wüstholz et al., 2017). Ensiled alfalfa displayed CP contents ranging from 213 to 231 g/kg DM (lysine 10.8 - 13 g/kg DM; CF 236–327 g/kg DM) (Wüstholz et al., 2017; Weltin et al., 2014; Messinger et al., 2021; Weber et al., 2024). In vivo digestibility of alfalfa is strongly affected by the preservation method. Messinger et al. (2021) demonstrated that dried alfalfa leaves with 198 g/kg DM CP and 9.4 g/kg DM lysine exhibited an in vivo CP digestibility of 42.7 %, whereas ensiling increased CP digestibility to 56.3 % in whole-plant silages. According to Weber et al. (2024), ATTD of organic matter (OM) and CP in silages derived from the top part of the plant exceeded that of whole-plant silages by 23 % and 30 %, respectively.

Alfalfa is generally considered difficult to ensile due to its high CP content, high buffering capacity and low levels of water-soluble carbohydrates (WSC, Gao et al., 2021). According to Wüstholz et al. (2017), ensiling chopped alfalfa reduced CP content by approximately 25 % and lysine content by 33 %, while CF concentrations increased by 50 % compared to the fresh forage. Liebhardt et al. (2019) observed moderate CP reductions of approximately 8–12 % during ensiling of alfalfa leaves without additives. In contrast, Szumacher-Strabel et al. (2019) reported no significant changes in CP and CF contents after ensiling whole alfalfa plants. The use of additives such as molasses (Guo et al., 2008) or combining alfalfa with red clover (Li et al., 2018) has been shown to improve silage quality and amino acid preservation (Liebhardt et al., 2019). By comparison, air drying and pelleting maintained stable protein and lysine concentrations (Blume et al., 2021; Weber et al., 2024).

In addition to preservation-related effects, plant-specific ingredients can also influence nutrient utilization. Saponins are secondary plant compounds produced by alfalfa. Elevated concentrations in leaves may contribute to decreasing the digestibility of alfalfa leaf silage as observed by Messinger et al. (2021). Saponin contents are variety-dependent and both, concentration and composition, may change during ensiling (Kalač et al. 1996; Szumacher-Strabel et al., 2019).

Clover-grass mixtures represent another relevant forage category. Freshly cut samples of clover-grass contained 199–284 g/kg DM CP, 10.8–15.6 g/kg DM lysine and 180–359 g/kg DM CF (Carlson et al. 1999; Eskildsen et al., 2020; Jørgensen et al., 2012; Roth and Reents, 2001).

Jørgensen et al. (2012) reported an ATTD of OM of 78 % and CP of 76 % for clover-grass silage at 10–12 % DM inclusion, whereas Presto Åkerfeldt et al. (2018) observed a wider range (8.1–16.8 %) at 20 % DM inclusion, most likely due to methodological limitations of the difference method and the young age of pigs rather than inherently poor digestibility. Eskildsen et al. (2020) reported a digestibility of 64 % of OM and 71 % of nitrogen in fresh clover, based on regression analysis using total collection. These values cannot be directly compared to marker-based ATTD results but nevertheless indicate a moderate to high utilization potential of clover-grass.

Preservation effects on clover-grass were not major: the focused values (CP, CF, lysine) remained largely stable during the ensiling of clover-grass (Carlson et al. 1999; Jørgensen et al., 2012; Roth and Reents, 2001). A higher WSC fraction in clover-grass mixtures, when compared to other forages, has been reported by Jørgensen et al. (2012) and may enhance fermentability in the hindgut and ensure adequate ensiling.

Vetches add a further legume forage with emerging data in pig nutrition. Whole plant vetch silages exhibited CP concentrations ranging from 169 to 211 g/kg DM, lysine concentrations of 8.7–10.4 g/kg DM, and CF contents between 194 and 305 g/kg DM depending on the

Table 1
Nutritient composition and total tract digestibility of organic matter and crude protein in pigs of overground biomass from legumes and grasses– overview over reviewed studies.

Forage	Processing	DM[a] (%)	CP[b] (g/kg DM)	CF[c] (g/kg DM)	Lys[d] (g/kg DM)	Met[e] (g/kg DM)	ATTD[f] OM[g] (%)	ATTD CP (%)	
Alfalfa	Freshly cut	17.9	299	217	18.0	5.3			1
	Dried		197	313	7.6	2.1			2
	Dried, pelleted		224	298	7.6	2.2			2
	Wilted, whole plant		204		11.7				3
	Silage, chopped	45.0	225	306	12	3.3			1
	Silage, chopped	45.0	225	306	12	3.3			4
	Silage, extruded	41.4	231	327	13	3.1			1
	Silage, extruded	41.5	231	327	13	3.1			4
	Dried, leaves (cobs)		198	218	9.4	2.9	45	42.7	5
	Wilted, leaves		265		16.3				3
	Silage, leaves		295	133	5.7	2.9	63	58	5
	Silage, leaves			107	2.1	2.8			6
	Silage, plant tips	34.0	267	139	13.4	4.3	69.5	68.8	7
	Silage, whole plant		213	236	12.7	3.4	53.6	56.3	5
	Silage, whole plant	32.6	216	203	10.8	3.4	56.5	52.9	7
	Air dried		207	293	7.7	2.1			2
	Air dried, plant tips	92.6	274	193	12.8	4.5	64.4	60	7
	Pellets		205.7	263	7.7	2.3			2
Red clover	Wilted, leaves		268		16.9				3
	Wilted, whole plant		203		11.4				3
	Silage		263	178	15.1	4	69.9	69.3	5
	Silage		158	244					8
	Silage			104	8.6	3.7			6
Clover grass	Fresh		241		10.8	3.6			9
	Fresh	13.3	230	180					10
	Fresh	12.5	199				79	76	11
	Fresh	16.3	284	359	15.6	4.5			12
	Silage, chopped	34.0	183		7.3	2.88			13
	Silage, chopped	32.5	190				23.6	8.1	8
	Silage, extruded	35.0	178		6.9	2.7			13
	Silage, extruded	33.2	187				31.1	16.8	8
	Silage		169		6.1	2.3			9
	Silage		143	287					14
	Silage	37.6	223	186					10
	Silage	33.2	181				78	76	11
	Silage	16.9	143						15
	Dried (75 % Red clover)	87.7	149						16
Vetch	Silage *V.* [h] *pannonica* whole plant	29.5	169	305	8.7	2.3	51	55	17
	Silage *V. sativa* whole plant	25.0	211	211	10.4	2.5	66	70	17
	Silage *V. villosa*, whole plant	36.3	194	194	9.1	2.4	60	65	17
Pea-Barley	Silage, Whole-crop	30.5	117				76	75	11
Pasture	Rye grass - Red clover	185	197						18
	40 % Red clover	17.4	176						16
	Alfalfa	30.1	301		17.0				19
	Rye grass	13.5	135		7.0				19
	Field grass	18.4	185						20
	Rye grass	50.9	42	142					21
	Winter wheat, vetch, rye grass	25.3	23.7	72.9					21
	Oat, vetch, rye grass	78.9	73.9	304.7					21

[a] DM, dry matter.
[b] CP, crude protein.
[c] CF, crude fiber.
[d] Lys, lysine.
[e] Met, methionine.
[f] ATTD, total tract digestibility.
[g] OM, organic matter.
[h] *V.*, *Vicia*.
[1] Wüstholz et al. (2017).
[2] Blume et al. (2021).
[3] Liebhardt et al. (2022).
[4] Weltin et al. (2014).
[5] Messinger et al. (2021).
[6] Renaudeau et al. (2022).
[7] Weber et al. (2024).
[8] Presto Åkerfeldt et al. (2018).
[9] Carlson et al. (1999).
[10] Roth and Reents (2001).
[11] Jørgensen et al. (2012).
[12] Eskildsen et al. (2020).
[13] Friman et al. (2021).
[14] Bellof et al. (1998).

[15] Machner et al. (2025)
[16] Aubé et al., 2021a
[17] Wiskandt et al. (2025).
[18] Sehested et al. (2004).
[19] Jakobsen et al. (2015).
[20] Juul et al. (2021).
[21] Dostálová et al. (2020).

species. ATTD values ranged from 51 to 66 % for OM and 55 to 70 % for CP (Wiskandt et al., 2025). To obtain pH-stable silages with appropriate fermentation acid profiles and high feed acceptance, plants were wilted to at least 28 % DM and supplemented with additives. Secondary plant ingredients, like β-cyanoalanine (BCA) and γ-glutamyl-β-cyanoalanine (GCA) were substantially reduced by ensiling, and vicine and convicine were not detected in the silage. The use of vetch as roughage appears promising, although the available data are not yet sufficient for a valid assessment.

As a major forage in ruminant nutrition, WPCS has rarely been considered in recent literature about pig feeding. Several peer-reviewed studies originate from China, where WPCS has been investigated as a cost-effective source of fiber and energy (Ma et al., 2024; Wang et al., 2024; Yin et al., 2024), whereas European and North American data are scarce. European studies, investigating corn silage with heavy pig breeds used for ham production, focused more on product quality than nutritional characterization (Capraro et al., 2014; Galassi et al., 2017; Zanfi, 2012). Although the chemical composition of corn silage in ruminant systems is well documented, no peer-reviewed studies report nutrient composition for the use in pig feeding. Consequently, practical feed value tables offer the most standardized reference values currently available. According to established sources (DLG, 2014; INRAE, 2016;

Table 2
Overview over key characteristics of forage derived of alfalfa, clover-grass mixtures, vetches and corn plants.

	Alfalfa	Clover–grass mixtures	Vetch silage	Whole-plant corn silage
CP[a] (g/kg DM[b])	197–299 (fresh)[1,2], 213–231[2,3,4,5] (ensiled)	199–284 (fresh)[11,13,14,19], 143–223 (ensiled)[11,13,14,15,16,17,18]	169–211[20]	69–85[i]
Lysine (g/kg DM)	7.6–18 (fresh)[1,2], 10,8–13[2,3,4,5] (ensiled)	10.8–15.6 (fresh)[11,19], 6.1–7.3 (ensiled)[11,15]	8.7–10.4[20]	∼2.1–2.3[i]
CF[c] (g/kg DM)	217–313 (fresh)[1,2], 236–327[2,3,4,5] (ensiled)	180–359 (fresh)[13,19], 186-287 (ensiled)[13,17]	194–305[20]	185-202[i]
ATTD[d]	OM[e] 53.6–56.5[4,5], CP 52.9–56.3[4,5]	OM ∼78% CP ∼76% at ∼10% inclusion[14]	OM 51–66% OM 62%	OM 62% CP 81%[21]
	OM 63–69.5[4,5] (tp[f]), CP 58–68.8[4,5] (tp[f])	OM 64%[j] CP 71%[19]		
Effects of preservation	Ensiling with molasses[6] or red clover[7] reduces CP & CF alterations; drying/pelleting: stabilize AA[g,1,5]	Ensiling: CP & CF stable[13,14]; scarce data availability	Ensiling with additives leads to stable pH values; data limited to single study	No pig-specific research addressing preservation effects
Specific characteristics	High CP content, high buffering capacity, low WSC[h] content = high risk for proteolysis[,8]; saponins may reduce digestibility[4,9,10]	High WSC content compared to other forages (sugars + fructans)[12,14]	Promising CP supply; secondary plant metabolites in low concentrations; data limited to single study	Major gap in pig-specific research

[a] CP, crude protein
[b] DM dry matter
[c] CF, crude fiber
[d] ATTD, apparent total tract digestibility
[e] OM, organic matter
[f] tp, top part of the plant or leaves
[g] AA, amino acid(s)
[h] WSC, water soluble carbohydrates
[i] ruminant reference values used due to lack of pig-specific data (DLG, 2014; INRAE, 2023; LfL, 2024)
[j] Digestibility values based on regression analysis using total collection (Eskildsen et al., 2020). Not directly comparable to marker-derived ATTD values
[1] Blume et al. (2021)
[2] Wüstholz et al. (2017)
[3] Weltin et al. (2014)
[4] Messinger et al. (2021)
[5] Weber et al. (2024)
[6] Guo et al. (2018)
[7] Li et al. (2018)
[8] Gao et al. (2021)
[9] Kalač et al. (2012)
[10] Szumacher-Strabel et al. (2019)
[11] Carlosson et al. (1999)
[13] Roth and Reents (2001)
[14] Jørgensen et al. (2012)
[15] Friman et al. (2021)
[16] Presto Åkerfeldt et al. (2018)
[17] Bellof et al. (1998)
[18] Machner et al. (2025)
[19] Eskildsen et al. (2020)
[20] Wiskandt et al. (2025)
[21] DLG (2014)

LfL, 2024), corn silage typically contains 32—35 % DM, 69–85 g/kg DM CP, 185–202 g/kg DM CF and 290–310 g/kg DM starch, with lysine and methionine ranging from approximately 2.1–2.3 and 1.1–1.3 g/kg DM, respectively. None of the studies examined published pig-specific digestibility data for WPCS. Instead, nutrient utilization has been inferred mainly from animal performance, physiological parameters and gut microbial activity rather than from marker-based digestibility trials. Wang et al. (2024) demonstrated that the inclusion of 10 % WPCS lowered the pH in the caecum and colon, enhanced cellulase activity, and increased short-chain fatty acid concentrations, indicating enhanced fiber degradation. In line with this, Yin et al. (2024) reported that diets containing 5–15 % WPCS improved feed conversion and increased serum protein levels while simultaneously enhancing microbial diversity in the hindgut (see Section 2.2), suggesting more efficient nutrient utilization. In contrast, European studies did not report improvements in nutrient digestibility: Galassi et al. (2017) observed a decreased ATTD of DM, OM, CP and energy for diets containing whole plant corn silage, likely related to the higher fiber content of the silage and the use of special heavy pig breeds not representative of modern genotypes.

To facilitate comparability across forage types, a synthesized overview of key characteristics of the most prevalent forages is given in Table 2. Overall, especially in feedstuffs with low digestibility, there is a difference in nutrient digestibility between growing pigs and adult sows (Fernandez et al. 1986). Friman et al. (2021); Messinger et al. (2022) and Wüstholz et al. (2017) reported that the ability of pigs to utilize silage improved with increasing age of the pigs.

3.1. Effects of plant fractionation and processing on nutrient availability

In general, the CP content is higher in the plant leaves than in the stems (Sommer and Sundrum, 2015; Liebhardt et al., 2022). Messinger et al. (2021); Liebhardt et al. (2022) and Weber et al. (2024) carried out experiments with alfalfa and red clover to take advantage of this distribution by either using a stripping technique to separate leaves and stems at harvest or harvesting only the top 40 % of the plant. Weber et al. (2024) reported an increased CP content by 58 g/kg DM when the top 40 % of the plant were ensiled as plant tip silage compared to the whole alfalfa plant. Using a leaf-stripping technique, Liebhardt et al. (2022) observed increases of approximately 60 g/kg DM in CP and 5 g/kg DM in lysine in wilted leaves compared to whole-plant material. Messinger et al. (2021) confirmed higher CP concentrations in alfalfa leaf silages (+80 g/kg DM compared to whole-plant silages), although ensiling leaf material resulted in a reduction of 7 g/kg DM in lysine.

The role of physical form in utilization efficiency is further highlighted by enhanced intake with finely processed silage (Presto Åkerfeldt et al., 2018; Jørgensen et al., 2012). Four studies investigated extrusion - typically involving particle size reduction to 1–3 mm and/or thermal treatment up to 70 °C - as a method to enhance the ensilability of forages by disrupting plant cell structures. This process may facilitate the release of WSC to induce more efficient ensiling and improve nutrient accessibility, as higher fiber contents can decrease ileal CP and amino acid digestibility (Zhang et al., 2024). Neither alfalfa (Weltin et al., 2014; Wüstholz et al., 2017) nor clover-grass (Friman et al., 2021; Presto Åkerfeldt et al., 2018) demonstrated improved ensiling capacity or increased nutrient availability due to extrusion. On the contrary, high fiber contents may have caused a rise in temperature during extrusion and hence have triggered Maillard reactions, particularly declining CP digestibility. Extrusion also eliminates the structural effectiveness of forages.

Fibrous carbohydrates can be fermented in the large intestine by microorganisms, contributing to energy production in form of short chain fatty acids (SCFA) (Gao et al., 2022). According to Becker et al. (2003), approximately 20 % of organic carbon may be recovered via hindgut fermentation in pregnant sows. However, a negative correlation between fiber content and the apparent ileal digestibility of CP and amino acids was observed (Zhang et al., 2024). As this effect was more pronounced in cereal-based diets than in non-cereal ones, improving protein utilization from fibrous feedstuffs needs further investigation.

3.2. Grazing systems and their nutrient supply

Grazing is another option for ensuring the proportion of forage in pig feeding and it differs fundamentally from supplying harvested forage. An important question in this context is how to ensure that supply meets demand, as pasture uptake is generally not quantified. The plant variety and growth and, thus, the nutrient composition of pasture is dependent on multiple factors (e.g., soil texture, sward composition, season) and therefore highly individual. In this review, five studies (Table 1) were evaluated, which reported nutrient availability from grazing systems. In a direct comparison conducted by Jakobsen et al. (2015), alfalfa pasture was shown to provide a CP content of 301 g/kg DM, with a lysine concentration of 17 g/kg DM. In contrast, the evaluated ryegrass sward supplied less than half the protein content, with 135 g CP/kg DM and 7 g lysine/kg DM. These, nevertheless high CP values for ryegrass were not confirmed by the study by Dostálová et al. (2020), which analyzed a lower CP-content of 42 g/kg DM. Grass mixtures with red clover yielded CP contents between 176 and 185 g/kg DM (Aubé et al., 2021a; Sehested et al., 2004). However, seasonal variation can strongly affect nutrient supply, and studies in outdoor systems indicate that grazing alone may not consistently cover herd requirements throughout the year (Bell et al., 2015).

Overall, the nutritional value of forages and pasture is highly variable and depends on various parameters, including plant species, maturity, preservation processes and intake conditions. Despite their potential to contribute to nutrient supply while simultaneously providing gut-stabilizing fiber, the high variability in nutrient composition and digestibility limits their predictability in practical pig feeding. Furthermore, excessive fiber levels can reduce the nutrient digestibility and energy availability of the whole diet and concentrate intake might be reduced due to satiation with forage. Thus, further standardized research is required to determine under which conditions forages can be reliably integrated into pig diets without compromising nutrient efficiency or performance.

4. Effects of forage and pasture on pig performance and product quality

The proportion of pasture and forage to concentrate, as well as the total intake of nutrients and energy play a key role in determining growth and reproductive performance.

4.1. Effects of forage intake on reproductive performance

Feeding fibrous feedstuffs to sows is often connected with the aim to reduce constipation or improve the degree of satiety. At present, few studies have specifically investigated the effects of forage feeding or grazing on the reproductive performance of pigs. Ma et al. (2022) reviewed studies on feeding alfalfa to gestating sows and concluded that alfalfa inclusion in the diet improves the reproductive performance of sows and the growth and digestion of piglets. A study conducted by Aubé et al. (2021a) gradually substituted ME of compound feed (CP 138 g/kg DM, ME 14.2 MJ/kg DM) with pasture (40 % red clover, CP 176 g/kg DM, ME 10.8 MJ/kg DM) or hay (75 % red clover, CP 176 g/kg DM, 10,6 MJ/kg DM). In that study sows which had to replace 60 % of the ME supply by pasture or hay were lighter during gestation and gave birth to lighter piglets compared to sows which had to compensate only 10 % of ME. These findings suggest that pasture or forage cannot cover as much as 60 % of ME requirements. Although, red clover contains phytoestrogens, similar to other legume species (Mustonen et al., 2014), Presto Åkerfeldt et al. (2025) reported that sows are able to adapt to these compounds, thereby reducing the risk of negative effects on fertility and hormonal balance. Moreover, forage feeding might reduce the need for supplements, because it elevates vitamin E and selenium concentrations in serum and milk of sows during both gestation and lactation, with a pronounced effect observed when grazing on alfalfa compared to grass (Mutetikka and Mahan, 1993).

In a study comparing restricted dry feeding with liquid total mixed ration feeding based on farm-grown whole plant wheat silage, the feeding systems including forage led to higher piglet vitality (Hartung et al., 2021). Unfortunately, the side-effects of the study design do not allow a conclusion regarding the effect of forage feeding. Furthermore, Leeb et al. (2019) observed the reproductive performance of sows in farming systems with outdoor husbandry mainly integrated in crop rotation in Europe to be lower than in farming systems with indoor or part-outdoor husbandry. While the sow replacement rate was lower, less piglets were born and weaned per litter. Bell et al. (2015) also observed a seasonal impact on reproductive performance, i.e., piglet body mass (BM) at birth and weaning-to-conception interval, which was enhanced in summer. However, the effect cannot solely be attributed to forage intake.

Although positive effects of forage feeding on reproductive performance might be expected (as reviewed by Ma et al., 2022), few studies were conducted and further information is needed to make recommendations regarding forage provision to sows.

4.2. Effects of forage intake on growth rate and feed consumption

Forage provision to growing pigs increases rooting behavior and can be an option to decrease adverse or aggressive behavior (Section 2). However, due to its variability in feed value, its high fiber contents and low nutrient digestibility as well as energy availability (Section 4), adverse effects on feed intake and growth performance might be expected.

Data on the effects of forages in the diet of suckling pigs on growth performance are scarce, but in a study by Baldinger et al. (2017) an ad libitum supply of clover-grass silage did not affect BM and body mass gain (BMG) of suckling and weaning piglets fed different organic diets. However, forage feeding or the provision of pasture can have diverse effects on the BMG of growing-finishing pigs depending on husbandry system, feeding regimen (ad libitum or restrictive as well as nutrient content of the diet), forage type, ingested forage amount and the current BM or age of the animals, as older pigs have a greater ability to digest fiber-rich feedstuffs (Noblet and Le Goff, 2001). For example, additional clover-grass silage in addition to semi ad libitum compound feeding did not affect BMG or feed conversion of growing-finishing pigs in a study of Schwalm et al. (2013a) and the provision of whole plant vetch silage instead of straw in addition to a protein-restricted diet can even lead to higher BMG effectively decreasing concentrate intake through a shortened finishing period (Wiskandt et al., 2025). Wüstholz et al. (2017) and Messinger et al. (2022) confirmed that ad libitum fed alfalfa silage can improve compound feed conversion and account for concentrate restriction. Although on a low performance level (454 - 548 g/d), the overall performance of finishing pigs in a treatment with up to 48 % alfalfa silage inclusion did not differ significantly from the one of the control treatment while saving about 100 kg compound feed per pig (Wüstholz et al. 2017). Other studies, though, showed that replacing parts of a compound feed with alfalfa silage (Messinger et al., 2022) or clover-grass silage (Friman et al., 2021; Wallenbeck et al., 2014) can lead to a lower BMG compared to animals fed a 100 % compound feed diet. This might be explained by a silage intake lower than expected (Messinger et al., 2022; Wallenbeck et al., 2014; Wüstholz et al., 2017), or sorting of the material (Wallenbeck et al., 2014). All studies concurred that, with silage in the diet, compound feed or CP content of compound feed can been reduced. Thus, even with lower BMG, it became evident that the silage contributed to the animals nutrient requirements (Friman et al., 2021; Messinger et al. 2022; Wallenbeck et al., 2014). However, the nutrient composition of the forage largely affects the extent to which the compound feed can be replaced. Exchanging corn meal and wheat bran with up to 30 % whole-ear corn silage in the diet of heavy pigs (90–170 kg BM) led to slightly reduced CP, NDF, ash and P as well as slightly increased ADF and gross energy contents in the diet and did not affect animals BMG (Zanfi et al., 2014). However, exchanging maize meal and wheat bran with 20 % high cut whole plant corn silage in the diet of finishing heavy pigs led to decreased contents of digestible CP, ether extract, digestible phosphorus and metabolizable as well as net energy and an increased content of ADF, NDF, ash and gross energy and to a significant decrease in BMG at a comparable BM (Galassi et al., 2017).

Regarding the impact of grazing on BMG of growing pigs, contradictory results have been reported. Access to pasture increases the animals' energy need for exercise and for thermoregulation. This can be especially challenging, when low or high temperatures arise and despite higher energy requirements, lower voluntary feed intakes occur (reviewed by Edwards 2005). As stated in Section 3, the extent of feed intake from pasture depends on the provision of compound feed. In a study comparing different feeding regimens, Oksbjerg et al. (2005) observed that rearing pigs on pasture with restricted compound feed leads to the best compound feed conversion compared to rearing them indoor or on pasture with ad libitum feed supply. Although Juul et al. (2021) did not observe an improved feed conversion, they reported that restrictively fed pigs on pasture covered greater percentages of their daily energy requirement from foraging. Ad libitum fed pigs can have a higher feed conversion when they are reared on pasture compared to indoors (Kelly et al., 2007; Oksbjerg et al., 2005; Strudsholm et al., 2005), which may be attributed to increased nutrient requirements due to activity or thermoregulation. Sather et al. (1997) observed increased feed consumption of outdoor reared pigs in winter, while it was on the same level compared to indoor raised pigs in summer. Studies with ad libitum or semi ad libitum feeding regimens showed that BMG on pasture can be on the same level or increased compared to indoor rearing (Juska et al., 2013; Kelly et al., 2007; Oksbjerg et al., 2005; Strudsholm et al., 2005; Talbott et al., 2004). Botermans et al. (2015) stated, that even when compound feed was restricted in the finishing period BMG was not affected. The findings of Kongsted et al. (2015) and Strudsholm, et al. (2005) detected that a restricted provision of compound feed on pasture leads to a decrease in BMG compared to an ad libitum feeding strategy.

These findings clearly demonstrate that both the type of forage and the overall diet formulation have a decisive impact on growth performance in pigs. Although the BMG of silage-fed pigs was lower in some cases, all reviewed studies agree that feeding silage results in reduced compound feed consumption per kilogram of BMG, thus possibly reducing feed costs and providing the opportunity to include more human-inedible feedstuffs. Pasture raised pigs can cover parts of their diet with pasture, but other factors like temperature and exercise can also impact the performance.

4.3. Effects of forage intake on carcass characteristics and meat quality

Feeding strategies can influence carcass composition and meat quality. The inclusion of forages can lead to a higher filling and a stronger formation of the gastrointestinal tract (Kaensombath et al., 2013), which can result in a decreased dressing percentage (Bellof et al., 1998; Holinger et al., 2018c; Messinger et al., 2022) even when the silage is chopped or pelleted (Wallenbeck et al., 2014). Nevertheless, numerous studies did not detect an effect of forage or grazing on dressing percentage (Argemí-Armengol et al., 2020; Giuliotti et al., 2007; Kaensombath et al., 2013; Kelly et al., 2007; Schwalm et al., 2013a; Sirtori et al., 2022; Wiskandt et al., 2025; Wüstholz et al., 2017). This might be due to dressing percentage being strongly affected by the amount of feed ingested before slaughter and the time span between the last meal and slaughter.

When part of the diet is replaced with forages, which are characterized by low energy and high fiber contents (see Section 4-nutritional values), the nutrient intake of the animal changes. The intake of energy, crude protein and amino acids and the ratio of energy to lysine in the diet influence the lipid accumulation in the carcass (reviewed by Yan et al., 2023) and a low energy intake leads to leaner carcasses. A lower growth rate and an increased lean meat percentage was observed to coincide with a decreased tenderness of the meat (reviewed by Edwards, 2005; Hansen et al., 2006) affecting its palatability. Study results are difficult to discuss due to the multitude of influencing factors. A restricted feeding strategy with silage or hay provision in the growing and finishing period was reported to increase the proportion of lean meat in the carcass (Hansen et al., 2006; Oksbjerg et al., 2005; Ma et al., 2022; Zanfi et al., 2014). However, Wüstholz et al. (2017) did not observe a significant effect of feeding strategy (complete compound feed vs. compound feed adjusted (lower CP, higher ME) to the silage plus chopped or extruded alfalfa silage) on the leanness of carcass, but a lower fat area indicated low energy intake. Similarly, Friman et al. (2021) observed no beneficial effect of feeding clover-grass silage on lean meat content and the authors concluded that, despite consuming silage as part of their diet, the animals' energy intake remained sufficient to support adipose tissue deposition. Messinger et al. (2022) observed the lean meat in silage fed pigs to be only numerically lower than in those fed a control diet and discussed the possibility of an insufficient amino acid supply. Although the intake of the finishing diets led to similar nutrient uptake in this study, the intake of energy, CP, lysine and methionine in the initial and growing phase was lower in the alfalfa silage treatment, caused by a silage intake lower than calculated for this phase. Ad libitum fed indoor raised pigs can exhibit lower lean meat contents than ad libitum fed pasture raised pigs, which were observed to have even higher lean meat percentages when fed restrictively (Bee et al., 2004; Oksbjerg et al., 2005). Nilzén et al. (2001) observed this positive effect of pasture on the lean meat percentage only in pigs that carry the RN^{-} genotype, indicating that genetics have a major effect. In contrast, no effect of pasture on lean meat percentage was detected in the study of Høøk Presto et al. (2007) with ad libitum fed pigs, in which the outdoor pigs exhibited a higher energy intake compared to those raised indoors, and in the study of Dostálová et al. (2020), in which both groups had the same nutrient intake from compound feed. A major issue of studies with outdoor husbandry is that the intake of nutrients from pasture cannot be determined reliably. Muscle depth, lean meat yield and the weight of the valuable parts like loins and hams can increase when pigs are raised free range (Sather et al., 1997).

When formulating a diet with forages, the nutrient requirements must be taken into account. The intramuscular fat content (IMF) of pork, which improves the eating quality (Lebret et al., 2008; Sundrum et al., 2011), can be increased by a reduction of dietary protein or amino acids while an energy restricted feeding can lead to a decrease in IMF (Candek- Potokar et al., 1998; Lebret et al., 2008). This was observed by Raj et al. (2015), who fed a protein- and energy restricted diet with 20 % grass meal inclusion as well as by Hansen et al. (2006), who restricted the total amount of compound feed to 70 % of the Danish recommendations and supplemented the diet with ad libitum clover-grass- or oat silage. Although the animals ingested 260 and 600 g MJ from silage per pen of 5 pigs, the diet supplied only 85 % of the total energy intake compared the full concentrate diet. Furthermore, Johannson et al. (2002), who offered 10 % of the total energy intake as silage (energy level of the diet 2 % lower compared to the conventionally fed animals) and Olkowski et al. (2019), who fed diets containing forages or herbs and calculated the same protein- and energy supply for the control and the test feeding groups also reported lower IMF. However, feeding forages does not necessarily lead to a reduction in IMF, for example when it is fed additionally to a semi ad libitum diet as in the study of Schwalm et al. (2013b). Moreover, no effect of silage on IMF was observed by Holinger et al. (2018c) and Messinger et al. (2022). Keeping growing pigs in outdoor housing systems might further influence IMF. Nilzén et al. (2001) and Sirtori et al. (2022) studied grazing systems in which IMF was not affected. However, Bee et al. (2004) measured lower fat concentrations in the loins of pigs reared on pasture in winter compared to indoor reared pigs. Outdoor rearing can lead to less marbling (Gentry et al., 2004) and the total intramuscular lipids in obese Alentanjo pigs were lower when they were reared on pasture (Martins et al., 2015).

Other meat quality traits, such as fatty acid composition, as well as technological traits and visual attributes, such as pH value, drip loss and meat color, must be considered when deciding on feeding strategies. The fatty acid profile of pig meat is affected by the one in the feed (Kouba and Mourot, 2011) and different forages have various fatty acid compositions (Dierking et al., 2010). In general pasture intake is associated with higher contents of poly unsaturated fatty acids (PUFA) and omega-3 (n-3) fatty acids in the meat and in subcutaneous fat, which is wanted for positive health effects in human diets, but can have negative effects for the storage of the meat (reviewed by Edwards 2005). High PUFA concentrations in the meat can lead to a shorter shelf-life ore off-flavors after a prolonged storage time (Jonsäll et al., 2000). Hansen et al. (2006); Johannson et al. (2002); Nilzén et al. (2001) and Olkowski et al. (2019) detected an effect on fatty acid composition of pig meat. In general, n-3 fatty acids and total PUFA concentration in the meat or fat of animals grown on pasture or supplemented with red clover or oat silage increase, while SFA and the n-6/n-3 ratio decrease. The same was observed when grass meal was included in the diet (Raj et al., 2015). Similarly, alfalfa products in the diet of growing pigs can increase the PUFA concentration in pork (reviewed by Ma et al., 2022). In contrast to leguminous and grass forages, maize silage contains high amounts of saturated fatty acids (SFA), which can increase the concentration of C18:0 in pork and, thus, improve technological qualities (Capraro et al., 2017).

No difference in tenderness, juiciness and flavor but reduced meat pH and/or increased drip loss in meat of outdoor reared pigs were reported by most of the 11 reviewed studies in Edwards (2005), who attributed this to a higher susceptibility for stress at slaughter. In contrast, the majority of other foremost recent studies found no effects of forages or pasture rearing on meat quality with regard to post mortem pH decline or meat pH (Dostálová et al., 2020; Gentry et al., 2004; Giuliotti et al., 2007; Holinger et al., 2018c; Juska et al., 2013) or drip loss (Dostálová et al. 2020; Gentry et al., 2004; Juska et al., 2013; Sirtori et al., 2022). Nevertheless Bee et al. (2004) found the ultimate pH (24 h post mortem) in *Musculus semitendinosus* and *Rectus femoris* was lower in grazing pigs compared to those in indoor rearing, which was confirmed by Lebret et al. (2015) in extensively reared pigs. Only limited evidence was found for increased drip loss (Bee et al., 2004; Nilzén et al., 2001; Talbott et al. 2004). Besides feeding management, pre-slaughter stress leads to depletion of muscle glycogen, which results in a change in muscle pH (Arsenoaia and Mălăncuş, 2023; Foury et al. 2011).

Several studies suggest that forage-based feeding strategies have no effect on meat color, which is an important visual quality attribute influencing consumer perception (Hansen et al., 2006; Holinger et al., 2018c; Schwalm et al., 2013b; Sirtori et al., 2022). Some studies indicated, that outdoor rearing may have a small effect on meat color, with meat from outdoor reared and grazing pigs being darker or redder compared to indoor reared pigs (Bee et al., 2004; Gentry et al. 2004; Lebret et al., 2015; Talbott et al. 2004).

In summary, although the impact of feeding strategies on pig carcass characteristics is complex and influenced by various factors, forage and pasture can be expected to fill the gut and, thereby, decrease the dressing percentage. The majority of the studies emphasized an increasing effect of forage supply and grazing on lean meat percentage. The IMF can vary depending on the feeding regimen and the nutrient supply of the diet. Furthermore, the impact of forage intake on meat quality is mostly determined by the forage type and its fatty acid profile, possibly influencing the storage characteristics. There might be an effect of outdoor grazing, maybe because of exercise and increased energy- and nutrient requirement, on the marbling of the meat.

5. Forages in pig nutrition can reduce feed-food competition and pressure on the environment

It is widely acknowledged that reducing the use of human-edible feedstuffs in animal nutrition and redistributing high productive croplands to human food production instead of livestock feed are key measures for sustainability. Livestock that feeds on food residues and co-products of the food industry does not compete with humans for cropland and can contribute to sustainable food security (van Zanten et al. 2016). In addition, non-human edible biomass from permanent meadows and pastures can be utilized by livestock, but its potential is mostly discussed in the context of ruminants, which are able to convert resources from marginal land into human-edible proteins (van Zanten et al. 2016). The potential to include forages in diets for pigs has largely been overlooked in this context. Zira et al. (2023) estimated a potential reduction of the direct feed-food competition by 16 %–20 % per kg pork meat, if the typical pig production system in Europe dominated by grain feeding was changed to including 12 % clover-grass biomass in a total mixed ration (TMR). In the literature analyzed for the present review saved nutrients of human-edible feedstuffs through substitution with non-human-edible feedstuffs were classified according to the replaced nutrient or feedstuff and the stage of animal development. For growing-finishing pigs, replacements of 30 % concentrate (Hansen et al., 2006), 20 % CP (Friman et al., 2021) or 20 % ME (Wallenbeck et al., 2014) with clover-grass silage and 20–50 % DM with alfalfa silage (Wüstholz et al., 2017) are reported. Edwards (2003) reviewed that ad libitum fed growing pigs cover approximately 5 % of their energy requirement from pasture. A more recent study on foraging behavior of growing pigs reported an intake of up to 25 % or 14 % of energy requirements by grazing (Juul et al. 2021), when compound feed was offered restrictively or ad libitum, respectively. These results support previous observations by Jakobsen et al. (2015), who estimated the lysine uptake from alfalfa grazing to reach a level of 48 % and stated that foraging on alfalfa can make a substantial contribution to the amino acid supply of growing pigs. Adult sows are reported to cover even higher parts of their nutrient requirements from forage, which can reduce the feed-food-competition distinctly. Dry sows ingest up to 2 kg DM/day from pasture (Edwards, 2003) and the inclusion levels of forage in the diet of sows can reach up to 20 % of their DM intake (Makalani et al. 2025). In fact, Sehested et al. (2004) estimated intake levels of up to 55 % of energy requirements for pregnant sows from clover-grass.

Feeding forages can additionally benefit the environment by reducing NH_3 volatilization from fresh pig manure by up to 70 % (Friman et al., 2023) and possibly improving intestinal P availability due to an increased InsP-P hydrolysis (reviewed by Metzler and Mosenthin, 2008; Heyer et al., 2022). Fibrous carbohydrates that reach the hindgut promote microbial activity, which uses nitrogen for fermentation and releases diverse enzymes. Accordingly, more nitrogen is incorporated into the microbial biomass and then excreted in the feces, leading to a shift in the excretion pattern from nitrogen excretion via urine to nitrogen excretion via feces (Friman et al., 2023; reviewed by Jha and Berrocoso, 2016).

Legume-based crop rotations show several benefits, including climate change mitigation and adaptation, soil degradation prevention, and reduction of pesticide use (Panagea et al., 2025). Further advantages of integrating legume-based crop rotations into the feeding plan for pigs can be a higher degree of self-sufficiency and use of locally produced feed sources. Nevertheless, a species-appropriate diet is fundamental to healthy and efficient pig production. In order to reduce human-edible feedstuffs in pig nutrition and benefit potential opportunities, further data on the substitution potential of forage are essential.

6. Conclusion

Using forages and pasture in pig nutrition can offer several benefits beyond providing enrichment. Pasture grazing can improve the pigs' welfare and contribute to meeting the dietary needs, when management strategies are optimized. Besides positive effects on animal welfare associated with pig typical behavior, positive effects of forage intake on gut health were reported. The kind of forage, the amount of forage and the characteristics of the pigs (performance level, age, etc.) play an important role in deciding on the feeding strategy. Furthermore, including forage legumes in pig diets could have the advantages of supplying protein without competing with human-edible resources and increasing the degree of feed self-sufficiency while reducing the need for imported protein. Legume-based cover crops can be incorporated in crop rotations on farms, thus reducing the need for mineral fertilizers and improve soil humus contents, while producing feed for livestock. In summary, fresh and preserved forages in pig nutrition offer great potential to increase animal welfare and gut health, diminish the competition over human-edible feeds and reduce NH_3 volatilization. Research is needed to understand and explore the effects of feeding different types of forages to pigs in different performance stages on animal health and performance. In addition, consumers' perspectives on product quality in relation to animal health and environmental aspects must be taken into account.

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CRediT authorship contribution statement

Fenja Klevenhusen: Writing – review & editing, Writing – original draft, Supervision, Investigation, Conceptualization. **Konstanze Hott:** Writing – original draft, Investigation. **Julika Wiskandt:** Writing – original draft, Investigation. **Stephanie Witten:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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