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Review

Husbandry practices associated with extensification in European pig production and their effects on pork quality

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ABSTRACT

This review has been developed as part of the *mEATquality* project with the main objective to examine the types of extensification practices used in European pig husbandry and their effect on intrinsic meat quality. Literature search has resulted in 679 references in total, from which 53 showed a strict compliance with the goals of this review: 1) the use of local European breeds and their crossbreds (22 papers); 2) addition of forage to diet (9 papers); 3) increased space allowance (3 papers); 4) enrichment of environment (19 papers). The evaluation of selected extensification factors showed that not all of them have a clear impact on meat quality, and are often confounded. The most clear differences were observed when comparing autochthonous with commercial breeds, and systems with access to pastures or woodlands vs. indoor housing. Despite many studies focusing on the extensification of husbandry practices, some of the factors cannot be confirmed to have a direct effect on pork intrinsic quality.

1. Introduction

Pork is currently the second most often consumed meat in the world (OECD/FAO, 2021). The future level of pork consumption will be affected by consumer expectations, and it will change over time with emerging new trends in human nutrition, socio-economic and socio-cultural factors (Chernukha et al., 2023; Vitale et al., 2020). Due to societal concerns over intensive pig production methods, consumers increasingly demand meat from animals produced under more extensive conditions. Extensive production conditions provide pigs with more space and greater environmental complexity (Früh et al., 2014), can offer a more varied diet with foraging opportunities (Jakobsen, Kongsted, & Hermansen, 2015; Rodríguez-Estévez, García, Peña, & Gómez, 2009), and may even apply to local breeds differing considerably from the highly productive breeds of conventional production both in terms of productivity and carcass/meat quality (Früh et al., 2014; Lebret, Ecolan, Bonhomme, Méteau, & Prunier, 2015). An increased extensification of production methods can improve many aspects of animal welfare and is thus a part of most welfare-label pig production systems, such as organic and free-range systems (Früh et al., 2014). Beyond improving animal welfare, organic production also considerably reduces the usage of antibiotics (EFSA, 2021), further contributing to high

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Table 1
Keywords used to obtain the literature on effect of breed, environmental enrichment, addition of forage to feed and space allowance on pork meat quality.

ALWAYS	WITH DIFFERENT COMBINATIONS OF				
pork	Breed	Enrichment	Farm	Feed	Meat
pig	native	deep bed	husbandry	feed	quality
meat	local	chains	housing	quality	fatty acids
	crossbreed	wood	outdoor	forage	profile
	Spanish	logs	indoor	diet	water
	Iberian	rope	slatted	rye	holding
	Italian	tough	concrete	harvest	capacity
	Polish	dog	slatted	residues	colour
	Pulawska	chews	plastic		marbling
	Złotnicka	alkathene	space		PUFA
	Apulo-	pipe	stocking		MUFA
	Calabrese	cloth strips	density		SFA
	Casertana	rubber	finisher		drip loss
	Cinta Senese	sheets	fattening		cooking
	Mora	paper	floor		loss
	Romagnola	cardboard	solid		pH
	Nero	toys			Warner-
	Siciliano	showers			Bratzler
	Sarda	baths			Shear
	Ibérico	heat stress			Force
	Celta	welfare			moisture
	Chato	straw			Crude
	Murciano				protein
	Euskal				IMF
	Txerria				Ash
	Gochu				
	Asturcelta				
	Negra				
	Canaria				
	Negra				
	Mallorquina				
	Mangalica				
	Europe				

consumer acceptance. Consumer willingness to pay for pork meat has shown an increase in animal welfare labelled products, particularly in organic production (Gross, Waldrop, & Roosen, 2021), characterised by high extensification. Furthermore, using choice tests following complete information regarding production systems, Gross et al. (2021) showed that consumers' hedonic liking for organic and animal welfare label pork was higher than for conventional pork, although some aspects of welfare can be impaired under extensive conditions as well (i.e. thermal comfort).

Pork quality is defined by a group of complex traits with multiple factors affecting it throughout the meat production chain (Lebret & Čandek-Potokar, 2022; Prache et al., 2022; Vitale et al., 2020). Moreover, the definition of pork quality depends on one's point of view. In general, consumers' purchase decisions considering culinary meat are an output of visual perception: colour, percentage of lean meat, and the amount of visible drip. Traits considered during meat consumption are taste, tenderness, and juiciness, and are evaluated after thermal processing of meat cuts (Moeller et al., 2010; Warner, Dunshea, & Channon, 2018). These sensory attributes of pork are the output value of other quality traits that are important from a scientific and technological point of view: pH, water holding capacity, texture, and instrumental colour parameters (Jankowiak, Cebulska, & Bocian, 2021; Richardson, Fields, Dilger, & Boler, 2018).

The goal of this study is to provide a comprehensive review of the impact of selected pig husbandry practices: (1) use of local breeds, (2) diet with addition of forage, (3) space allocation during fattening, and (4) environmental enrichment (namely housing conditions, i.e. deep bedding). The aforementioned factors were selected on the basis of the goals defined in the mEATquality project; and these were also recognised as a cause of variability in pork quality across Europe (Rosenvold & Andersen, 2003; Wood et al., 2008). Moreover, because of a substantial number of autochthonous pig breeds in Europe we focused on studies where direct comparison between such breeds with their crosses with modern and commercial breeds or with commercial breeds were directly compared. This review is focused on autochthonous pigs from the Czech Republic, Slovakia, Hungary, Italy, Poland, Portugal and Spain. However, it should be stressed that local breeds could be reared in intensive/conventional systems as well, although the selected breeds and their crossbreds are more often used in traditional and extensive rearing systems with specific characteristics such as outdoor housing, pasture availability, and specific feeding management.

2. Materials and methods

2.1. Paper selection

The selection of studies used in this review was conducted in July 2022, within the following databases: Web of Science, Scopus, PubMed, and Google Scholar. The main focus was on four aspects related to extensification: 1) the use of autochthonous breeds versus commercial ones, 2) the use of any type of environmental enrichment, 3) the addition of forage to the diet, and 4) increased/decreased space allowance during rearing, and the effect of those factors on pork quality, e.g.: pH, fatty acids, shear force, colour etc. The search for appropriate literature was done using various combinations of the keywords collected in Table 1. The papers were kept for the main part of our study if they were:

- a scientific study and not a literature review;
- a peer-reviewed study in English;
- a comparison of local European breed with its crosses or commercial breeds;
- a study on any type of environmental enrichment (e.g., bedding);
- a study on forage addition to the diet (i.e., no possibility for foraging - due to no access to pasture);

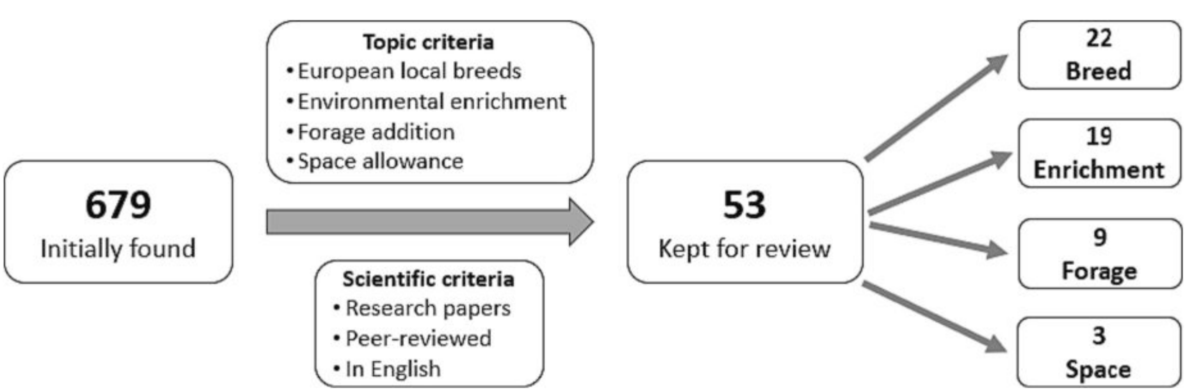

Fig. 1. Process of paper selection.

Table 2
Comparison of local and commercial breeds in terms of pH, intramuscular fat, drip loss and shear force levels.

Reference	Experimental setup, country	Parameter	Breed (and number of animals)					Sig.
Aboagye et al. (2020)	commercial rearing, Apulo-Calabrese up to 135 kg, commercial cross up to 155 kg		**Apulo-Calabrese (51)**	**Duroc x (Landrace x Large White) (52)**				
		pHu (LT)	5.57	5.45		n.s.		n.s.
		IMF (LT, %)	2.09a	1.68b		$p < 0.05$		$p < 0.05$
Serra et al. (1998)	commercial rearing conditions, females & males, SW: 118 kg, Spain		**Iberian (12, CW = 93 kg)**	**Landrace (20, CW = 76 kg)**				
		pHu (LL)	5.75 ± 0.02a	5.59 ± 0.02b				$p < 0.001$
		pHu (SM)	5.80 ± 0.03a	5.58 ± 0.02b				$p < 0.001$
		IMF (LL, %)	3.91 ± 0.2a	0.66 ± 0.15b				$p < 0.001$
		IMF(SM, %)	3.68 ± 0.22a	1.58 ± 0.17b				$p < 0.001$
Čandek-Potokar et al. (2003)	commercial rearing, females & castrated males, Slovenia		**Krškopolje (17, CW = 98 kg)**	**Landrace male line x Krškopolje (17, CW = 95 kg)**				
		pH 24 h (LL)	5.60 ± 0.03a	5.51 ± 0.03b				$p < 0.05$
		IMF (%)	3.00 ± 0.2	2.10 ± 0.3				$p < 0.05$
Fortina et al. (2005)	commercial rearing conditions, females & castrated males, Italy		**Casertana (6, SW = 200 kg)**	**Mora R. (11, SW = 193 kg)**				
		pH 24 h (LT)	5.96 ± 0.08a	6.15 ± 0.18b				$p < 0.05$
		pH 24 h (SM)	6.37 ± 0.24	6.30 ± 0.27				n.s.
Florowski et al., 2006	commercial rearing, females, SW: 100 kg, Poland		**Zlotnicka Spotted (17)**		**Pulawska (17)**	**Polish Landrace (18)**		
		pH 48 h (LT)	5.54 ± 0.08		5.52 ± 0.05	5.52 ± 0.1		n.s.
		Drip loss (%) (LT)	3.30 ± 1.3a		3.70 ± 1.5a	5.10 ± 1.4b		$p \leq 0.001$
Juárez et al. (2009)	semi-extensive rearing, SW: 160–180 kg, Spain		**Lampiño (10)**	**Entrepelado (10)**	**Retinto (10)**	**Torbiscal (10)**	**Iberian x Duroc (10)**	
		pH 24 h (LT)	6.12 ± 0.04	6.13 ± 0.03	6.10 ± 0.04	6.14 ± 0.03	6.09 ± 0.03	n.s.
		Shear force (kg/cm2) (LT)	4.56 ± 0.31	4.63 ± 0.30	4.53 ± 0.31	4.98 ± 0.31	4.89 ± 0.30	n.s.
Bocian et al. (2012)	commercial rearing, Poland		**Złotnicka Spotted (61, SW = 107 kg; CW = 79.6 kg)**		**Polish Large White × Polish Landrace (35, SW = 119 kg, CW = 91.6 kg)**			
		pHu (LL)	5.52 ± 0.01a		5.45 ± 0.02b			$p < 0.05$
		IMF (%) (LL)	1.87 ± 0.09		1.70 ± 0.12			n.s.
		Drip loss (%)(LL)	2.55 ± 0.19a		4.31 ± 0.31b			$p < 0.05$
		Shear force (N/ cm2) (LL)	43.61 ± 1.66		43.57 ± 1.47			n.s.
Szulc, Lisiak, et al. (2012)	commercial rearing, females & castrated males, Poland		**Złotnicka Spotted 100% (20, SW = 119 kg, CW = 93.0 kg)**	**Złotnicka Spotted 75% (20, SW = 122 kg, CW = 90.3 kg)**		**Złotnicka Spotted 50% (20, SW = 114 kg, CW = 90.1 kg)**		
		pH 24 h (LTL)	5.42 ± 0.03a	5.44 ± 0.03		5.51 ± 0.03b		$p < 0.05$
Szulc, Skrzypczak, et al. (2012)	commercial rearing, females & males, Poland		**Złotnicka Spotted (20, SW = 114 kg, CW = 88.9 kg)**	**Złotnicka Spotted x Polish Large White (20, SW = 113 kg; CW = 87.2 kg)**	**Złotnicka Spotted x Duroc (10, SW = 113 kg, CW = 88.5 kg)**	**Złotnicka Spotted x(Złotnicka Spotted x Duroc) (10, SW = 123 kg, CW = 90.5 kg)**		
		pH 24 h (LTL)	5.50 ± 0.09	5.40 ± 0.09	5.41 ± 0.08	5.51 ± 0.17		n.s.
		Drip loss (%) (LTL)	2.36 ± 1.14	2.31 ± 1.12	2.94 ± 1.4	1.76 ± 0.41		n.s.
Maiorano, Gambacorta, et al., 2013	commercial rearing in deep straw, castrated males, Italy		**Casertana (10, SW = 140 kg, CW = 112 kg)**	**Duroc x (Landrace x Italian Large White) (10, SW = 202 kg, CW = 161 kg)**		**Italian Large White (10, SW = 207 kg, CW = 168 kg)**		
		ph 24 h (LL)	5.51	5.41		5.49		n.s.
Franco et al. (2014)	extensive production with commercial feed, females & castrated males, Spain		**Celta (16, SW = 167 kg, CW = 133 kg)**	**Celta x Duroc (20, SW = 168 kg, CW = 136 kg)**		**Celta x Landrace (16, SW = 165 kg, CW = 135 kg)**		
		pH 24 h (LTL)	5.46a	5.63b		5.62b		$p < 0.001$

(continued on next page)

Table 2 (*continued*)

Reference	Experimental setup, country	Parameter	Breed (and number of animals)					Sig.
		IMF (LTL)	5.22b	3.08a		3.96a		p < 0.001
		Drip loss (LTL)	1.77a	2.68b		3.10b		p < 0.001
		Shear force (kg / cm2) (LTL)	3.64c	2.86b		2.03a		p < 0.001
			Puławska (54, SW = 100 ± 3 kg, CW = 76.3 kg)	**Polish Large White (60, SW = 100 ± 3 kg, CW = 78.8 kg)**				
Wojtysiak and Połtowicz (2014)	commercial rearing, females, Poland	pH 24 h (LL)	5.63a	5.48b				p < 0.01
		IMF (%) (LL)	3.33a	1.89b				p < 0.01
		Drip loss (%) (LL)	1.75a	3.68b				p < 0.05
		WB (kg/ cm2) (LL)	5.62a	6.39b				p < 0.05
			Złotnicka Spotted (24, SW = 102 kg)	**Puławska (10, SW = 99 kg)**	**(Polish Large White × Polish Landrace) × (Duroc × Pietrain) (16, SW = 101 kg)**			
Bogucka and Kapelański (2016)	commercial rearing, females & castrated males, Poland	pHu (LL)	5.69 ± 0.06a	5.73 ± 0.05a	5.45 ± 0.01b			p < 0.05
			Prestice Black-Pied (32, SW = 111 kg)	**Large White × Landrace sows × Duroc × Pietrain boars (32, SW = 111 kg)**				
Nevrkla et al., 2017	commercial rearing, females & males, Czech	pH 24 h (LTL)	5.61 ± 0.12	5.43 ± 0.48				P < 0.01
		IMF (%) (LTL)	2.89 ± 0.42	1.99 ± 0.41				P < 0.01
		Drip loss (%)(LTL)	2.65 ± 0.50	4.83 ± 0.85				P < 0.001
			Puławska (25, SW = 100–105 kg)	**Złotnicka (25, SW = 100–105 kg)**	**(Large White × Polish Landrace) x (Duroc × Pietrain) (25, SW = 100–105 kg)**			
Cebulska et al. (2018)	commercial rearing, Poland	pHu (LL)	5.71 ± 0.12b	5.61 ± 0.24b	5.45 ± 0.05a			p < 0.01
		Drip loss (%)(LL)	2.26 ± 1.67a	2.95 ± 2.04a	4.57 ± 1.61b			p < 0.05
		Shear force (N/cm) (LL)	36.07 ± 8.81a	43.27 ± 11.05b	38.62 ± 6.74			p < 0.01
			Mangalica (9, SW = 100 kg, CW = 81.1 kg)	**Mangalica x Duroc (9, SW = 108 kg, CW = 84.1 kg)**	**Large White (10, SW = 100 kg, CW = 97.7 kg)**	**Złotnicka Spotted (10, SW = 103 kg, CW = 86.0 kg)**	**Polish Large White (10, SW = 102 kg, CW = 83.1 kg)**	
Debrecéni, Lípová, Bucko, et al. (2018)	commercial rearing, Hungary/Poland	pH 24 h (LTL)	5.60a	5.60a	5.50b	5.60a	5.0	p < 0.01
		IMF (%) (LTL)	1.90b	2.40b	1.20b	2.60b	5.50a	p < 0.001
		Drip loss (%) (LTL)	8.80a	9.00a	7.30ab	2.90c	4.70bc	p < 0.001
		Shear force (kg/cm^2) (LTL)	2.30b	2.10c	4.30a	4.20a	3.70a	p < 0.001
			Polish Landrace (8, SW = 100 ± 2.5 kg)	**Puławska (8, SW = 100 ± 2.5 kg)**				
Piórkowska et al. (2018)	commercial rearing, females, Poland	pH 24 h (LTL)	5.63 ± 0.05	5.60 ± 0.06				n.s.
		IMF (%) (LTL)	1.08 ± 0.21	1.19 ± 0.12				n.s.
			DanBred (30, SW = 100–105 kg)	**Naima (30, SW = 100–105 kg)**	**Pulawska (30, SW = 100–105 kg)**			
Kasprzyk and Bogucka (2020)	commercial rearing, females & castrated males, Poland	pH 24 h	5.59 ± 0.06	5.62 ± 0.07	5.61 ± 0.14			n.s.
		Drip loss (%)	3.56 ± 1.07	4.63 ± 1.04	3.82 ± 1.15			n.s.
			Alentejano (10, SW = 64.6 kg, CW = 47.0 kg)	**Bísaro (10, SW = 64.2 kg, CW = 48.0 kg)**	**Alentejano x Bisaro (10, SW = 64.4 kg, CW = 48.1 kg)**	**Bisaro x Alentejano (10, SW = 65.1 kg, CW = 47.8 kg)**		
Martins et al., 2020a	outdoor rearing with commercial diet, castrated males, Portugal	pH 24 h (LL)	5.57a	5.44b	5.45b	5.50b		p < 0.01

(continued on next page)

Table 2 (*continued*)

Reference	Experimental setup, country	Parameter	Breed (and number of animals)				Sig.
		IMF (%) (LL)	6.70a	5.50b	5.90ab	5.60b	$p < 0.05$
		Drip loss (%) (LL)	1.35c	3.76a	2.24b	2.74b	$p < 0.001$
		Shear force (N) (LL)	26.60b	47.40a	30.40b	34.10b	$p < 0.001$
			Alentejano (10, SW ~ 65 kg)	**Bísaro (10, SW ~ 65 kg)**	**Alentejano x Bísaro (10, SW ~ 65 kg)**	**Bísaro x Alentejano (10, SW ~ 65 kg)**	
Martins et al. (2020b)	outdoor rearing with commercial diet, castrated males, Portugal	pH 24 h (SM)	5.76a	5.51b	5.67	5.66	$p < 0.05$
		IMF (%) (SM)	5.00	4.50	4.60	5.10	n.s.
			Prestice Black-Pied (39, SW = 88–99 kg, CW = 69.1–77.1 kg)	**(Large White x Landrace) x Large White (37, SW = 95–100 kg, CW = 73.7–77.5 kg)**			
Nevrkla et al. (2021)	commercial rearing, females & castrated males, Czech	pH 24 h (LTL)	5.68a	5.63b			$p < 0.001$
		IMF (%) (LTL)	2.38	2.20			n.s.
		Drip loss (%) (LTL)	2.95	2.94			n.s.

LTL – m. longissimus thoracis et lumborum; LT – m. longissimus thoracis; LL – m. longissimus lumborum; SM – m. semimembranosus; SW - slaughter body weight; CW - carcass weight.
a, b, c, d - Different letters in the same row mean significant differences.

- a study on change in space allowance during rearing;
- a description or measure of at least one parameter describing the intrinsic meat quality.

Collectively, 679 papers were evaluated, from which 53 remained in this review after removing duplicates and following remaining criteria as shown in Fig. 1.

2.2. Meat intrinsic characteristics selection

Pork loin is one of the most culinary valuable muscles cut, thus our main focus was on the *m. longissimus thoracis et lumborum* quality attributes. However, in this review we also used studies that evaluated other valuable pork cuts. Out of the broad range of parameters used to describe the intrinsic meat characteristics, we decided to focus on:

- pH as it affects water holding capacity (WHC) and colour, and influences the microbiological quality of meat during chilled storage;
- intramuscular fat (IMF; %) which is associated with sensory traits of pork, mainly tenderness and juiciness;
- drip loss (%), cooking loss (%) as indicators of WHC;
- shear force measured by means of the Warner-Bratzler method as indicator of meat toughness, dependent upon the microstructure of muscle fibres;
- meat colour measures of lightness (L*), redness (a*) and yellowness (b*) as those affect consumers' purchasing decisions;
- fatty acids profile because they are important for consumers as an indicator of pork nutritional value.

3. Results and discussion

3.1. Literature research results

The literature search provided 679 references in total, from which 53 showed strict compliance with the goal of this review. We have used over 80 research papers and reviews for general discussion on pig husbandry practices, pork quality, and consumer preferences. The main goals of this review were evaluated based on 22 papers on the European autochthonous pig breeds and their crossbreeds, nine on the addition of forage to the diet, three on the space, and 19 on the enrichment of the environment (including access to deep bedding i.e., straw).

3.2. Use of local European breeds

It needs to be noted that there were many differences between the experimental setup used in the reviewed studies: rearing conditions (mostly intensive), diet (mostly commercial feed), and finishing slaughter weight (varied from 95 to 220 kg). This could affect the composition of intrinsic meat quality parameters found in different breeds.

Local, non-commercial breeds of pigs are usually more robust under changing environmental factors (e.g., heat waves) and more resilient to diseases and parasites than crossbreed animals (Blacksell, Khounsy, Van Aken, Gleeson, & Westbury, 2006; Nevrkla, Václavková, & Rozkot, 2021; Razmaitė et al., 2019). In addition, these breeds can be easily fed with diets based on natural resources, fodder, and by-products (Friman, Lundh, & Presto Åkerfeldt, 2021; Razmaitė et al., 2019; Rodríguez-Estévez et al., 2009). There is, however, a drawback considering the profitability of rearing local breeds, as they are characterised by a higher feed conversion rate, higher body fat content, and lower carcass meatiness compared to commercial breeds (Cebulska et al., 2018; Franco, Vazquez, & Lorenzo, 2014; Maiorano et al., 2013; Muñoz et al., 2018). Even so, it has been emphasised that work aiming at the improvement of pork quality may increasingly consider the use of local breeds for commercial crossbreeding; for example, the Iberian breed is very frequently crossed with Duroc breed (Ortiz et al., 2020; Ramírez & Cava, 2007). Local pigs represent a valuable genetic reserve for recovering some properties of meat, e.g., high intramuscular fat content (Čandek-Potokar et al., 2003; Franco et al., 2014; Nevrkla et al., 2017; Serra et al., 1998; Wojtysiak & Połtowicz, 2014). However, some breeds are carriers of unwanted gene mutations, e.g., Krskopolje with the *RYR1* mutation responsible for Porcine Stress Syndrome (PSS) or Iberian and Alentejana pigs showing an intermediate frequency of gene polymorphism responsible for boar taint (Muñoz et al., 2018). In commercially-bred pigs, the effect of unwanted genes can be successfully selected against without losing valuable meat quality traits, since those breeds are constantly under genetic improvement. Thus, it is essential to study local purebreds and their crosses to investigate the added value of the

Table 3
Comparison of local and commercial breeds in terms of meat colour.

Reference	Experimental setup, country	Parameter	Breed (and number of animals)					Sig.
Aboagye et al. (2020)	commercial rearing, Apulo-Calabrese up to 135 kg, commercial cross up to 155 kg		**Apulo-Calabrese (51)**	**Duroc x (Landrace x Large White) (52)**				
		L* (LT)	52.8b	56.2a				$p < 0.05$
		a* (LT)	6.80b	4.92a				$p < 0.05$
		b* (LT)	9.69	9.43				n.s
Serra et al. (1998)	commercial rearing conditions, up to 100 kg, Spain		**Iberian (12)**	**Landrace (20)**				
		L* (LL)	54.10 ± 0.7a	55.90 ± 0.6b				$p < 0.05$
		a* (LL)	7.47 ± 0.39	6.57 ± 0.3				n.s.
Čandek-Potokar et al. (2003)	commercial rearing, up to 98 kg, Slovenia		**Krškopolje (17)**		**Landrace male line x Krškopolje (17)**			
		L* (LTL)	54.10 ± 1.1		53.90 ± 1.3			n.s.
Fortina et al. (2005)	commercial rearing conditions, up to 200 kg, Italy		**Casertana (6)**		**Mora R. (11)**			
		L* (LT)	43.26 ± 1.02		42.32 ± 2.05			n.s.
		a* (LT)	9.39 ± 0.08		8.74 ± 0.83			n.s.
		b* (LT)	2.59 ± 0.79		2.24 ± 0.58			n.s.
Florowski et al. (2006)	commercial rearing, up to 100 kg, Poland		**Zlotnicka Spotted (17)**		**Pulawska (17)**	**Polish Landrace (18)**		
		L* (LT)	49.29 ± 2.93		50.68 ± 2.4	50.66 ± 2.47		n.s.
Juárez et al. (2009)	semi-extensive rearing, up to 160-180 kg, Spain		**Lampiño (10)**	**Entrepelado (10)**	**Retinto (10)**	**Torbiscal (10)**	**Iberian x Duroc (10)**	
		L* (LT)	31.37 ± 0.639b	31.58 ± 0.608b	30.06 ± 0.626b	36.99 ± 0.632a	38.28 ± 0.620a	$p < 0.001$
		a* (LT)	12.87 ± 0.529b	14.25 ± 0.504ab	14.53 ± 0.518a	10.11 ± 0.523c	10.24 ± 0.513c	$p < 0.001$
		b* (LT)	9.54 ± 0.356b	12.54 ± 0.339a	12.36 ± 0.349a	5.04 ± 0.352d	6.89 ± 0.346c	$p < 0.001$
Bocian et al. (2012)	commercial rearing, up to 110 kg, Poland		**Złotnicka Spotted (61)**	**Polish Large White × Polish Landrace (35)**				
		L* (LL)	49.30 ± 0.32a	52.37 ± 0.42a				$p < 0.05$
		a* (LL)	17.34 ± 0.11a	16.28 ± 0.15a				$p < 0.05$
		b* (LL)	3.74 ± 0.22	4.49 ± 0.28				n.s.
Szulc, Skrzypczak, et al., 2012	commercial rearing, up to 190 kg, Poland		**Złotnicka Spotted 100% (20)**	**Złotnicka Spotted 75% (20)**		**Złotnicka Spotted 50% (20)**		
		L* (LTL)	49.78 ± 2.52	50.47 ± 2.04		50.15 ± 2.47		n.s.
		a* (LTL)	3.67 ± 0.73	5.17 ± 0.59		4.68 ± 0.7		n.s.
		b* (LTL)	7.41 ± 0.79	8.16 ± 0.78		8.61 ± 0.97		n.s.
Szyndler-Nędza et al. (2021)	commercial rearing, up to 120 kg, Poland		**Złotnicka Spotted (20)**	**Złotnicka Spotted x Polish Large White (20)**	**Złotnicka Spotted x Duroc (10)**	**Złotnicka Spotted x (Złotnicka Spotted x Duroc) (10)**		
		L* (LTL)	46.43 ± 5.46	47.12 ± 1.74	47.33 ± 4.15	46.05 ± 6.71		n.s.
		a* (LTL)	8.17 ± 0.99	6.67 ± 0.7	6.87 ± 1.54	7.98 ± 1.46		n.s.
		b* (LTL)	2.89 ± 1.88	2.17 ± 0.62	2.93 ± 1.8	2.86 ± 1.65		n.s.
Franco et al. (2014)	extensive production with commercial feed, up to 165 kg, Spain		**Celta (16)**	**Celta x Duroc (20)**		**Celta x Landrace (16)**		
		L* (LTL)	47.26a	51.71b		49.47ab		$p < 0.01$
		a* (LTL)	13.07b	9.75a		9.58a		$p < 0.001$
		b* (LTL)	11.71b	10.91ab		10.18a		$p < 0.01$
Maiorano, Kapelański, et al. (2013)	commercial rearing in deep straw, CT up to 140 kg, DU up to 200 kg, LW up to 210 kg, Italy		**Casertana (10)**	**Duroc x (Landrace x Italian Large White) (10)**		**Italian Large White (10)**		
		L* (LL)	39.6	43.43		42.24		n.s.
		a* (LL)	8.99b	6.80a		7.85a		$p < 0.05$
		b* (LL)	2.10	2.84		2.91		n.s.
Wojtysiak and Połtowicz (2014)	commercial rearing, up to 100 kg, Poland		**Puławska (54)**		**Polish Large White (60)**			
		L* (LL)	47.16a		49.62b			$p < 0.05$
		a* (LL)	14.36a		12.63b			$p < 0.05$
		b* (LL)	3.39		3.04			n.s.
Bogucka and Kapelański (2016)	commercial rearing, up to 100 kg, Poland		**Złotnicka Spotted (24)**	**Puławska (10)**	**(Polish Large White × Polish Landrace) × (Duroc × Pietrain) (16)**			
		L* (LL)	49.3 ± 0.45b	51.99 ± 0.90a	53.84 ± 0.60a			$p < 0.05$
		a* (LL)	17.22 ± 0.31a	15.88 ± 0.33b	14.81 ± 0.31b			$p < 0.05$
		b* (LL)	2.53 ± 0.29	2.87 ± 0.31	2.29 ± 0.26			n.s.

(*continued on next page*)

Table 3 (*continued*)

Reference	Experimental setup, country	Parameter	Breed (and number of animals)					Sig.
Cebulska et al., 2018	commercial rearing, up to 105 kg, Poland		**Puławska (25)**	**Złotnicka (25)**	**(Large White × Polish Landrace) x (Duroc × Pietrain) (25)**			
		L* (LL)	52.86 ± 2.67b	49.19 ± 2.31a	53.13 ± 1.97b			$p < 0.05$
		a* (LL)	15.97 ± 0.74b	17.45 ± 1.29c	15.02 ± 1.10a			$p < 0.05$
		b* (LL)	3.53 ± 1.26b	2.66 ± 1.23a	2.40 ± 1.08a			$p < 0.05$
Debrecéni, Lípová, Bučko, et al. (2018)	commercial rearing, up to 100 kg, Hungary/Poland		**Mangalica (9)**	**Mangalica x Duroc (9)**	**Large White (10)**	**Złotnicka Spotted (10)**	**Polish Large White (10)**	
		L* (LTL)	53.00c	63.60a	57.40b	49.20d	52.10 cd	$p < 0.001$
		a* (LTL)	2.7	2.90	0.90	2.70	3.10	n.s.
		b* (LTL)	10.40d	13.10c	10.60d	17.80a	16.10b	$p < 0.001$
Piórkowska et al. (2018)	commercial rearing, up to 100 kg, Poland		**Polish Landrace (8)**		**Puławska (8)**			**Sig.**
		L* (LTL)	55.08 ± 2.21		53.72 ± 1.74			n.s.
		a* (LTL)	16.70 ± 1.19		16.16 ± 0.81			n.s.
		b* (LTL)	2.16 ± 0.99		2.25 ± 0.62			n.s.
Kasprzyk and Bogucka (2020)	commercial rearing, up to 102 kg, Poland		**DanBred (30)**		**Naima (30)**	**Pulawska (30)**		
		L* (LL)	57.80 ± 0.97a		56.59 ± 1.19b	54.94 ± 1.74c		$p < 0.01$
		a* (LL)	0.80 ± 0.70c		1.59 ± 1.40b	1.86 ± 0.90a		$p < 0.01$
		b* (LL)	10.01 ± 0.85		9.93 ± 0.94	9.84 ± 0.46		n.s.
Martins et al., 2020a	outdoor rearing with commercial diet, up to 150 kg, Portugal		**Alentejano (10)**	**Bísaro (10)**	**Alentejano x Bísaro (10)**	**Bísaro x Alentejano (10)**		
		L* (LL)	50.80c	55.7a	53.00b	53.50b		$p < 0.001$
		a* (LL)	10.30a	7.80b	10.30a	10.20a		$p < 0.001$
		b* (LL)	3.57	4.00	4.04	3.93		n.s.
Martins et al. (2020b)	outdoor rearing with commercial diet, up to 150 kg, Portugal		**Alentejano (10)**	**Bísaro (10)**	**Alentejano x Bísaro (10)**	**Bísaro x Alentejano (10)**		
		L* (SM)	35.40	38.40	35.00	35.60		n.s.
		a* (SM)	14.50	14.30	14.00	15.00		n.s.
		b* (SM)	6.70	8.00	6.50	8.00		n.s.
Nevrkla et al. (2021)	commercial rearing, up to 95 kg, Czech		**Prestice Black-Pied (39)**	**(Large White x Landrace) x Large White (37)**				
		L* (LTL)	53.45a	51.80b				$p < 0.001$
		a* (LTL)	1.38	1.56				n.s.
		b* (LTL)	11.35a	10.74b				$p < 0.01$

LTL – m. longissimus thoracis et lumborum; LL – m. longissimus lumborum; SM – m. semimembranosus.
a, b, c, d - Different letters in the same row mean significant differences.

autochthonous breed's genetics and the effect of raising conditions on the meat quality. Such comparisons will help to establish the source of underlying differences between local and commercial breeds. Although local breeds are economically and socially relevant, they can be threatened by inefficient use of feed, and, therefore, sustainable pork chains need to be developed (Vonderohe, Brizgys, Richert, & Radcliffe, 2022).

In this review, 22 research papers comparing the intrinsic meat quality of various local European pig breeds (from the Czech Republic, Hungary, Italy, Poland, Portugal, Slovenia and Spain) and their crosses with commercial lines or different commercial lines have been collected (Table 2, Table 3, Table 4). It should be noted that not only differences in rearing conditions but also pre-slaughter management, the method of slaughter, and post-slaughter management of pig carcasses may also be a source of variation in the quality attributes of pork, hindering the comparison between research papers. Also, the measurement conditions, calibration, and type of equipment used significantly affect traits such as pH and colour.

3.2.1. Pork quality of selected breeds

3.2.1.1. Meat pH and colour. Parameters such as pH at 24 h post mortem (referred to as the ultimate pH), IMF, drip loss (also referred to as natural drip), and shear force (measured with the Warner-Bratzler method) were evaluated in almost all studies comparing meat quality among breeds (Table 2) and only four of them did not provide any significant differences (Juárez, Clemente, Polvillo, & Molina, 2009; Kasprzyk & Bogucka, 2020; Piórkowska, Żukowski, Ropka-Molik, Tyra, & Gurgul, 2018; Szulc et al., 2012; Szulc, Lisiak, Grześkowiak, & Nowaczewski, 2012).

The pH of meat from local breeds is higher than in commercial crosses in Spanish (Serra et al., 1998), Slovenia (Čandek-Potokar et al., 2003), Czech Republik (Nevrkla et al., 2017), Polish (Bocian et al., 2012; Wojtysiak & Połtowicz, 2014; Bogucka & Kapelański, 2016; Cebulska et al., 2018; Debrecéni, Lípová, Bucko, Cebulska, & Kapelánski, 2018; Nevrkla et al., 2021) and Hungarian (Debrecéni, Lípová, Bučko, Cebulska, & Kapelánski, 2018) breeds. Only in three studies on the Spanish breed (Franco et al., 2014). The Polish breed (Szulc, Skrzypczak, et al., 2012) and the Italian breed (Aboagye et al., 2020) were opposite differences reported.

Almost all reviewed papers on comparison among breeds contain at least one parameter of the meat colour (Table 3).

Many of those studies found no significant differences in meat colour between breeds (Čandek-Potokar et al., 2003; Florowski, Pisula, Adamczak, Buczyński, & Orzechowska, 2006; Fortina et al., 2005;

Table 4
Comparison of local and commercial breeds in terms of fatty acids composition (%).

Reference	Experimental setup, country	Parameter	Breed (and number of animals)					Sig.
Aboagye et al. (2020)	commercial rearing, Apulo-Calabrese up to 135 kg, commercial cross up to 155 kg		**Apulo-Calabrese (51)**	**Duroc x (Landrace x Large White) (52)**				
		SFA (LTL)	38.82 ± 0.28	37.96 ± 0.49				n.s.
		MUFA (LTL)	48.76 ± 0.64	47.26 ± 1.09				n.s.
		PUFA (LTL)	12.42 ± 0.67	14.77 ± 1.15				n.s.
Serra et al. (1998)	commercial rearing conditions, up to 100 kg, Spain		**Iberian (12)**	**Landrace (20)**				
		SFA (LL)	34.79 ± 0.42a	32.16 ± 0.33b				$p < 0.001$
		MUFA (LL)	51.67 ± 0.51a	49.50 ± 0.4b				$p < 0.01$
		PUFA (LL)	13.50 ± 0.48a	18.21 ± 0.38b				$p < 0.001$
Fortina et al. (2005)	commercial rearing conditions, up to 200 kg, Italy		**Casertana (6)**		**Mora R. (11)**			
		SFA (LTL)	39.97 ± 0.6		41.31 ± 1.3			n.s.
		MUFA (LTL)	48.23 ± 0.5		47.63 ± 1.3			n.s.
		PUFA (LTL)	11.78 ± 1.1		11.04 ± 0.6			n.s.
Franci et al. (2005)	commercial rearing conditions, up to 136-155 kg, Italy		**Cinta Senese (29)**		**Large White (12)**	**Large White x Cinta Senese (29)**		
		SFA (BF)	36.16a		37.65b	37.12b		$p < 0.05$
		MUFA (BF)	53.25a		51.1b	52.52a		$p < 0.05$
		PUFA (BF)	10.4a		11.11b	10.16a		$p < 0.05$
Juárez et al., 2009	semi-extensive rearing, up to 160-180 kg, Spain		**Lampiño (10)**	**Entrepelado (10)**	**Retinto (10)**	**Torbiscal (10)**	**Iberian x Duroc (10)**	
		SFA (LTL)	38.24 ± 0.680b	38.55 ± 0.648b	38.09 ± 0.667b	40.42 ± 0.673a	41.32 ± 0.660a	$p < 0.01$
		MUFA (LTL)	45.22 ± 1.072	43.68 ± 1.02	43.21 ± 1.05	43.08 ± 1.06	44.54 ± 1.04	n.s.
		PUFA (LTL)	16.53 ± 1.175a	17.76 ± 1.105a	18.69 ± 1.145a	16.48 ± 1.159a	14.13 ± 1.131b	$p < 0.05$
Franco et al., 2014	extensive production with commercial feed, up to 165 kg, Spain		**Celta (16)**	**Celta x Duroc (20)**		**Celta x Landrace (16)**		
		SFA (LT)	42.85b	39.34a		39.90a		$p < 0.001$
		MUFA (LT)	49.57a	52.05b		52.20b		$p < 0.001$
		PUFA (LT)	7.56	8.59		7.89		n.s.
Nevrkla et al. (2017)	commercial rearing, up to 112 kg, Czech		**Prestice Black-Pied (32)**		**Large White × Landrace sows × Duroc × Pietrain boars (32)**			
		SFA (LT)	36.76 ± 2.95		38.59 ± 2.41			n.s.
		MUFA (LT)	50.27 ± 0.55a		47.86 ± 2.09b			$p \leq 0.01$
		PUFA (LT)	12.97 ± 3.37		13.55 ± 3.46			n.s.
Cebulska et al. (2018)	commercial rearing, up to 105 kg, Poland		**Puławska (15)**	**Złotnicka (15)**	**(Large White × Polish Landrace) x (Duroc × Pietrain) (15)**			
		SFA (LL)	37.79 ± 1.89	37.20 ± 1.54	37.49 ± 1.58			n.s.
		MUFA (LL)	52.72 ± 2.06b	47.37 ± 3.02a	45.55 ± 2.55a			$p < 0.05$
		PUFA (LL)	9.32 ± 2.30a	15.19 ± 3.11b	16.77 ± 3.06b			$p < 0.05$
Debrecéni, Lípová, Bucko, et al. (2018)	commercial rearing, up to 100 kg, Hungary/Poland		**Mangalica (9)**	**Mangalica x Duroc (9)**	**Large White (10)**	**Złotnicka Spotted (10)**	**Polish Large White (10)**	
		SFA (LTL)	36.81b	36.89b	39.36a	36.95b	38.16a;b	<0.001
		MUFA (LTL)	50.37b;c	51.24b	54.51a	47.70c	52.45a;b	<0.001
		PUFA (LTL)	12.15a;b	11.53b;c	8.18d	15.09a	9.23c;d	<0.001
Aboagye et al. (2020)	commercial rearing, Apulo-Calabrese up to 135 kg, commercial cross up to 155 kg		**Apulo-Calabrese (51)**			**Duroc x (Landrace x Large White) (52)**		
		SFA (LTL)	38.82 ± 0.28			37.96 ± 0.49		n.s.
		MUFA (LTL)	48.76 ± 0.64			47.26 ± 1.09		n.s.
		PUFA (LTL)	12.42 ± 0.67			14.77 ± 1.15		n.s.

LTL – m. longissimus thoracis et lumborum; LT – m. longissimus thoracis; LL – m. longissimus lumborum; BF – outer layer of backfat.
a, b, c, d - Different letters in the same row mean significant differences.

Martins et al., 2020a; Piórkowska et al., 2018; Szulc, Lisiak, et al., 2012; Szulc, Skrzypczak, et al., 2012). However, certain patterns can be observed. In the studies on Spanish breeds, it can be observed that meat lightness is significantly lower (Franco et al., 2014; Juárez et al., 2009; Serra et al., 1998) than in commercial breeds or crosses with local pigs, whereas redness and yellowness are significantly higher in local breeds (Franco et al., 2014; Juárez et al., 2009). The same direction of the difference between breeds in meat colour can also be observed among Polish local breeds (Bocian et al., 2012; Bogucka & Kapelański, 2016; Cebulska et al., 2018; Debrecéni, Lípová, Bucko, et al., 2018; Kasprzyk & Bogucka, 2020; Wojtysiak & Połtowicz, 2014).

For Czech (Nevrkla et al., 2021), Italian (Aboagye et al., 2020; Maiorano, Gambacorta, et al., 2013), and Hungarian breeds (Debrecéni, Lípová, Bučko, et al., 2018), most of these studies show significant differences between breeds. Czech (Nevrkla et al., 2021), Italian (Aboagye et al., 2020) and Hungarian pig breed (Debrecéni, Lípová, Bucko, et al., 2018) show greater meat lightness than crossbreds with commercial meat breeds (Debrecéni, Lípová, Bucko, et al., 2018; Nevrkla et al., 2021). Lower lightness in these local breeds is reported in comparison to commercial crossbreeds, as in Polish and Spanish breeds. Comparison of the colour of meat of Italian breeds indicated higher redness in local breeds than in commercial breeds (Aboagye et al., 2020; Maiorano, Gambacorta, et al., 2013. Portuguese breeds were compared only to each other and with crosses of two local breeds and that study led to inconclusive results (Martins et al., 2020a, 2020b).

Based on most of the presented research papers it can be concluded that there is a darker colour of pork from local breeds compared to their crosses with commercial breeds.

3.2.1.2. Water holding capacity. Only six studies focused on Polish (Bocian et al., 2012; Cebulska et al., 2018; Debrecéni, Lípová, Bucko, et al., 2018; Florowski et al., 2006), Czech (Nevrkla et al., 2017), and Hungarian breeds (Debrecéni, Lípová, Bucko, et al., 2018) reported significant differences between breeds in terms of drip loss (%) (Bocian et al., 2012; Cebulska et al., 2018; Debrecéni, Lípová, Bucko, et al., 2018; Florowski et al., 2006; Nevrkla et al., 2017). All studies indicated lower drip loss in local breeds than in commercial ones, with the exception of the Hungarian breed with a very high drip loss (Table 2).

Finally, only three studies reported significant differences in shear force between studied traits. The Spanish Celta breed got a higher value of shear force than crosses of this breed with commercial lines (Franco et al., 2014), whereas in Polish (Wojtysiak & Połtowicz, 2014) and Hungarian breeds lower values were obtained (Debrecéni, Lípová, Bucko, et al., 2018). Thus, drawing a conclusion would be very difficult only based on these three studies.

3.2.1.3. Intramuscular fat content. In the case of IMF all studies clearly indicate higher values for local breeds in comparison with commercial ones (Aboagye et al., 2020; Bocian et al., 2012; Čandek-Potokar et al., 2003; Debrecéni, Lípová, Bucko, et al., 2018; Franco et al., 2014; Nevrkla et al., 2017; Serra et al., 1998; Wojtysiak & Połtowicz, 2014). This comes as no surprise as modern commercial breeds are intensively selected for a very limited body fat in general, whereas in local breeds, quite a lot of this fat is very much desired. Pugliese and Sirtori (2012) indicated that the examination of the IMF content is the best way to distinguish local pig breeds from commercial ones. Only in the case of the cross of Mangalica with Duroc did the IMF achieve a higher value than in pure Mangalica (Debrecéni, Lípová, Bučko, et al., 2018). At the same time, it is clear that Spanish and Portuguese breeds, which are all called Iberian ones, have the highest IMF of all local breeds.

3.2.1.4. Fatty acids content in different breeds. The fatty acid (FA) profile of monogastric animals, such as pigs, are strongly affected by the FA composition of their feed, and can be easily manipulated by changes in the diet composition (Dinh et al., 2021; Komprda et al., 2020; Wood et al., 2004, 2008). Thus, the differences between the expected and observed FA profile in this review are mostly linked with the diet offered to the pigs in the comparison studies. The section "Addition of forage in the feed - diet and feed management" describes this aspect in more detail. Moreover, the slaughter weight of pigs may also contribute to FA profile variation in pork (Apple, Maxwell, Galloway, Hamilton, & Yancey, 2009), as well as the sex of examined animals (Zhang et al., 2007).

Only nine reviewed studies focused on the meat quality of local breeds evaluated FA content in meat (Table 4). From those studies two did not find any significant difference between breeds; both focused on local Italian breeds (Aboagye et al., 2020; Fortina et al., 2005). In terms of fatty acids, it is expected that local breeds have a higher content of polyunsaturated fatty acids (PUFA) and monounsaturated fatty acids (MUFA) than commercial breeds, which have a lower content of saturated fatty acids (SFA) (Edwards, 2005; Franci et al., 2005; Nieto et al., 2019). The high content of MUFA may reveal differences in de novo lipid synthesis between local and commercial breeds. Moreover, local pigs are usually slaughtered at higher weights and older ages (Nieto et al., 2019). However, it depends on the studied area; for example, the Italian Parma ham specifications concern Italian Large White, Italian Landrace, Italian Duroc crossbreeds and hybrids pigs >9 months and with 160 ± 10% kg of average body weight at slaughtering per batch (Vitali, Nannoni, Sardi, & Martelli, 2021), while the Spanish Iberian ham specifications require pigs >10 months and with >108 kg of individual carcass weight (Ministerio de Agricultura Pesca y Alimentación, 2014.), approximately >144 kg of individual body weight.

According to Edwards (2005), the pigs' capacity to deposit monounsaturated fatty acids increases with age, increasing MUFA in local pork. Only two studies on Hungarian and Polish breeds (Debrecéni, Lípová, Bucko, et al., 2018) and on Spanish breeds (Juárez et al., 2009) can be used to support the assumption for PUFA, whereas for MUFA there are three studies on Spanish (Serra et al., 1998), Czech (Nevrkla et al., 2017) and Polish breeds (Cebulska et al., 2018). In the case of SFA studies either did not confirm significant differences or actually showed opposite differences than expected; i.e., higher SFA in local breeds in comparison with commercial ones (Cebulska et al., 2018; Franco et al., 2014; Nevrkla et al., 2017), although Debrecéni, Lípová, Bucko, et al. (2018) reported a significant decrease in SFA for Hungarian and Polish breeds, and Franci et al. (2005) showed less SFA in the Italian breed Cinta Senese (CS) than in Large White (LW) and LWxCS. This last study also showed less PUFA in CS and LWxCS than in LW. Besides that, Pugliese et al. (2005) found higher percentages of MUFA in subcutaneous fat of CS outdoor-pigs (55.1% vs. 53.3%) and PUFA (13.2% vs. 10.4%), and higher PUFA/SFA ratio.

3.2.2. Discussion on differences between breeds

Based on the above-listed parameters it is clear that local pig breeds differ from commercial breeds and crossbreeds in many aspects of intrinsic meat quality. Even crosses of the local breed with commercial ones are more similar to pork from commercial breeds (Čandek-Potokar et al., 2003; Franco et al., 2014; Juárez et al., 2009; Szulc, Skrzypczak, et al., 2012; Szyndler-Nędza, Światkiewicz, Migdał, & Migdał, 2021), although their meat quality differs from fully commercial lines. Studies evaluating the quality of pork from the local breeds have also shown that meat from local breeds has higher juiciness and a more unique flavour than crossbreeds (Cebulska et al., 2018; Franco et al., 2014; Ventanas, Ventanas, & Ruiz, 2007). These breed-related differences may affect the usefulness of pork for culinary purposes or processing, the purchasing decisions of consumers (based on visual attributes of raw pork), as well as the quality and shelf life of processed products (Gramyn, 2020; Meier et al., 2021; Moeller et al., 2010). This is especially important when considering local breeds for crossbreeding purposes with commercial lines. However, it needs to be kept in mind that the breed type is responsible for intrinsic meat quality to a limited extent, since diet, rearing conditions, pre-slaughter handling and slaughtering, carcass refrigeration, as well as meat aging conditions and duration greatly contribute to the final quality of the pork.

Table 5
Overview of studies focused on comparison of the effect of addition of forage to feed on meat intrinsic quality.

Reference	Breed	Rearing conditions	Weight at slaughter	Muscle	Tested diets (number of animals)				
Sundrum, Bütfering, Henning, and Hoppenbrock (2000)	Pietrain × [Landrace×Large White]	individually housed (2.5 × 1 m)	120 kg	LTL	Conventional diet (25)	Faba beans + Potato proteins (25)	Peas + Lupines (25)	Faba beans + Lupines (25)	
Johansson et al. (2002)	Hampshire x [Swedish Landrace x Swedish Yorkshire]	commercial rearing	108 kg	LTL	Conventional diet (19)	Conventional feed with red clover silage (21)			
Hansen et al. (2006)	DurocxDanish LandracexLarge White	organic	108 kg	LTL	Concentrate (39)	Organic concentrate (37)	Roughage -barley/pea silage (38)	Roughage - clover grass silage (38)	
Turyk et al. (2014)	Polish Synthetic Line 990 x Polish White Large	pens with straw bedding	108 kg	LTL	conventional feed (8 gilts +8 barrows)	grass forage (8 gilts +8 barrows)	grass forage + herbs (8 gilts +8 barrows)		
Degola and Jonkus (2018)	Yorkshire Landrace	commercial rearing	100 kg	LTL	Soybean meal (10)	Pea 15% (10)	Pea 28% (10)	Faba bean 20% (10)	Faba bean 25% (10)
Jordan et al. (2018)	Swedish Landrace x Large White	commercial rearing	96 kg	LTL SM	Control (32)	Straw (32)	Hay (32)		
Degola et al. (2021)	Yorkshire × Landrace	commercial rearing	112 kg	LTL	Compound feed with local coated barley (20)	Compound feed with local hulless barley (20)			
Szyndler-Nędza et al. (2021)	Złotnicka Spotted	commercial rearing	100 kg	LTL	Indoor with commercial feed (6)	Outdoor with roughage (grass, whole-crop maize silage, acorns) (7)			
Argemí-Armengol et al. (2022)	Spanish local breed	organic	95 kg	LTL	Concentrate (23)	Oat silage (33)			

LTL – m. longissimus thoracis et lumborum; SM – m. semimembranosus.

3.3. Addition of forage into the diet and feed management

Diet and feed management most obviously affect intrinsic pork quality, along with the breed. The structure of the gastrointestinal tract of monogastric animals causes many dietary components, such as FA, to be readily transferred from the feed to the muscle and fat tissues, subsequently affecting pork quality (Rosenvold & Andersen, 2003; Sundrum, 2007). Thus, through the use of adequate feed components in animal nutrition (i.e. vitamins and minerals, fatty acids, phytobiotics, and other feed additives) the characteristic of the meat can be modified and improved (Kasprowicz-Potocka, Zaworska-Zakrzewska, & Rutkowski, 2020; Pettigrew & Esnaola, 2001; Rosenvold & Andersen, 2003; Sundrum, 2007). Diet was shown to affect some health indicators, as some studies reported that a low crude protein diet improved enteric health, growth performance, and immune status and decreased the risk of diarrhoea (Fang et al., 2019; Kiki et al., 2019). Moreover, high fibre diets are known to improve some aspects of pig health and welfare. Provision of roughage and dietary fibre stimulates gut health (Bach Knudsen, Hedemann, & Lærke, 2012), increases time spent eating, and improves satiety (De Leeuw, Bolhuis, Bosch, & Gerrits, 2008). Fibre also decreases nutrient use depending on the properties of the fibres used (Lindberg, 2014; Noblet & Le Goff, 2001), and thus these may negatively impact the growth rate. Besides, fermentable carbohydrates in the diet shift nitrogen excretion from urine towards foeces, thereby reducing nitrogen losses into the environment (Jarrett & Ashworth, 2018). The bacterial fermentation of carbohydrates results in methane production, while increasing fermentable carbohydrates in the diet reduces ammonia emission but increases methane emission (Aarnink & Verstegen, 2007). The provision of a fibre-rich diet may also affect some meat quality attributes (Li et al., 2021). Thus, the addition of forage to the diet is one of the husbandry extensification factors with a possible effect on intrinsic meat quality that is studied in this review.

3.3.1. Meat characteristics under diets with forage

Nine studies on the use of forage in the diet have been reviewed (Table 5). These studies unfortunately differ in many aspects of the experimental set up: rearing conditions, the breed used, slaughter weight, and most importantly, the tested diet. On top of that, there was very limited overlap between studies in the evaluated meat parameters, and most of those analyses did not give significant results.

3.3.1.1. Meat pH and colour. The pH at 24 h was measured in only five of the reviewed studies (Degola, Jansons, & Šterna, 2021; Degola & Jonkus, 2018; Hansen, Claudi-Magnussen, Jensen, & Andersen, 2006; Jordan, Gorjanc, Štuhec, & Žgur, 2018; Turyk, Osek, Olkowski, & Janocha, 2014) with a significant difference only reported in the study by Jordan et al. (2018), where the addition of straw and hay to commercial diet (the pigs received daily 100 g of wheat straw or hay per animal) led to the development of a lower pH in the LTL in comparison to fully commercial diet (control: 5.85; straw: 5.71; hay: 5.74).

The colour parameters (L*, a*, b*) were only measured in three studies (Hansen et al., 2006; Szyndler-Nędza et al., 2021; Turyk et al., 2014), although one of them reported significant differences.

3.3.1.2. Water holding capacity. Insignificant differences were also reported for drip loss by Hansen et al. (2006) when three feeding regimes were compared: 100% organic concentrate according to Danish recommendations, 70% organic concentrate (restricted) plus ad libitum organic barley/pea silage, and 70% organic concentrate (restricted) plus ad libitum organic clover grass silage.

3.3.1.3. Intramuscular fat content and fatty acids composition. Only two of the reviewed studies reported IMF when comparing the meat from conventionally-fed vs. feed with forage. Johansson, Lundström, and Jonsäll (2002) showed that IMF in meat of commercially-fed pigs was higher than in pigs fed with commercial diet and roughage (2.2% vs. 1.7%; $p \leq 0.01$), a difference that was confirmed by Hansen et al. (2006)

Table 6
Overview of studies focused on comparison of the effect of space allowance on meat intrinsic quality.

Reference	Breed	Rearing conditions	Weight at slaughter	Muscle	Tested space (with number of pigs)	
Liorančas et al. (2006)	Danish Landrace × Danish Yorkshire × Danish Duroc	commercial rearing	114 kg	LTL	0.5 m^2/pig (10)	1.2 m^2/pig (10)
Serrano et al. (2013)	Large White x (Landrace × Large White)	commercial rearing	110 kg	LT	0.76 m^2/pig (114)	0.84 m^2/pig (114)
Nannoni et al. (2019)	Duroc × (Landrace × Large White) barrows	commercial rearing	160 kg	LTL SM	1 m^2/pig (30)	1.3 m^2/pig (30)

LTL – m. longissimus thoracis et lumborum; LT – m. longissimus thoracis; SM – m. semimembranosus.

(conventional: 1.6%, conventional organic: 1.5% vs. barley/pea silage: 1.2%, clover grass silage: 1.2%; $p < 0.05$). These results are interesting since Johansson et al. (2002) only added some forage to commercial feed, whereas Hansen et al. (2006) composed the whole diet based on roughage. Based on these two studies alone it could be concluded that only a small proportion of forage would affect the IMF in pork, but it should be considered that the fat deposition, including the IMF in pork, is affected by excessive or restrictive feeding. Therefore, in the case of restricted feed (energy) allowance, a low content of IMF in the muscle tissues is expected (Chen et al., 2021; Liu et al., 2007).

More differences were expected to be observed in FA composition within diets with forage. However, from four studies evaluating FA composition in meat (Argemí-Armengol et al., 2022; Degola et al., 2021; Hansen et al., 2006; Johansson et al., 2002) only two of them reported significant effects of the diet with forage. Hansen et al. (2006) evaluated the effect of four diets: 1) concentrate, 2) organic concentrate, 3) roughage - barley/pea silage, and 4) roughage - clover grass silage, with different levels of feed allowance (ad libitum or restricted). The fatty acids in the meat of pigs fed with a roughage-based diet were always significantly different from pigs with concentrate: percentages of SFA were lower (40.7, 40.4 vs. 38.6, 38.5%; $p < 0.05$), percentages of MUFA were also lower (45.3, 43.3, 42.5 and 41.9%, respectively, $p < 0.05$) whereas percentage of PUFA were higher (13.6, 15.4, 17.5 and 18.0%, respectively, $p < 0.05$). The same direction of the differences was shown by Johansson et al. (2002) in a study comparing the effect on meat quality of a purely conventional diet vs. conventional feed with silage addition (the amount of forage, on a wet weight basis, was 1.25 kg/day, equal to 10% of the total energy intake); SFA: 36.0 vs. 35.3 ($p = 0.035$), MUFA: 48.2 vs. 45.4 ($p = 0.019$), PUFA: 15.9 vs. 19.2 ($p = 0.009$).

Based on these studies, it could be concluded that a higher amount of forage in the diet does not affect the FA composition; however, feed allowance is a source of variation of this trait, and is connected to different IMF content.

3.3.2. *Meat quality affected by foraging and pasture availability*

To fully understand how a forage-based diet can affect meat quality, it is necessary to investigate the effect of natural foraging on pork. In Spain, where Iberian pigs are fattened in the *montanera* system ('pannage' in English) foraging acorns and grass (Rodríguez-Estévez et al., 2009), the meat shows high oleic, linoleic, and total n-3 fatty acids contents (e.g. Daza, Ruiz-Carrascal, Olivares, Menoyo, & Lopez-Bote, 2007; Rey, Daza, López-Carrasco, & López-Bote, 2006). It should be stressed that montanera is not limited to foraging acorns and grass as feed resources, but includes also differences in pig environmental and rearing conditions (Ortiz et al., 2020).

3.3.2.1. Intramuscular fat and fatty acids profile. Daza et al. (2007) found that the content of these beneficial fatty acids in pork increases with the time spent in the montanera fattening system. This relation was also confirmed by Rey et al. (2006). The authors observed that the grass intake significantly increased the proportion of C18:3n − 3 in the inner and outer fat layers in IMF. Also, Lebret and Guillard (2005) observed a higher content of C18:3n-3 in the LTL of sows reared outdoors compared to those from an indoor system. The outdoor rearing affects the proportion of linolenic acid but also C22:5 and C22:6 of the inner backfat layer and IMF (Rey et al., 2006).

There are, however, not only positive effects of altering the fatty acid profile in pork. An increased amount of PUFA in muscles makes the tissue more susceptible to lipid oxidation and makes the fat softer, which may affect the sensory and technological properties of meat (Amaral, Da Solva, & Lannes, 2018; Shimizu & Iwamoto, 2022). In this context, the composition of antioxidants in the feed and the meat, such as vitamin E, are relevant. Several studies have shown that the content of α-tocopherol, a powerful antioxidant, is higher in the pork of pigs reared with access to natural forage (Nilzén et al., 2001), whereas González and Tejeda (2007) showed that pork from Iberian pigs free-range reared or fed with concentrated diets supplemented with α-tocopherol from natural sources has a more effective defense against lipid oxidation in muscle than pigs supplemented with synthetic α-tocopheryl acetate.

It needs to be noted that the possibility to forage has proven to be an important factor affecting pig growth (Carcò et al., 2018; Kavlak & Uimari, 2019; Rauw, Soler, Tibau, Reixach, & Gomez Raya, 2006; Rodríguez-Estévez, Sánchez-Rodríguez, García, & Gómez-Castro, 2010), which was recently confirmed in a comprehensive review on the link between feeding behaviour and carcass quality (Fornós et al., 2022).

Based purely on the studies comparing the addition of forage to the diet, not many conclusions can be drawn due to the many differences between studies and limited differences found between diets in those studies. In fact, it is required to provide pigs with the access to outdoor pasture, where natural foraging behaviour can take place in order to see more clear direction in the effect of forage on meat quality. However, many more factors have effects on pigs, e.g.: natural daylight, temperature, changing weather conditions, space allowance, exercise or physical activity, among others; thus, it is very difficult to assume that the observed differences are only due to forage/foraging.

3.4. *Indoor space allowance during rearing*

The European pig welfare regulation (Council of the European Union, 2008) sets down the minimal space area of 0.30m^2 per growing pig of 20–30 kg live weight (LW), and 0.65m^2 per finishing pig of 85–110 kg LW. By contrast in organic pig farming that is 0.6 m^2/pig up to 30 kg LW and 1.3 m^2/pig for 85–110 kg LW for the indoor area, and for the 'outdoor' area (mandatory): 0.4 m^2/pig up to 30 kg LW and 1.0 m^2/pig for 85–110 kg LW (European Commission, 2018).

3.4.1. *Meat quality affected by space allowance*

Only three studies purely focused on additional space allowance and its effect on pork quality have been found: Liorančas, Bakutis, and Januškevičiene (2006), Serrano et al. (2013), and Nannoni, Martelli, Rubini, and Sardi (2019) (Table 6). Each of these studies compared different square metre footage per pig using the different commercial three-way crosses, and measuring different intrinsic meat parameters.

3.4.1.1. Meat pH and colour. The pH measured 24 h post mortem was reported by these three studies, but only Liorančas et al. (2006) indicated significant differences when comparing 0.5 vs. 1.2 m^2/pig: 5.61 vs. 5.64 ($p < 0.0001$). Colour was measured in two studies, by Liorančas et al. (2006) and Nannoni et al. (2019), only in the latter a significant difference was found between groups of different space allowance (1.0 vs. 1.3 m^2/pig) for parameter a*: 9.5 vs. 7.9 ($p < 0.01$).

3.4.1.2. Intramuscular fat and fatty acids content in different breeds. Serrano et al. (2013) was the only study to look into IMF, but again without reporting significant differences between groups of different space allowance. Serrano et al. (2013) and Nannoni et al. (2019) also presented FA profiles in pork coming from pigs provided with different space allowance. However, only the first study showed some significant results when comparing 0.72 vs. 0.84 m^2/pig for MUFA content in meat: 49.47 vs. 48.04% ($p < 0.01$).

3.4.2. Discussion on the effect of space allowance on meat quality

It should be noted that despite the general lack of significant differences in meat quality between the studied space allowances, in two studies, the pigs in pens with extra space grew faster than those in smaller pens: 800 vs. 760 g/day ($p < 0.001$; Liorančas et al., 2006) and 619 vs. 583 g/day ($p < 0.01$; Nannoni et al., 2019). This is an important finding that could give the farmer an indication of added value to welfare; even though a lower number of pigs can be reared, the animals will have easier access to feeders, and thus, they will grow faster than those reared in smaller pens. However, a meta-analysis by Averós et al. (2010) predicted different effects of space allowance depending on the presence/absence of a slatted floor on the feed conversion rate of growing-finishing pigs, with a negative effect of space for the slatted floor (more consumption) and positive effect for a solid floor. Nonetheless, based on these findings, it can be concluded that space allowance during rearing is the least investigated factor affecting the meat quality in pigs. Naturally, this statement refers only to the studies that focused on this one factor. In the section on "Environmental enrichment and housing conditions" (section 4) space allowance and its interaction with other factors will be reviewed.

3.5. Environmental enrichments under different production conditions

The level of environmental enrichment (here defined as availability of bedding, manipulable enrichments including novelty, addition of forage in feed) differs largely between intensive and extensive production systems, particularly between indoor and outdoor rearing systems. Therefore, in the majority of studies, the effects of environmental enrichment on meat quality are confounded with either rearing system (indoor versus outdoor) and/or with space allowance.

Pigs spend a considerable amount of their awake time on foraging behaviour when reared under semi-natural and natural conditions (Holm, Jensen, Pedersen, & Ladewig, 2008; Jensen & Pedersen, 2008; Rodríguez-Estévez et al., 2010; Stolba & Wood-Gush, 1989), therefore the provision of edible enrichment materials such as straw, hay, or corn-silage in intensive production systems contribute to fulfill the behavioural need for rooting and exploration (Bolhuis, Schouten, Schrama, & Wiegant, 2005; Jordan et al., 2018; Studnitz, Jensen, & Pedersen, 2007; Wallgren & Gunnarson, 2022). Unfortunately, conventional production conditions are barren and generally lack environmental enrichments. Slatted floor pens with slurry systems underneath do not allow for the provision of biologically relevant materials in which pigs can root and forage (Pedersen, 2018). Also, the costs for bedding material and labour, and biosecurity risks (e.g. straw or green forage may be African Swine Fever virus vectors) often discourage the farmers to use materials that are truly valued by pigs (How, Have, Come, & Van De Weerd, 2019; Tuyttens, 2005; Woźniakowski, Pejsak, & Jabłoński, 2021). However, the lack of environmental enrichments causes frustration and stress, and thus is a common risk factor for tail biting (Averós et al., 2010; D'Eath et al., 2016; Godyń, Nowicki, & Herbut, 2019; Larsen, Andersen, & Pedersen, 2018). For that reason, the European Commission (2001/93/EC) demands that "*pigs must have permanent access to a sufficient quantity*

Table 7
Effect of housing conditions (access to outdoors; space allowance, access to bedding; straw in racks etc.) on pork quality – characteristic of the research materials.

References	Breed	Housing conditions	
Beattie et al. (2000)	Large White x Landrace	EN: extra space with peat and straw in the rack; 1.75 m^2/ pig at 8–14 weeks 3.5 m^2/ pig at 15–21 weeks	CON: indoors (slatted floor with minimum space allowance) 0.36 m^2/ pig at 8–14 weeks 0.76 m^2/ pig at 15–21 weeks
Bee et al. (2004)	Large White	OUT: housed outdoor (0.92 ha pasture)	CON: housed indoor (individually, 2.6 m^2 pens)
Dostálová, Svitáková, Bureš, Vališ, and Volek (2020)	Prestice Black-Pied	OUT: outdoor pen 1 m^2/ pig; straw bedding	CON: indoor pen 1 m^2/ pig; straw bedding
Foury et al. (2011)	Housing conditions 1 and 2: pigs born from Large White x Pietrain boars Housing conditions 3: pigs born from P76 boars	OUT: 150 m^2/ pig; straw bedding 1.30 m^2/pig; hut with access to courtyard 1.30 m^2/ pig	CON: fully slatted floors; 0.65 m^2/ pig
Galián et al. (2009)	Chato Murciano; 2 groups according to slaughter weight: > 125 kg and < 125 kg	OUT: 120 m^2/ pig; 5 huts; commercial diet	CON: indoor; 2 m^2/ pig; commercial diet
Gentry et al. (2002)	No data	Experiment 1: OUT: outdoor pens 2.0 m^2/ pig; two huts 9 × 15 m with bedding and a wallow	CON: controlled conditions; concrete-slatted flooring: 1.0 m^2/ pig
		Experiment 2: OUT: alfalfa pasture; 212m^2/ pig; one hut/ pen with straw as bedding	CON: controlled conditions; concrete-slatted flooring: 1.2 m^2/ pig
		Experiment 3: EN: indoor pens 12.0 m^2/ pig; fescue hull bedding	CON: controlled conditions; concrete-slatted flooring: 7.5 m^2/ pig
Hoffman et al. (2003)	Landrace x Large White	OUT: housed outdoors; 1800 m^2 pen with a hut filled with straw	CON: indoors; 100 m^2 Pen with concrete floor
Klont et al. (2001)	Great Yorkshire x [Great Yorkshire x Dutch Landrace]	EN: pens (4.64 m^2) with half concrete area covered with straw and half concrete slats.	CON: pens (3.36 m2) with half concrete lying area and half concrete slatted floor
Latoch et al. (2021)	No data	OUT: indoor 1 m^2 pen with sawdust bedding and access to outdoor 1 m2 pen (organic system); fed organic feed	CON: indoor, 1 m^2 pens; fed commercial feed
Lebret et al. (2006)	Crossbred synthetic line x (Large White x Landrace)	OUT: sawdust bedding; 1.3 m^2/ pig, access to outdoor area: concrete floor, 1.1 m^2/pig	CON: fully slatted floor, 0.62 m^2/ pig

(*continued on next page*)

Table 7 (*continued*)

References	Breed	Housing conditions	
Lebret et al. (2015)	Large White French local Basque	OUT: free-range 10 pigs/ 2.5 ha pasture EN: sawdust bedding and outdoor area a total of 2.4 m^2/pig	CON: indoors, slatted floor 1.0 m^2/pig
Maiorano, Kapelański, et al. (2013)	Polish Landrace	OUT: outdoors; 24 m^2 paddocks; commercial diet and corn grain silage	CON: indoor; 6 m^2 pens; 2 pigs/ pen; commercial diet
Millet et al. (2004)	Piétrain x (Belgian Landrace x Duroc)	OUT: indoor area 2 m^2/ animal, with straw bedding; outdoor area 2 m^2/ animal, concrete floor; conventional or organic diet	CON: indoors; 1 m^2/ animal Pen with 75% concrete floor and 25% slats; conventional or organic diet
Omana et al. (2014)	Large White x Landrace	OUT: indoors with bedding; access to outdoors	CON: indoors; controlled environment
Ortiz et al. (2021)	Iberian x Duroc	OUT: finishing phase (67 days) in the Montanera system; 0.60 pigs/ ha; unlimited access to acorns and grass	CON: indoors; 2 m^2/ pig; the commercial feed
Patton et al. (2008)	No data	EN: deep bedded with hoop structures 0.70 m^2/pig	CON: Indoors; conventional system 0.70 m^2/pig
Pugliese et al. (2004)	Nero Siciliano	OUT: pastures and woods	CON: indoors in pens; fed commercial diet
Pugliese et al. (2005)	Cinta Sense	OUT: pastures and woodlands; access to a shed	CON: indoors in pens; fed commercial diet
Wójciak et al. (2021)	No data	OUT: indoor area with gravitation ventilation; 1 m^2/ pen; access to 1 m^2 outdoor area	CON: indoors in pens; 1 m^2/ pen; controlled climate

CON – conventional; OUT – outdoors; EN – access to enrichments.

of materials to enable proper investigation and manipulation activities, such as straw, hay, wood, sawdust… which does not compromise the health of the animals".

3.5.1. *Meat quality affected by environmental enrichment*

Studies focusing purely on one factor of environmental enrichment, e.g., barren pens vs. deep-straw bedding pens, are widely used in the evaluation of the welfare and behaviour of pigs, but these rarely investigate the effect of enrichment on pork quality. In this section we will review the existing literature comparing the effect of different rearing conditions (conventional vs. enriched, indoor vs. outdoor) on meat quality parameters. In total, 19 papers on environmental enrichment have been found (Table 7) and used in this review.

3.5.1.1. Meat pH. The pH ultimate (pHu) value in the meat is strongly affected by pre-slaughter stress. It was shown that pigs housed either outdoors or in indoor systems with access to any type of enrichments (deep bedding, straw in racks etc.) seem to cope with pre-slaughter stress better compared to pigs from barren environments, based on the speed and level of lactate formation in the postmortem muscles (Chaloupková, Illmann, Neuhauserová, Tománek, & Vališ, 2007; Ekkel, van Doorn, Hessing, & Tielen, 1995; Millet, Moons, Van Oeckel, & Janssens, 2005). From the 19 studies selected, the pHu value was examined in 16 of them. There seems to be a clear effect of rearing pigs outdoors on the pHu in most muscles (Bee, Guex, & Herzog, 2004 - pasture; Millet et al., 2004 - access to outdoor paddock; Galián, Poto, & Peinado, 2009 - outdoor run with a hut and trees; Foury et al., 2011- hut and access to courtyard; Lebret et al., 2006, Lebret et al., 2015 - outdoor paddock; Maiorano, Kapelański, Bocian, Pizzuto, & Kapelańska, 2013 - indoor pen with straw and access to outdoor paddock Omana et al., 2014 - access to outdoor paddock), except for the LTL which was not always affected (Bee et al., 2004; Lebret et al., 2006) (Table 8). It should be stressed that the pigs kept outdoors are exposed to seasonal weather changes and heat stress, and these have been shown to strongly affect the muscle metabolism and the pHu of meat (Čobanović et al., 2020). In addition, it is not clear from these studies if the outdoor rearing can be contributed to factors such as more space, or due to increased environmental enrichment. One study on indoor-kept pigs points to an effect

Table 8
The pH levels of pork affected by the housing conditions.

References	Groups/ muscles	OUT/EN	CON	Sig.
Bee et al. (2004)	LTL	5.50	5.50	n.s.
	RF	5.60b	5.70a	$p < 0.01$
	STD	5.70b	5.90a	$p < 0.01$
	STL	5.60b	5.70a	$p < 0.01$
Dostálová et al. (2020)	LL	5.55	5.58	n.s.
Foury et al. (2011)	SM			
	Housing conditions 1	5.53b	5.58a	$p < 0.001$
	Housing conditions 2	5.69b	5.90a	$p < 0.001$
	Housing conditions 3	5.62	5.69	n.s.
Galián et al. (2009)	LTL			
	> 125 kg BW	5.60b ± 0.06	5.70a ± 0.1	$p < 0.05$
	< 125 kg BW	5.60 ± 0.2	5.60 ± 0.1	n.s.
Gentry et al. (2002)	LTL			
	Outdoors; Summer	5.60	5.50	n.s.
	Outdoors; Winter	5.70	5.70	n.s.
	Enriched	5.50	5.50	n.s.
Hoffman et al. (2003)	LTL	5.52	5.53	n.s.
Klont et al. (2001)	LL	5.68a	5.56b	$p < 0.05$
	BF	5.81a	5.67b	$p < 0.05$
Latoch et al. (2021)	loin	5.70 ± 0.1	5.80 ± 0.1	n.s.
	ham	5.80 ± 0.1	5.80 ± 0.1	n.s.
	shoulder	6.00 ± 0.2	6.10 ± 0.1	n.s.
Lebret et al. (2006)	LTL	5.50	5.49	n.s.
	BF	5.49b	5.52a	$p < 0.05$
	SM	5.50b	5.57a	$p < 0.001$
Lebret et al. (2015)	LW: EN vs. CON	5.48	5.47	n.s.
	BA: EN vs. CON	5.54	5.58	n.s.
	BA: OUT vs. CON	5.67a	5.58b	$p < 0.01$
Maiorano, Kapelański, et al. (2013)	LTL	5.38	5.41	n.s.
Millet et al. (2004)	LTL (OF/ CF)	5.59/ 5.42	5.52/ 5.48	$p < 0.05$
	SM (OF/ CF)	5.63/ 5.53	5.65/ 5.63	$p < 0.01$
Omana et al. (2014)	loin	5.48b	5.52a	$p < 0.05$
Ortiz et al. (2021)	LTL	~5.70		n.s.
Patton et al. (2008)	LTL	5.32	5.40	n.s.
Pugliese et al. (2005)	LL	5.78	5.78	n.s.

CON – conventional; OUT – outdoors; EN – access to enrichments.
LTL – m Longissimus thoracis et lumborum; BF – m. Biceps femoris; SM – m. Semimembranosus; RF – m. Rectus femoris; STD – m. Semitendinosus dark portion; STL – m. Semitendinosus light portion.
LW- Large White; BA - French local Basque.
OF – organic feed; CF – conventional feed.
a, b, – Different letters in the same row mean significant differences.

Table 9
Colour coordinates of pork as affected by the housing conditions.

Literature		L*			a*			b*		
		OUT/EN	CON	Sig.	OUT/EN	CON	Sig.	OUT/EN	CON	Sig.
Bee et al. (2004)	LTL	47.30b	48.8a	$p < 0.01$	8.50	8.20	n.s.	6.30	6.30	n.s.
	RF	44.60	45.10	n.s.	12.00	10.80	n.s.	7.90a	7.00b	$p < 0.01$
	STD	44.70	45.00	n.s.	14.00	13.90	n.s.	8.50	8.50	n.s.
	STL	51.90	52.40	n.s.	9.70	10.00	n.s.	7.60	7.70	n.s.
Galián et al. (2009)	BW									
	> 125 kg	46.50	43.40	n.s	13.10b	14.50a	$p < 0.05$	5.30	3.10	n.s.
	< 125 kg	49.60	49.70	n.s.	13.30b	18.40a	$p < 0.05$	5.50	6.60	n.s.
Gentry et al. (2002)	Outdoors; Summer	42.20	48.10	n.s.	3.70	3.20	n.s.	11.40	11.10	n.s.
	Outdoors; Winter	56.30	54.10	n.s.	9.90	10.70	n.s.	17.50	17.10	n.s.
	Enriched	46.00	46.20	n.s.	5.60	5.70	n.s.	12.20	12.00	n.s.
Hoffman et al. (2003)	LTL	53.98	55.32	n.s.	3.46a	2.81b	$p < 0.05$	10.10	10.47	n.s.
	LL	56.60	56.60	n.s.	6.50	6.90	n.s.	12.90	13.40	n.s.
Klont et al. (2001)	BF	48.60	49.60	n.s.	10.40	10.40	n.s.	12.80	13.30	n.s.
Latoch et al. (2021)	loin	57.75a	55.44b	$p < 0.05$	1.98a	0.62b	$p < 0.05$	10.28a	8.96b	$p < 0.05$
	ham	50.27	49.40	n.s.	5.52	6.05	n.s.	10.73a	9.57b	$p < 0.05$
	shoulder	48.23	49.45	n.s.	7.84a	6.38	$p < 0.05$b	10.04a	9.08b	$p < 0.05$
Lebret et al. (2006)	LTL	55.20	55.40	n.s.	5.8	5.50	n.s.	5.70a	5.00b	$p < 0.01$
	BF	52.00	51.20	n.s.	10.90	10.70	n.s.	6.70a	6.20b	$p < 0.05$
	SM	53.00	53.00	n.s.	9.70	9.00	n.s.	6.90a	6.40b	$p < 0.05$
Lebret et al. (2015)	LW: EN vs. CON	53.80	53.60	n.s.	9.14	8.65	n.s.	7.23	6.70	n.s.
	BA: EN vs. CON	51.60	51.20	n.s.	9.67	9.61	n.s.	6.85	6.55	n.s.
	BA: OUT vs. CON	48.10b	51.20a	$p < 0.01$	9.30	9.61	n.s.	4.89b	6.55a	$p < 0.001$
Millet et al. (2004)	LTL (OF/ CF)	55.6/ 60.1	57.6/ 58.3	n.s.	8.24/ 7.41	6.96/ 6.70	$p < 0.001$	16.39/ 16.60	15.92/ 16.11	$p < 0.05$
Omana et al. (2014)	Loin	55.69a	53.41b	$p < 0.05$	6.94a	6.70b	$p < 0.01$	7.05a	6.11b	$p < 0.05$
Ortiz et al. (2021)	LTL	46.97b	51.05a	$p < 0.001$	13.66a	10.72b	$p < 0.001$	8.03a	7.31b	$p < 0.05$
Patton et al. (2008)	LTL	54.48	54.40	n.s.	8.06	8.26;	n.s.	14.19	14.17	n.s.
Pugliese et al. (2005)	LL	45.78b	50.13a	$p < 0.05$	14.95	11.77	$p < 0.05$	5.38	4.81	n.s.

CON – conventional; OUT – outdoors; EN – access to enrichments.
LTL – m Longissimus thoracis et lumborum; BF – m. Biceps femoris; SM – m. Semimembranosus; RF – m. Rectus femoris; STD – m. Semitendinosus dark portion; STL – m. Semitendinosus light portion.
LW- Large White; BA - French local Basque.
OF – organic feed; CF – conventional feed.
a, b, c, d - Different letters in the same row mean significant differences.

of either space or environmental enrichment on lactate formation in the carcass of pigs from indoor systems, with more space and increased enrichment leading to lower lactate formation in LL muscle compared to indoor-kept pigs with conventional space and no enrichment (access to straw), resulting in a lower pHu (Klont et al., 2001). Most researchers observe a lower value of pHu in pork from outdoor-reared fatteners than in pork from pigs reared in conventional systems (Bee et al., 2004; Foury et al., 2011; Galián et al., 2009; Lebret et al., 2006; Maiorano, Kapelański, et al., 2013; Omana et al., 2014). In these studies it is not possible to differentiate between the factors related to outdoor conditions, the ones that contributed to this effect (e.g. space, enrichment or other factors related to outdoor rearing). Only two trials reveal a totally reverse impact of an extensive system with outdoor access on pHu in pork (Lebret et al., 2015; Millet et al., 2004).

3.5.1.2. Meat colour. Fifteen of the reviewed papers report the effect of the housing system on the colour of pork expressed as L*, a*, b* (Table 9). Only six of these papers confirm that access to an outdoor area significantly affects pork lightness (L* coordinate) (Bee et al., 2004; Latoch, Wójciak, Popek, Rohn, & Halagarda, 2021; Lebret et al., 2015; Omana et al., 2014; Ortiz et al., 2021; Pugliese et al., 2005), but the results are discrepant and do not lead to a clear conclusion. Enriched environments and/or increased space and outdoor access did not affect the L* of pork (Klont et al., 2001; Lebret et al., 2006; Patton et al., 2008). Of the selected research papers, 8 of them pointed to the effect of the access to outdoors on the a* coordinate, with most research stating that pork from outdoor-reared pigs is redder compared to those kept on conventional indoor farms (Hoffman, Styger, Muller, & Brand, 2003; Latoch et al., 2021; Lebret et al., 2015; Millet et al., 2004; Omana et al., 2014; Ortiz et al., 2021; Pugliese et al., 2005), and only one shows redder meat from indoor-reared pigs (Galián et al., 2009). As for the

Table 10
The drip loss of the loin affected by the housing conditions.

References	Drip loss [%]		Sig.
	OUT/ EN	CON	
Bee et al. (2004)	2.00a	1.85b	$p < 0.05$
Dostálová et al. (2020)	3.03	3.01	n.s.
Gentry et al. (2002)	1.70a	0.70b	$p < 0.05$
	0.80	0.90	n.s.
Hoffman et al. (2003)	3.91	4.11	n.s.
Klont et al. (2001)	2.90	4.00	$p = 0.05$
Latoch et al. (2021)	5.66	4.73	n.s.
Lebret et al. (2006)	3.30a	2.30b	$p < 0.05$
Lebret et al. (2015)	2.73	2.73	n.s.
LW: EN vs. CON	1.11	0.85	n.s.
BA: EN vs. CON	0.55b	0.85a	$p < 0.01$
BA: OUT vs. CON			
Maiorano, Kapelański, et al. (2013)	5.02	4.58	n.s.
Millet et al. (2004)	7.20/ 8.50	7.20/ 7.50	n.s.
Omana et al. (2014)	3.17	3.03	n.s.
Patton et al. (2008)	3.68	4.64	n.s.
Pugliese et al. (2005)	0.66b	2.24a	$p < 0.05$

CON – conventional; OUT – outdoors; EN – access to enrichments.
LW- Large White; BA - French local Basque.
a, b, – Different letters in the same row mean significant differences.

yellowness (b*), the results clearly show that the pork of pigs from extensive systems is yellower compared to those from conventional systems (Bee et al., 2004; Latoch et al., 2021; Lebret et al., 2006; Lebret et al., 2015; Millet et al., 2004; Omana et al., 2014; Ortiz et al., 2021). The strongest variation in the colour of pork loin is found when the effect of the housing system includes high difference in space allowance, i.e. when pigs reared outdoors in their finishing period are kept in pastures and woodlands, allowing a high level of physical activity (Pugliese et al.,

Table 11
The shear force in the loin affected by the housing conditions.

References	Unit/ Groups	OUT/ EN	CON	Sig.
Beattie et al. (2000)	Kg/ cm^2	3.01a	2.74b	$p < 0.01$
Gentry et al. (2002)	Kg			
	Outdoors	2.30	2.20	n.s.
	Enriched	3.00	3.00	n.s.
Lebret et al. (2015)	N/m^2			
	LW: EN vs. CON	31.7	30.6	n.s.
	BA: EN vs .CON BA:	22.7	24.5	n.s.
	OUT vs. CON	30.3a	24.5b	$p < 0.001$
Maiorano, Kapelański, et al. (2013)	N	45.9	43.6	n.s.
Millet et al. (2004)	N; OF/ CF	36.8/ 33.4	38.2/ 38.2	n.s.
Omana et al. (2014)	N	56.1a	51.4b	$p < 0.05$
Ortiz et al. (2021)	N/ cm^2	69.8a	54.9b	$p < 0.05$
Pugliese et al. (2004)	kg	9.70	9.04	n.s.
Pugliese et al. (2005)	N	150a	105b	$p < 0.05$

CON – conventional; OUT – outdoors; EN – access to enrichments.
LW- Large White; BA - French local Basque.
OF – organic feed; CF – conventional feed.

Table 12
Intramascular fat content (as ether extract and expressed in percentage of muscle) in pork as affected by the housing conditions.

References	OUT/ EN	CON	Sig.
Bee et al. (2004)			
barrow/ gilt			
LTL	2.20b/ 1.60b	2.60a/ 2.20a	$p < 0.01$
RF	1.60/ 1.40	1.40/ 1.60	n.s.
SMD	5.50/ 3.70	5.30/ 3.70	n.s.
SML	4.70/ 3.80	4.40/ 4.50	n.s.
Hoffman et al. (2003)			
LTL	1.52	1.82	n.s.
Galián et al. (2009)			
LTL			
> 125 kg BW	7.90	9.90	n.s.
< 125 kg BW	6.10	3.80	n.s.
Lebret et al. (2006)			
LTL	1.68a	1.44b	$p < 0.01$
BF	2.23a	1.96b	$p < 0.01$
SM	2.00a	1.71b	$p < 0.01$
Lebret et al. (2015)			
LTL			
LW: EN vs. CON	2.14	2.32	n.s.
BA: EN vs .CON	4.07	3.79	n.s.
BA: OUT vs. CON	3.28	3.79	n.s.
Millet et al. (2004)			
LTL (OF/ CF)	1.37b/ 1.19b	1.61a/ 1.39a	$p < 0.05$
Omana et al. (2014)			
LTL	3.70a	2.60b	$p < 0.05$
Ortiz et al. (2021)			
LTL	3.92b	6.04a	$p < 0.001$
Pugliese et al. (2004)			
LL	4.27a	3.32b	$p < 0.05$
Pugliese et al. (2005)			
LL	7.19a	4.68b	$p < 0.05$
Wójciak et al. (2021) loin	4.50	4.06	n.s.

CON – conventional; OUT – outdoors; EN – access to enrichments.
LTL – m Longissimus thoracis et lumborum; LL - m. Longissimus lumborum; BF – m. Biceps femoris; SM – m. Semimembranosus; RF – m. Rectus femoris; SMD – m. Semimembranosus dark portion; SML – m. Semimembranosus light portion.
LW- Large White; BA - French local Basque; OF – organic feed; CF – conventional feed.

2004; Pugliese et al., 2005). Thus, based on the above papers, there seem to be an effect on L* from outdoor rearing but it is unclear which single factors contribute to this effect (more space, increased enrichment or other factors related to outdoor rearing).

3.5.1.3. Water holding capacity. Thirteen of the reviewed studies examined the effect of the housing conditions on the water capacity of pork defined by the drip loss (Table 10) and only four of these papers noted a significant effect of access to outdoor areas on drip loss. Gentry, McGlone, Blanton, and Miller (2002), Bee et al. (2004); pasture), and Lebret et al. (2006) found that the pork of animals with outdoors access has greater drip loss compared to those reared indoors in conventional systems; while Lebret et al. (2015) pointed to a reverse relation, when comparing outdoor in extensive system to conventional. Only one study shows that deep bedding has an influence on pork reducing its drip loss (Klont et al., 2001). As for the other meat quality parameters, it cannot be concluded which factors related to outdoor keeping contribute to the effect on drip loss.

3.5.1.4. Shear force. Ten of the reviewed papers study the effect of access to the outdoors or other enrichments on the shear force of pork (Table 11). It was expected that increased exercise in outdoor housing systems, especially those that include fattening on pastures and in woodlands, affects the muscle microstructure and texture. In spite of this, many authors show no difference in shear force levels in LTL muscles from indoor and outdoor systems. However, Pugliese et al. (2005), Omana et al. (2014), Lebret et al. (2015), and Ortiz et al. (2021) confirm the hypothesis about the increased shear force in pork of outdoor-reared pigs, and one study confirms increased shear force in meat of pigs housed in deep-bedded systems (Beattie, O'Connell, & Moss, 2000).

3.5.1.5. Intramuscular fat content and fatty acids profile. The IMF content is usually affected by the relation between age, diet and housing environment; therefore, this trait is significantly affected in systems based on pastures and woodlands. Twelve of the reviewed research articles examine the effect of housing conditions on IMF in pork (Table 12), with half of them showing a significant influence. Five studies show a greater IMF in LTL of pigs with access to outdoor areas compared to those kept on conventional farms (Bee et al., 2004; Lebret et al., 2006; Omana et al., 2014; Pugliese et al., 2004; Pugliese et al., 2005). These findings can be due to the different energy intake and exposure of outdoor-reared pigs to seasonal weather conditions (Chen et al., 2021; Lebret et al., 2021; Liu et al., 2007).

The FA composition in pig diet is shown to affect not only the subcutaneous fatty acids profile, but also the IMF in the muscles (Olsson & Pickova, 2005; Wood et al., 2008; Yi, Huang, Wang, & Shan, 2023). FA profiles of LTL muscle are more affected by the diet or the interaction between the diet and the housing system (i.e.. together with access to pastures and woodlands) than by the measurable traits of the housing system itself (i.e. pen size; access to inedible enrichments). Seven research papers examining the effect of housing conditions on the fatty acid profile of pork have been found (Table 13). In housing systems where pigs had access to outdoor pens without green forage to graze on, their pork had greater PUFA and lower MUFA content compared to indoor-kept animals (Bee et al., 2004; Hoffman et al., 2003; Wójciak, Halagarda Michałand Rohn, Kęska, Latoch, & Stadnik, 2021). Once again, this explains the direct relation between the consumption of green forage (high content of C18:3) and high content of MUFA in pork of pasture-grazed pigs (Lebret & Guillard, 2005; Rey et al., 2006).

3.5.2. Discussion on the effect of housing conditions on pork attributes

Based on the collected literature, we can conclude that indoor space allowance has a slight effect on pork quality, and both consumers of culinary pork and meat processors could not notice the difference in

Table 13
Fatty acids (SFA, MUFA and PUFA) profile in the loin (LTL or LL) of pigs as affected by the housing conditions.

References	SFA			MUFA			PUFA		
	OUT/EN	CON	**Sig.**	OUT/EN	CON	**Sig.**	OUT/EN	CON	**Sig.**
Dostálová et al. (2020) mg/ 100 g of the muscle	1131	869	n.s.	1461	1192	n.s.	n-3: 51.6 n-6: 304	n-3: 69.2 n-6: 289	n.s.
Bee et al. (2004) mg/ 100 g of the muscle									
Barrows									
Gilts	37.2	38.0	n.s.	50.8b	52.7a	$p < 0.01$	12.0a	9.6b	$p < 0.01$
	36.1	36.5		48.1b	51.6a		15.6a	11.7b	
Hoffman et al. (2003) mg/ 100 g of the muscle	38.8	42.3	n.s.	36.4	39.1	n.s.	24.6a	18.43b	$p < 0.001$
Patton et al. (2008) mg/ 100 g of the muscle	40.1b	41.0a	$p < 0.01$	37.1b	38.5a	$p < 0.01$	22.5a	20.4b	$p < 0.01$
Pugliese et al. (2004) % of total fatty acids	35.8b	38.3a	$p < 0.05$	53.3a	42.2b	$p < 0.05$	10.8b n-3: 0.8 n-6: 9.3b	14.4a n-3: 0.6 n-6: 12.6a	$p < 0.05$ n.s. $p < 0.05$
Pugliese et al. (2005) % of total fatty acids	31.4b	36.0a	$p < 0.05$	55.0a	53.5b	$p < 0.05$	n-3: 1.0a n-6: 12.0b	n-3: 0.3b n-6: 16.0a	$p < 0.05$
Wójciak et al. (2021) % of total fatty acids	42.5	41.9	n.s.	50.5	50.7	n.s.	6.5 n-3: 0.7b n-6: 5.8	7.28 n-3: 0.8a n-6: 6.4	n.s. $p < 0.05$ n.s.

CON – conventional; OUT – outdoors; EN – access to enrichments; SFA -saturated fatty acids, MUFA- monounsaturated fatty acids; PUFA - polyunsaturated fatty acids.

pork quality as affected by only the space allowance in the fattening phase of pigs. Access to enrichments such as deep bedding or straw in racks has a limited influence on pork attributes as well.

The clearest differences are established between pork of fatteners reared with access to the outdoors (outdoor pens; free-range), compared to those kept indoors on concrete-slatted flooring. Generally, the pork of pigs that had access to outdoors had a lower pH ultimate value, darker and a redder colour, and lower water holding capacity compared to pork of indoor-housed pigs. Also, pork from pigs kept with access to the outdoors is likely to be more yellow (greater b*), than indoor-housed animals fed with a commercial diet. However, for the shear force, most of the research discussed in this review did not show an effect by access to the outdoors, pastures, enrichments, or space allowance.

The housing system significantly affects the pork FA profile, which is especially stressed when the outdoor area is pasture or woodland.

4. Conclusions

The evaluation of the selected extensification factors shows that not all of them have a clear impact on meat quality. Also, factors were often confounded and thus it is difficult to link only one of these with observed meat characteristics. From the evaluated factors, the most clear differences were observed when comparing local with commercial breeds. Moreover, certain characteristics were similar for all local breeds, i.e., higher pH, IMF, a* and b*, or lower L*, compared to modern commercial pig breeds and their crossbreeds. Nonetheless, when choosing meat from local European breeds, it should be expected to find a different intrinsic quality than in meat from commercial pigs.

Studies on the addition of forage to diet did not provide as clear results as the local breeds. One of the reasons is the fact that each study used different diets for different breeds and housing conditions. Moreover, many meat parameters were measured in only a few studies, which further limits the possibility of drawing conclusions. Actually, only access to outdoor pasture, where natural foraging behaviour can take place, leads to a more apparent effect of forage on meat quality. Then, however, many more factors affect the meat than pure forage.

Finally, the studied effects of environmental enrichment prove to be a difficult factor due to clear interactions between pig breed and slaughter body weight, housing conditions including space, and type of diet, as well as the level of energy. Even so, certain patterns in the observed meat characteristics have been shown, but only for outdoor vs. indoor rearing conditions. Pigs kept outdoors (or with access to outdoors) generally have lower pH, darker and a redder colour and lower water-holding capacity, compared to pork of commercially-housed pigs. Most importantly, the housing system, especially with more extensive husbandry practices, significantly affect pork fatty acid composition towards better nutritional value.

Despite many studies focusing on the extensification of husbandry practices, some of the factors cannot be confirmed to have a direct effect on pork intrinsic quality. Based on this review there is still a lot to be researched, especially in terms of forage, space allowance and environmental enrichment, which are part of the aims in the *mEATquality* project.

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Author contribution

AL, ESK, VRE, PF, LJP, IR – Conceptualization, Methodology; AL, ESK – Investigation, Writing – original draft; AL, ESK – Data curation; IR – Validation; IR, MKP, AZZ, JSB, VRE, SSF, CDG, PF, LJP, MYRC – Writing – review & editing. All authors have read and accepted the final version of the manuscript.

Declaration of Competing Interest

The Authors of the review titled: 'The extensification of husbandry practices in European pig production and their effect on pork quality', declare no conflict of interest.

Data availability

No data was used for the research described in the article.

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