

# Forage plants as an alternative feed resource for sustainable pig production in the tropics: a review

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*Globally, pressure on concentrate feed resources is increasing, especially in the tropics where many countries are net importers of food. Forage plants are a possible alternative, but their use as feed ingredients for pigs raises several issues related to their higher fibre and plant secondary metabolites contents as well as their lower nutritive value. In this paper, the nutritive value of several forage species and the parameters that influence this nutritive value in relationship to the plant family, the physiological stage, the plant part and the preservation method (fresh, hay and silage) are reviewed. The influence of the breed and the physiological status of the animal on animal voluntary intake of fibre-rich ingredients, digestibility as related to gastrointestinal volume and transit time and growth performances are also discussed. The final section highlights the advantages and drawbacks of forage plants in pig diets and stresses the need for proper economic evaluation to conclude on the benefits of the use of forage plants in pig feed.*

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**Keywords:** forage, pigs, tropics, digestibility

## Implications

This work reviews the possibility of using forage plants for feeding pigs reared in tropical areas. It highlights the constraints of forage as low digestible feed ingredients because of their high content in fibre and anti-nutritive compounds. However, their rich protein and mineral contents can be useful for improving the diets of pigs fed poorly balanced diets. The advantage of forage as pig feed, however, remains controversial as the economical and environmental implications at the farm level in mixed-farming systems have seldom been quantified.

## Introduction

Forage was considered in the past as an essential component of the feed of pigs in all production environments. The development of high growth performance breeds over the past decades and the widespread adoption in developed and developing countries of industrial indoor grain-fed production systems have led to the abandonment of forage in the diets of industrially raised pigs and a scarcity in up-to-date knowledge on the nutritional value of forage plants for pigs (Blair, 2007). Forage is nonetheless still widely used by

smallholding farmers in low-input and semi-intensive pig production systems of tropical Asia, Africa and America. Forage is only one part of the various ingredients that smallholders usually feed to their pigs, which include agricultural by-products from local food-processing units, weeds that grow naturally in the forests and along the banks of rivers, aquatic plants and plant of previous crops on fallow (Kumaresan *et al.*, 2009; Phengsavanh *et al.*, 2010). Various reasons explain why smallholders still include significant amounts of forage in the diets of their animals: their low income as compared with the high prices of imported grains or oil-seed cakes (Kagira *et al.*, 2010; Kaensombath *et al.*, 2013); the remoteness and inaccessibility of their farms increasing the energy and protein concentrate costs at the farm gate (Kumaresan *et al.*, 2007); and the lack of accessible market (Lemke *et al.*, 2007). This maintains most smallholders in low-input agricultural systems with little room for mid- or long-term investments, as improvement in the genetics and the feeding systems would require. In addition, when the activity is driven by socio-cultural motivations and is more oriented towards auto-consumption than to the market (Lemke *et al.*, 2006; Kumaresan *et al.*, 2009), little effort is made to improve growth performances of animals by seeking feed with high nutritional value. For example, it is reported that, in Gambia, animals are only managed intensively when they make a significant contribution to

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production and income, but not if savings is their main function (Bennison *et al.*, 1997). Moreover, feeding forage is often used with indigenous pigs, which are the preferred breed of smallholders in rural areas (Lemke *et al.*, 2007; Len *et al.*, 2009a), and investigations in Burkina Faso and Cameroon reveal that under specific conditions the low-input by-products and forage-based sector can even be more profitable than industrial pigsties (Lekule and Kyvsgaard, 2003).

The extent to which forage species can economically contribute to supplying pigs with nutrients for growth and reproduction will depend on the voluntary feed intake as well as the digestibility of the forage itself and the relative cost and availability of forage as opposed to concentrate feeds. The present review examines the nutritive value of several tropical forage species as well as how the breed and physiological status of the animal influence the animal's ability to sustain on forage-based diets. Finally, the socio-economical and environmental implications of feeding forage to pigs in low-input farming systems are discussed.

### Chemical composition and feeding value of tropical forage species in pigs

#### *Diversity of tropical forage species used in pigs*

Forage used in the diets of pigs across the tropics covers a wide range of plant materials as listed in Table 1. It includes grasses, legumes, aquatic plants and leaves from shrubs and trees. Forage is fed, either in fresh or in preserved form, as hay or silage (Ogle, 2006). Some tropical forage species such as *Manihot esculenta*, *Ipomoea batatas*, *Leucaena leucocephala*, *Arachis hypogaea*, *Stylosanthes guianensis*, *Colocasia esculenta*, *Azolla filiculoides*, *Salvinia molesta*, *Xanthosoma sagittifolium* and *Morus alba* have been already assessed *in vivo* in pigs. However, although they are locally used by smallholders, most species have not been assessed further than the determination of their chemical composition and sometimes their *in vitro* digestibility for pigs (Feedipedia, 2013). Examples of such plants are numerous and they include, among others, *Moringa oleifera*, *Psophocarpus scandens* (Kambashi *et al.*, in press), *Crassocephalum crepidioides* and *Amaranthus viridis* (Phengsavanh *et al.*, 2010).

#### *Chemical composition and variability*

Forage ingredients are by definition rich in fibre as opposed to concentrate feed ingredients (Gillespie and Flanders, 2010). However, the composition of forage ingredients is highly variable, including within a given species, as the stage of harvesting, climatic stresses during the plant growth and variety or cultivars exert an influence on the chemical composition of the forage. This high variability coupled with unpredictability due to the factors outlined above limits the possibility of using forage plants for feeding pigs. Forage plants used as pig feed have NDF contents ranging from 174 g/kg dry matter (DM) in *M. alba* to 732 g/kg DM in *Brachiaria mulato*, with a lignin fraction ranging from 13 to 200 g/kg DM. Moreover, they are usually low in crude fat and starch. As stated later in this review, if one excludes the influence on

the intestinal eco-physiology, fibre is not of particular interest for pigs in terms of supply of nutrients to the animal. The benefits of forage feed ingredients for pigs lie in their richness in protein, essential amino acids (AAs) and minerals. Most forage species used by smallholders in the tropics have high CP contents (up to 370 g/kg DM, Table 1), especially *fabaceae*. In semi-intensive or extensive pig-rearing systems in tropical countries, many energy sources are locally available: peelings or millings of bananas, tubers and grains, palm oil by-products or sugarcane juices. Forage as an alternative ingredient should therefore supply protein, which is the most limiting nutrient in smallholder pig-feeding systems in tropical areas (Leterme *et al.*, 2005; Martens *et al.*, 2012). Some forage species such as *S. guianensis*, *I. batatas*, *C. esculenta* and *L. leucocephala* present AA profiles (Table 2) that match that of the ideal protein for pigs quite well, whereas others are deficient in one or more essential AAs (Phuc and Lindberg, 2001; An *et al.*, 2004; Régnier *et al.*, 2012; Kaensombath and Lindberg, 2013). Cassava (*M. esculenta*) and sweet potato (*I. batatas*) leaves, for example, are rich in protein but have a deficient profile in methionine and lysine, respectively (Nguyen *et al.*, 2012). Some forage species suffer from a low bioavailability of their AAs, and from the presence of plant secondary metabolites (PSMs) that reduce protein digestibility. Using forage species therefore does not allow maximising growth performance of genetically improved breeds, but this strategy makes sense for smallholder pig producers or local breeds with lower requirements.

Several studies showed the high content of minerals in plants and plant parts (Cook *et al.*, 2000; Kumari *et al.*, 2004; Leterme *et al.*, 2006a). However, the mineral content of plants varies not only between species but also on the maturity stage of the harvested material (Wawire *et al.*, 2012), the season, the number of harvests (Baloyi *et al.*, 2013), the physicochemical properties of the soil and the environmental conditions, including plant stress (Kabata-Pendias, 2004). A rational use of plant materials will allow the farmer to cover a significant portion of micronutrients, essential minerals and vitamins required for animal growth (Agte *et al.*, 2000; Ishida *et al.*, 2000).

Besides fibre content, the second major drawback of tropical forage is related to the presence in some species of PSMs that might at best exert some anti-nutritive properties through a decrease in diet palatability and digestibility (Acamovic and Brooker, 2005; Halimani *et al.*, 2005) and at worst be toxic for the animal, as described later in this review. Such compounds fall under different molecular families such as phenolic compounds, cyanogenic glucosides, oxalic acid, lectins, alkaloids, antitryptic molecules, non-physiological AAs, etc. Some PSMs are rather specific to some species or botanical families, such as hydrogen cyanide (HCN) in cassava, oxalic acid in cocoyam or mimosine in *L. leucocephala*, whereas others such as tannins are present in plant foliage of many forage species at different concentrations (Acamovic and Brooker, 2005; Makkar, 2007). As for other nutrients such as fibre, protein or minerals, the content of PSM depends of course on botanical families,

**Table 1** Range of proximate chemical composition (g/kg DM) and energy (MJ/kg DM) of plant materials used in pig diets

Plant species	Family	Plant part	OM	CP	GE	NDF	ADF	ADL	Ca	P	References
<i>Trichanthera gigantean</i>	Acanthaceae	Leaves	823 to 864	115 to 219	15.8	299 to 468	166 to 337	40 to 124	nd	nd	Leterme <i>et al.</i> (2006b)
<i>Colocasia esculenta</i>	Araceae	Leaves	854	90 to 225	10.3*	316 to 505	nd	nd	0.10 to 1.00	0.20 to 3.20	Kaensombath and Lindberg (2013)
<i>Lemna minor</i>	Araceae	Plant	808 to 830	296 to 370	9.1*	370	283	nd	3.27	1.43	Dung <i>et al.</i> (2006)
<i>Xanthosoma sagittifolium</i>	Araceae	Leaves	843 to 910	169 to 258	18.0	186 to 371	115 to 253	11 to 75	nd	nd	Leterme <i>et al.</i> (2006b), Leterme <i>et al.</i> (2005), Régnier <i>et al.</i> (2013)
<i>Azolla filiculoides</i>	Azollaceae	Plant	855 to 902	232 to 237	12.8 to 16.4	469 to 620	284 to 387	104 to 168	0.08 to 0.11	0.20 to 0.40	Leterme <i>et al.</i> (2009)
<i>Ipomoea aquatica</i>	Convolvulaceae	Leaves	867 to 871	256	8.3*	349	283	nd	1.03	0.59	Dung <i>et al.</i> (2006), Ty and Preston (2005)
<i>Ipomoea batatas</i>	Convolvulaceae	Leaves and Stem	855 to 986	187 to 298	16.9 to 17.7	232 to 449	136 to 327	93 to 125	0.07 to 0.19	0.02 to 0.07	Régnier <i>et al.</i> (2013), An <i>et al.</i> (2004), An <i>et al.</i> (2003)
<i>Manihot esculenta</i>	Euphorbiaceae	Leaves or tops	894 to 965	208 to 306	19.0 to 21.4	320 to 615	202 to 428	237	0.62 to 0.75	0.30 to 0.40	Phuc and Lindberg (2000), Nguyen <i>et al.</i> (2012), Khieu <i>et al.</i> (2005)
<i>Aeschynomene histrix</i>	Fabaceae	Leaves and stem	931	237	8.7*	467	260	nd	nd	nd	Phengsavanh and Lindberg (2013)
<i>Arachis hypogaea</i>	Fabaceae	Tops	906	175	18.1	419	219	nd	nd	nd	Phuc and Lindberg (2000)
<i>Erythrina glauca</i>	Fabaceae	Leaves	900	287	19.6	477	288	108	nd	nd	Régnier <i>et al.</i> (2013)
<i>Leucaena leucocephala</i>	Fabaceae	Leaves	901 to 910	225 to 283	nd	318 to 388	175 to 215	nd	0.49 to 2.40	0.12 to 0.25	Régnier <i>et al.</i> (2013), Laswai <i>et al.</i> (1997)
<i>Stylosanthes guianensis</i>	Fabaceae	Tops	853 to 917	141 to 188	7.8*	549 to 602	424	nd	2.20	0.48	Kambashi <i>et al.</i> (in press), Sarria <i>et al.</i> (2012)
<i>Psophocarpus scandens</i>	Fabaceae	Leaves and stem	852 to 904	231 to 297	nd	326 to 418	228	66	1.45	0.34	Kambashi <i>et al.</i> (in press), Kaensombath <i>et al.</i> (2013)
<i>Vigna unguiculata</i>	Fabaceae	Leaves and stem	859	243 to 360	12.3 to 13.0	365	235	nd	0.96 to 3.70	0.34 to 0.42	Kambashi <i>et al.</i> (in press), Uusiku <i>et al.</i> (2010)
<i>Morus alba</i>	Moraceae	Leaves	908 to 837	113 to 239	17.54	174 to 301	82 to 189	13 to 27	nd	nd	Leterme <i>et al.</i> (2006b), Kaensombath and Lindberg (2013)
<i>Musa paradisiaca</i>	Musaceae	Leaves	880	74	17.3	701	400	108	nd	nd	Ly <i>et al.</i> (1998)
<i>Brachiaria mulato</i>	Poaceae	Plant	nd	58	nd	732	468	200	nd	nd	Sarria <i>et al.</i> (2012)
<i>Talinum triangulare</i>	Portulacaceae	Plant	754	211	nd	347	277	76	nd	nd	Bindelle <i>et al.</i> (2007)
<i>Eichhornia crassipes</i>	Pontederiaceae	Plant	853 to 870	110 to 267	8.4*	nd	nd	nd	1.08	0.14	Kambashi <i>et al.</i> (in press), Men <i>et al.</i> (2006)
<i>Salvinia molesta</i>	Salviniaceae	Plant	768 to 849	92 to 191	14.7 to 16.4	518 to 629	358 to 414	123 to 168	1.00 to 1.20	0.60 to 0.70	Leterme <i>et al.</i> (2009)

DM = dry matter; OM = organic matter; GE = gross energy; nd = not determined.

\*Metabolisable energy instead of GE.

**Table 2** Amino acid profiles of some forage (% protein)

	Arg	His	Ile	Leu	Lys	Met	Phe	Thr	Trp	Val	References
Requirements for growing pigs (20 to 50 kg)	3.19	2.49	3.76	7.20	7.14	2.04	4.33	4.59	1.21	4.78	NRC (2012)
<i>Arachis hypogaea</i>	5.20	2.00	3.70	7.00	4.10	0.90	5.40	4.00	nd	5.10	Phuc and Lindberg (2001)
<i>Erythrina glauca</i>	4.10	1.70	3.10	5.30	4.30	1.00	3.90	2.90	1.40	4.00	Régnier <i>et al.</i> (2012)
<i>Colocasia esculenta</i>	5.20	1.20	5.00	7.60	2.90	2.20	4.20	4.10	nd	5.00	Régnier <i>et al.</i> (2012), Kaensombath and Lindberg (2013)
<i>Ipomoea batatas</i>	4.50 to 6.60	1.70 to 3.30	3.70 to 5.20	6.40 to 8.70	3.90 to 4.80	1.30 to 1.50	4.10 to 6.70	3.60 to 5.50	1.20 to 1.50	4.70 to 5.70	Régnier <i>et al.</i> (2012), Nguyen <i>et al.</i> (2012), An <i>et al.</i> (2003)
<i>Leucaena leucocephala</i>	4.00 to 5.70	1.80 to 2.00	4.10 to 9.50	5.80 to 7.90	4.30 to 5.80	1.20 to 1.60	3.90 to 5.60	3.30 to 4.00	nd	4.70 to 5.40	Phuc and Lindberg (2001), Ly <i>et al.</i> (1998)
<i>Manihot esculenta</i>	4.40 to 5.93	1.70 to 2.19	3.90 to 5.51	6.80 to 8.30	4.21 to 5.60	1.20 to 1.50	4.18 to 5.70	3.30 to 4.46	1.6	4.11 to 5.30	Phuc and Lindberg (2001), Régnier <i>et al.</i> (2012), Nguyen <i>et al.</i> (2012)
<i>Morus alba</i>	5.30	2.10	4.30	8.20	5.70	1.60	5.20	4.60	1.10	5.40	Leterme <i>et al.</i> (2005)
<i>Trichanthera gigantea</i>	4.90	2.20	4.10	7.20	4.30	1.50	4.60	4.30	1.00	5.00	Leterme <i>et al.</i> (2005)
<i>Xanthosoma sagittifolium</i>	3.10 to 5.00	1.50 to 1.90	2.60 to 3.90	4.90 to 7.50	4.00 to 5.60	1.10 to 1.80	2.90 to 4.70	2.90 to 4.50	0.80 to 1.70	3.80 to 4.80	Régnier <i>et al.</i> (2012), Leterme <i>et al.</i> (2005)
<i>Stylosanthes guianensis</i>	4.80 to 5.12	1.90 to 1.97	3.30 to 4.13	6.80 to 7.32	4.30 to 4.51	1.10 to 1.60	4.60	4.00 to 4.13	1.10 to 1.78	3.90 to 4.84	Kaensombath <i>et al.</i> (2013), Phengsavanh and Lindberg, 2013
<i>Vigna unguiculata</i>	4.70 to 4.90	1.80 to 4.10	6.60	13.40	9.50	2.60 to 5.0	6.10 to 7.80	6.60	nd	6.10 to 9.50	Nielsen <i>et al.</i> (1997), Heinitz <i>et al.</i> (2012)

nd = not determined.

<sup>1</sup> Calculated from amino acid estimated requirements in a diet with 2.51% nitrogen fed *ad libitum* to growing pigs (90% dry matter).

plant species and variety or cultivar, but in some cases also on the plant part, the stage of maturity and growing conditions such as soil fertility and season (Ravindran and Ravindran, 1988; Acamovic and Brooker, 2005). Young leaves contain higher concentrations of PSMs than senescing tissues and stems (Wink, 2004), similar to proteins. Conversely, lignin and fibre contents increase with age and stem-to-leaf ratio in the forage (Buxton and Redfean, 1997).

*Feeding value of tropical forage species in pigs*

*Energy content.* The richness in fibre as well as the degree of lignification of the fibre fraction of forage is probably the major constraint to their use as pig feed (Noblet and Le Goff, 2001; Högberg and Lindberg, 2006). Due to the lack of foregut fermentation and caecotrophic behaviour, the ability of pigs to recover nutrients from fibre, in particular energy, is limited to the uptake through the intestinal wall of short-chain fatty acids produced during hindgut intestinal fermentation (reviewed by Bindelle *et al.*, 2008). Therefore, with total tract organic matter (OM) digestibility ranging from 0.30 to 0.63 (Table 3) as well as digestible and metabolisable energy contents ranging from 5.2 to 11.9 MJ/kg DM and from 5.0 to 8.3 MJ/kg DM, respectively (Phuc and Lindberg, 2000; Leterme *et al.*, 2006b; Régnier *et al.*, 2013), the energy value of plant foliages is quite lower than that of concentrate feed ingredients such as cereal grains (Table 3). Cereals have OM digestibility values usually falling between 0.84 and 0.98, and digestible and metabolisable energy contents as high as 12.9 to 15.4 MJ/kg DM and 12.4 to 15.0 MJ/kg DM, respectively (Sauvant *et al.*, 2004). As stated previously, the composition of forage is also more variable than that of concentrate feed ingredients. Owing to this variability, it is more difficult to study the actual nutritive value of these high fibre materials from an experimental point of view. The measured nutritive values depend on animal factors such as age or breed, experimental design such as rate of incorporation in the diet, presentation form and factors related to tropical foliage itself, as shown previously.

As a consequence of the low digestibility of the fibre fraction, growth performances of pigs fed forage-based diets are often below those of concentrate-fed pigs, depending on the forage inclusion rate (Laswai *et al.*, 1997; Halimani *et al.*, 2005; Phengsavanh and Lindberg, 2013; Régnier *et al.*, 2013). Nonetheless, if one goes through the list of plants that have been reported as being used for pigs in the literature, wide differences in total tract OM and energy digestibility between forage species are reported (Table 3). For example, some accessions of *X. sagittifolium*, *M. alba*, *A. filiculoides* and *A. hypogaea* have total tract OM and energy digestibility ranging, respectively, from 0.49 to 0.71 and 0.60 to 0.69. Conversely, the aquatic fern *S. molesta* used in production systems integrating pig production to pond aquaculture has an OM digestibility as low as 0.29 to 0.33 and an energy digestibility of 0.31. Such differences can be ascribed not only to the difference in total fibre content, which varies with (1) species, with *poaceae* generally containing more fibre

**Table 3** In vivo ileal and total tract digestibility coefficients of nutrients of tropical forage species in pigs

	Ileal digestibility					Total tract digestibility					References
	OM	CP	NDF	ADF	Energy	OM	CP	NDF	ADF	Energy	
<i>Ipomoea batatas</i>	nd	0.74	0.23 to 0.25 <sup>1</sup>	nd	nd	nd	0.75 to 0.77 <sup>1</sup>	0.55 to 0.57 <sup>1</sup>	0.32 to 0.36 <sup>1</sup>	nd	An <i>et al.</i> (2004)
	nd	nd	nd	nd	nd	nd	0.21	nd	nd	0.38 (leaves) to 0.48 (leaves + stems)	Régnier <i>et al.</i> (2013)
<i>Manihot esculenta</i>	nd	nd	nd	nd	nd	nd	0.08 (leaves) to 0.15 (leaves + stems)	nd	nd	0.31	Régnier <i>et al.</i> (2013)
	0.42	0.37	0.26	0.16 to 0.17	0.41	0.54 to 0.59	0.45 to 0.46	0.31 to 0.32	0.20 to 0.21	0.52 to 0.57	Phuc and Lindberg (2000)
<i>Arachis hypogaea</i>	0.55	0.43	0.49	0.34	0.52	0.64	0.47	0.58	0.46	0.60	Phuc and Lindberg (2000)
<i>Leucaena leucocephala</i>	0.44	0.39	0.24	0.12	0.40	0.53	0.42	0.27	0.18	0.51	Phuc and Lindberg (2000)
<i>Azolla filiculoides</i>	nd	nd	nd	nd	nd	0.33 to 0.50 <sup>2,3</sup>	0.31 to 0.66 <sup>3</sup>	nd	nd	0.30 to 0.63 <sup>3</sup>	Leterme <i>et al.</i> (2009)
<i>Salvinia molesta</i>	nd	nd	nd	nd	nd	0.29 to 0.33 <sup>2,3</sup>	0.31 to 0.56 <sup>3</sup>	nd	nd	0.31	Leterme <i>et al.</i> (2009)
<i>Morus alba</i>	nd	nd	nd	nd	nd	0.56 <sup>2</sup>	0.33	nd	nd	0.51	Leterme <i>et al.</i> (2005)
	nd	nd	nd	nd	nd	0.63 <sup>2</sup>	0.49	nd	nd	0.65	Leterme <i>et al.</i> (2006b)
<i>Trichanthera gigantea</i>	nd	nd	nd	nd	nd	0.47 <sup>2</sup>	0.36	nd	nd	0.60	Leterme <i>et al.</i> (2005)
	nd	nd	nd	nd	nd	0.49 <sup>2</sup>	0.30	nd	nd	0.54	Leterme <i>et al.</i> (2006b)
<i>Xanthosoma sagittifolium</i>							0.65			0.47	Régnier <i>et al.</i> (2013)
	nd	nd	nd	nd	nd	0.57 <sup>2</sup>	0.34	nd	nd	0.57	Leterme <i>et al.</i> (2005)
	nd	nd	nd	nd	nd	0.71	0.57	nd	nd	0.69	Leterme <i>et al.</i> (2006b)

DM = dry matter; OM = organic matter; nd = not determined.

<sup>1</sup>Range according to preservation method (fresh, dried, ensiled).

<sup>2</sup>DM digestibility instead of OM digestibility.

<sup>3</sup>Range according differences in estimates because of varying proportion of forage in the basal diet for the calculation of digestibility of leaves alone with the difference method.

than *fabaceae*, but also to (2) plant parts, as stems have higher fibre content than do leaves, and (3) maturity at harvest (Buxton and Redfean, 1997). Other differences can be ascribed to differences in fermentability between fibre types (Noblet and Le Goff, 2001; Anguita *et al.*, 2006) and the insoluble-to-soluble fibre ratio, with soluble fibre affecting voluntary fibre intake and ileal digestibility more negatively.

*Interaction between fibre content and digestibility of nutrients.* High fibre content, and especially viscous fibre, reduces enzyme contact and traps nutrients and minerals in a voluminous chyme, away from absorption sites in the intestine (Anguita *et al.*, 2006; Urriola and Stein, 2012). Leterme *et al.* (2009), for example, observed a relatively high faecal digestibility for *A. filiculoides* and low digestibility for *S. molesta* (Table 3), a species rich in fibre with high water-holding capacity, although both species have similar NDF contents (523 v. 539 g/kg DM, Table 1).

The increase in chyme volume especially with foliage or fibre fractions with high water-holding capacity also increases the digesta passage rate, decreasing the accessibility and time of action of digestive enzymes and decreasing global digestibility (Partanen *et al.*, 2007; Régnier *et al.*, 2013). However, the influence of fibre on intestinal transit time is controversial, as several authors mention increases (Wilfart *et al.*, 2007), decreases (Wenk, 2001) or no influence (Partanen *et al.*, 2007) of fibre on this parameter. As mentioned above, such variability between studies may originate from differences in methodology – that is, experimental design, rate and form of forage incorporation, analytical methods, etc.

*Digestibility of protein and bioavailability of AAs.* CP can include non-protein nitrogen (N) as the analytical procedure for CP yields the N content  $\times 6.25$  (method 981.10; Association Official Analytical Chemists (AOAC), 1990). It is reported that N-to-protein conversion factors of some vegetal materials (rice, oats and wheat) are lower than 5.36 (Chang, 2010). For instance, Régnier *et al.* (2012) found that the sum of AA in tropical plant leaves (cassava, sweet potato, cocoyam and erythrina foliages) was 25% lower than the CP content. This gap between CP and individual AA analysis is one of the first factors to be considered when determining the actual protein value of a forage species. In addition, the individual AA profile as well as their bioavailability must be considered. Fibre strongly interferes with protein digestibility. Proteins can be bound to the NDF fraction preventing them from being hydrolysed by the digestive enzymes of pigs. This NDF-bound protein fraction is higher in dicotyledons than in grasses (Bindelle *et al.*, 2005). This was observed, for example, by Leterme *et al.* (2006b) with *Trichanthera gigantea*, a tropical tree fed to pigs in Colombia. NDF-bound N in this species reaches 59% of the total N, leading to low ileal and faecal protein digestibility of  $\sim 0.15$  and 0.30, respectively. However, low faecal-N-digestibility values not always mean low protein value. High fermentable fibre content of some forage species decreases the faecal

apparent digestibility of N through a shift in N excretion from urinary-N (urea) to faecal-N (bacterial protein) without systematically altering the protein value of the diet (Bindelle *et al.*, 2009). Therefore, the only actual protein value should mention ileal digestibility or possibly the standardised ileal digestible (SID) AAs of the forage ingredients, as these values might strongly differ from raw AA composition (Tables 2 and 4). Many authors report a decrease in N and AA digestibility in growing pigs when tropical leaves are included in a basal diet (e.g. Phuc and Lindberg, 2001; An *et al.*, 2004; Régnier *et al.*, 2013). The values for apparent ileal digestibility (AID) are established when total ileal outflow of AA is related to dietary AA intake. Total ileal outflow consists of non-digested dietary AA as well as endogenous AA secretions or losses. The latter may be separated into (i) basal losses, which are considered in the SID calculations and are not influenced by feed ingredient composition, and (ii) specific losses, which are induced by feed ingredient characteristics such as fibre levels and types, the presence of PSMs, or mineral contents (Stein *et al.*, 2007). The high content in fibre and PSMs of some forage plants that lead to the increase in specific endogenous AA losses explain the low AID of AA.

*Mineral digestibility.* The bioavailability of minerals in tropical forage species should be investigated, as the few data available in the literature indicate that it strongly varies between plant species and the considered minerals. For example, mineral bioavailability for pigs in tropical forage ranges from 41% to 58% for P (Poulsen *et al.*, 2010), from 3% to 27% for Fe (Kumari *et al.*, 2004), from 11% to 26% for Zn and from 18% to 48% for Cu (Agte *et al.*, 2000). Furthermore, the high dietary mineral content of some forage species is likely to have a negative influence on energy and protein values. Noblet and Perez (1993) reported that the digestibility coefficients of energy and CP were highly dependent on dietary fibre and mineral contents. They also suggested that dietary minerals increase protein endogenous losses through intestinal cell debris with subsequent increase in endogenous energy and AA losses.

*PSMs.* As stated before, PSMs can display various effects on the animals, including some specifically related to the feeding value of the forage ingredient such as a reduction in digestibility and voluntary intake (reviewed by Martens *et al.*, 2012). Tannins are diverse regarding their chemical structure but share common biochemical properties in their ability to precipitate proteins at neutral pH. As a consequence, some tannin-containing feeds decrease the voluntary intake, which may be associated with astringency caused by the formation of tannin–salivary protein complexes in the mouth or signals of gut distension resulting from tannin interactions with proteins of the gut wall (Acamovic and Brooker, 2005). Tannins decrease protein and DM digestibility in pigs via an increase in faecal N excretion, an inhibition of digestive enzymes or intestinal microorganisms and an effect on gut permeability (Walton *et al.*, 2001). Tannins also increase endogenous losses from animals, including mineral losses by

Table 4 Ileal apparent digestibility of amino acid (AA) of forage species in pigs

	Arg	His	Ile	Leu	Lys	Met	Phe	Thr	Trp	Tyr	Val	References
<i>Arachis hypogaea</i>	0.77	0.73	0.71	0.72	0.73	0.73	0.68	0.69		0.65	0.72	Phuc and Lindberg (2001)
<i>Erythrina glauca</i>	0.47 <sup>1</sup>	0.13 <sup>1</sup>	0.04 <sup>1</sup>	0.22 <sup>1</sup>	0.13 <sup>1</sup>	0.43 <sup>1</sup>	0.29 <sup>1</sup>	-0.07 <sup>1</sup>	0.00 <sup>1</sup>		0.08	Régnier <i>et al.</i> (2012)
<i>Ipomoea batatas</i>	0.51 <sup>1</sup> to 0.80	0.25 <sup>1</sup> to 0.80	0.32 <sup>1</sup> to 0.78	0.45 <sup>1</sup> to 0.80	0.43 <sup>1</sup> to 0.83	0.46 <sup>1</sup> to 0.75	0.40 <sup>1</sup> to 0.78	0.22 <sup>1</sup> to 0.75	0.14 <sup>1</sup>		0.31 to 0.78	Régnier <i>et al.</i> (2012), An <i>et al.</i> (2004)
<i>Leucaena leucocephala</i>	0.48	0.67	0.52	0.52	0.61	0.57	0.55	0.52		0.60	0.61	Phuc and Lindberg (2001)
<i>Manihot esculenta</i>	0.41 <sup>1</sup> to 0.56	0.15 <sup>1</sup> to 0.68	0.20 <sup>1</sup> to 0.48	0.30 <sup>1</sup> to 0.57	0.29 <sup>1</sup> to 0.64	-0.36 <sup>1</sup> to 0.56	0.34 <sup>1</sup> to 0.55	0.08 <sup>1</sup> to 0.54	0.13 <sup>1</sup>	0.64	0.18 to 0.62	Phuc and Lindberg (2001), Régnier <i>et al.</i> (2012)
<i>Xanthosoma sagittifolium</i>	0.63 <sup>1</sup>	0.44 <sup>1</sup>	0.46 <sup>1</sup>	0.61 <sup>1</sup>	0.54 <sup>1</sup>	0.36 <sup>1</sup>	0.60 <sup>1</sup>	0.25 <sup>1</sup>	0.20 <sup>1</sup>	0.80	0.46	Régnier <i>et al.</i> (2012)

<sup>1</sup>Standardised ileal digestible of AA instead of ileal apparent digestibility.

chelation. Nevertheless, the effect varies with the binding strength in protein-tannin complexes, which can vary over several orders of magnitude between species (Mueller-Harvey, 2006) and the total tannin content. For example, condensed tannins from *L. leucocephala* have the ability to precipitate proteins approximately by half than that from *Leucaena pallida* or *Leucaena trichandra* on g of protein/g of tannins basis. In addition, tannins from *Leucaena collinsi* precipitate almost no proteins (Osborne and McNeill, 2001). However, the effect of tannins on pigs is controversial as some authors mention improvements (Myrie *et al.*, 2008; Biagi *et al.*, 2010), whereas others report detrimental (Halimani *et al.*, 2005; Kim *et al.*, 2007) or neutral effects on digestive processes (Lizardo *et al.*, 2002; Stukelj *et al.*, 2010). Moreover, the inclusion of 4 g/kg of tannin in the diet resulted in improved feed efficiency and reduction in intestinal bacterial proteolytic reactions (Biagi *et al.*, 2010) and 15 g/kg tannin in the diet did not affect growth performance (Myrie *et al.*, 2008). Furthermore, when reduced growth performance is reported in monogastric animals fed tannin-rich feed, the latter are generally characterised by the presence of significant amounts of other PSMs that altogether might result in reduced animal growth (Biagi *et al.*, 2010). For example, HCN increases methionine requirements for detoxication (Mansoori and Acamovic, 2007); therefore, in *M. esculenta*, protein-binding tannins and HCN act together to worsen the deficiency in methionine in cassava leaves-based diets.

HCN and alkaloids decrease intake because of their bitter taste. Ingestion of a non-lethal dose of HCN (<100 ppm in the diet for pigs) also reduces growth rates associated with increased serum and urinary levels of thiocyanate, which is a continuous cause of depletion of sulphur-containing AAs and reduces the blood thyroxine levels (Tewe, 1992). At high concentration (>100 ppm), HCN may be lethal for the animal through the inhibition of cytochrome oxidase in the mitochondria. The lethal dose for most animal species is ~2 mg HCN/kg BW (Kahn, 2010). However, the intake rate is also important. Animals that eat rapidly are more likely to be poisoned as the drop in pH in the stomach destroys the enzymes responsible for the release of HCN. Finally, variety, maturity and fertiliser application levels also play a role in the possibility of using some cyanide-containing plants as forage for pig. *M. esculenta*, for example, displays HCN contents in foliage ranging from 80 to 2000 mg/kg DM, depending on the previously mentioned factors (Feedipedia, 2013).

Some alkaloids are hepatotoxic and can reduce the growth rate of pigs, mainly by decreasing feed intake and affecting feed efficiency (Gdala *et al.*, 1996). For example, alkaloids in *Erythrina glauca* did not affect feed intake and health, likely because of restrictive feeding and the moderate rate of this plant in the diet. Despite this, this plant showed a low nutritive value (-0.328 and 0.266 for CP and energy, respectively; Régnier *et al.*, 2013).

Oxalic acid is found at high levels (34.3 to 48.2 mg/g DM) in some cocoyam species (Oscarsson and Savage, 2007). With its astringent taste, it decreases intake levels and affects the physical properties of the oral mucosa by

denaturing proteins in the surface epithelium, by increasing the friction of mucosa caused via aggregation of saliva (De Wijk and Prinz, 2006), and causes irritations of the gastrointestinal tract (Leterme *et al.*, 2005). In addition to these negative effects, one notices increased kidney and liver weight (Kaensombath and Lindberg, 2013) probably due to the deposit of crystals of calcium oxalate.

Mimosine is known to act as a tyrosine analogue inhibiting protein biosynthesis (ter Meulen *et al.*, 1979) and metal-containing enzymes because of its ability to chelate metal ions, reducing plasma AA and mineral concentrations, reducing the absorption of some AAs from the gastrointestinal tract (Smuts *et al.*, 1995), and causing toxic symptoms including retardation of growth. In the pig diet, mimosine decreases feed intake (ter Meulen *et al.*, 1979). Although very few studies report signs of acute short-term poisoning, long-term exposure to levels of 772 ppm in rat diets induced mild alopecia, cataract, reversible paralysis of the hind limbs, severe retardation of growth, and mortality as high as 50%, whereas the addition of 2% of FeSO<sub>4</sub> protected the animals against these symptoms (El-Harith *et al.*, 1979).

Considering these PSM-negative impacts, it is important to bear in mind that (1) some treatments such as heating or ensiling are able to significantly reduce the content in some PSMs (see Martens *et al.*, 2012 for a review) and (2) forage is not intended to be fed alone and inclusion with other feed ingredients will possibly mitigate these deleterious effects. For example, HCN content in fresh cassava leaves can be as high as 349 mg/kg DM (Ty *et al.*, 2007). However, when cassava is included at a level of 0.21 on DM basis in a broken rice and sugar palm juice-based diet, the HCN content of the diet is reduced to 73 mg/kg DM, a moderately poisonous range, and pigs show no symptoms of ill health, nor do they show effects on DM intake and N retention.

*Effect of preservation method on feeding value.* Preservation methods are used to ensure longer availability of the forage resource on the farm than the growing season itself. However, preservation can also have an interesting influence on the feeding value: enhancement in palatability, intake and digestibility, detoxication of PSM and concentration of some nutrients (Martens *et al.*, in press).

Nonetheless, changes in feeding value vary between preservation methods and plant species. DM intake was higher in sun-dried than in fresh and ensiled *I. batatas* leaves owing to their higher water content (An *et al.*, 2004; Khieu *et al.*, 2005). Drying can reduce the volume of forage to more than half and increase intake of water-rich aquatic ferns such as *Azolla* sp. and *S. molesta* in pigs (Leterme *et al.*, 2010). Milling dried forage reduces the volume and animal selectivity and increases feed efficiency (Kim *et al.*, 2009; Martens *et al.*, 2012).

An *et al.* (2004) noticed changes in AA profiles and fibre fraction between fresh, dried and ensiled *I. batatas*, with the highest contents of NDF and ADF in fresh leaves and lowest in ensiled leaves. The reduction in NDF during ensiling (Hunt *et al.*, 1993; Bagheripour *et al.*, 2008) originates from cell

wall degradation by plant and bacterial enzymes, such as cellulase produced by Clostridia, cellulolytic clostridia, acid hydrolysis (McDonald *et al.*, 1991) and a small amount of hydrolysis of hemicellulose (Hunt *et al.*, 1993). A decrease in protein content may also be observed, resulting from proteolysis after harvesting, during wilting and in the silage itself. This decrease is more important when wilting occurs in a poor humid environment than under dry conditions (McDonald *et al.*, 2010).

As a consequence of these changes, *M. esculenta* leaves silage had a higher total tract apparent digestibility (TTAD) (0.84 v. 0.79, 0.71 v. 0.48, 0.54 v. 0.42 and 0.77 v. 0.70, respectively, for DM, CP, crude fibre (CF) and NDF) than sun-dried leaves (Khieu *et al.*, 2005). A similar trend was noticed with ensiled *I. batatas* leaves except for proteins (Nguyen *et al.*, 2012). In contrast, no difference was observed between fresh, ensiled and sun-dried sweet potato diets in TTAD (An *et al.*, 2004).

Besides major nutrients, preservation also affects PSM content in forage (reviewed by Martens *et al.*, 2012). Preparation steps for conservation can be necessary to eliminate the anti-nutrients in forage. For example, HCN is strongly reduced when plants are sun-wilted and chopped into small pieces before silage probably because of the action of endogenous linamarase on cyanogenic glucosides (Santana *et al.*, 2002). In addition, a combination of shredding and sun-drying can simultaneously reduce high HCN (by 96%), tannin (by 38%) and phytic acid (by 59%) contents of *M. esculenta* leaves (Fasuyi, 2005). Mechanical damage of plant tissues during chopping, wilting and ensiling promotes the contact between endogenous enzymes and PSMs and thus facilitates their removal (Lyon, 1985).

### Forage utilisation by pigs

Forage feeding value depends not only on the forage plant itself. As it contains high levels of fibre and sometimes PSM, the age of the animal, its BW, its breed and the inclusion levels in the diet are other factors determining the efficiency of forage utilisation as feed ingredient by pigs.

#### *Influence of physiological status*

Forage is rich in fibre and has a high bulking capacity, reducing the energy density of the diet as shown before. The efficiency with which pigs are able to cope with this reduction in energy density by increasing feed intake strongly varies with their physiological status. Whittemore *et al.* (2003) showed that the ability of pigs to ingest bulk feeds was correlated to live weight. While 600 g sugar beet pulp/kg of diet was constraining for pigs of 12 kg, 600 and 800 g/kg did not limit the live weight gain at 36 and 108 kg, respectively. High bulk feed causes a significant size increase in parts of the gut involved in digestion and fermentation (Whittemore *et al.*, 2003; Len *et al.*, 2009a). Furthermore, adult pigs have a larger hindgut in proportion to their live weight and a lower feed intake relative to gut size compared with young pigs, which increases retention and fermentation times in the intestines. This change in hindgut volume

affects the ability of the pig to digest fibre and consequently partially explains the higher digestibility of energy originating from fibre in adult sows (Noblet and Le Goff, 2001). Besides fibre and energy, protein digestibility of plant leaves is also influenced by live weight. Leterme *et al.* (2006b) observed that, when tropical foliage was included at 300 g/kg DM diet, protein digestibility was higher (0.49) in sows (0.12 to 0.36) than in pigs weighing 18 to 35 kg for which the digestibility of the diet decreased sharply when the rate of incorporation of leaves increased from 0 to 200 g/kg diet (Leterme *et al.*, 2005; Leterme *et al.*, 2009). Therefore, in farming systems in the tropics relying partly on forage to feed pigs, this feed resource should be preferentially fed to gestating sows.

#### *Differences in pig breeds in the ability to thrive on forage-based diets*

Besides live weight as discussed above, the breed can also strongly influence the potential of animals to thrive on forage and fibre-rich diets. Nevertheless, whether indigenous tropical breeds have superior ability than genetically improved breeds remains controversial depending on which parameter is taken into account: (1) the ability to consume a large amount of forage; (2) the ability to digest fibre more extensively; or (3) the feed conversion potential when consuming high levels of dietary fibre. Indeed, the negative impact of forage inclusion on performances is usually lower in local breeds with lower requirements as compared with exotic breeds with high requirements but also with high growth potential. The results of a literature overview on the comparison of indigenous and improved breeds regarding TTAD and DM intake when fed on fibre-rich diets are displayed in Table 5. When Zimbabwean Mukota (Ndindana *et al.*, 2002) and Vietnamese Mong Cai (Ngoc *et al.*, 2013) were compared with Large White pigs, those breeds showed no difference in intake levels when fed a high-fibre diet. However, in other

studies, Mong Cai pigs consumed more (70 v. 60 and 85 v. 78 g/kg metabolic BW) compared with improved pigs (Landrace × Yorkshire) (Len *et al.*, 2009a and 2009b). This ability is important as the low energy density of forage requires a compensation by an increase in intake to maintain energy intake in line with the requirement levels.

Regarding digestibility, Mong Cai (Len *et al.*, 2009b) and Mukota pigs (Ndindana *et al.*, 2002) showed higher (0.63 v. 0.57 and 0.87 v. 0.83, respectively) TTAD compared with improved pigs. Other studies showed similar trends (Len *et al.*, 2009b; Ngoc *et al.*, 2013). Khieu *et al.* (2005) with Mong Cai found a higher digestibility by local breeds but only for the fibre fraction of the feed. Genetic selection of indigenous pigs also seems to allow improvement in fibre digestibility. When Macías *et al.* (2008) compared native Cuban Creole pigs with 12-year-improved Cuban Creole pigs, the latter showed an increase in ileal fibre digestibility from 12% to 16%. Although quite intriguing, the authors provided no insight on the reasons why this influence of selection was specifically observed with fibre. These initial observations therefore deserve further research. The differences in digestibility between indigenous and improved breeds are, however, more frequent regarding TTAD than for ileal digestibility (Table 5). Research on the effects of genotype on digestibility has been mostly carried out during a single stage of growth, either on growing or on finishing pigs. This can partially explain the lack of consistency between some studies reported in Table 5. Barea *et al.* (2011) found two different trends in digestibility during growth and fattening periods when comparing Iberian and Landrace × Large White pigs. Whereas digestibility of OM and energy seem not to differ between breeds during the growing period, they were higher for Iberian pigs than for Landrace during the finishing period. This difference in response to breed effect with weight possibly originates from differences in digestive tract development between Iberian and Landrace × Large White pigs. In the study by Barea *et al.* (2011), Iberian

**Table 5** Comparison of digestibility and forage-based diets dry matter intake (DMI, g/kg<sup>0.75</sup>) between tropical and improved breeds

Breeds	DM	OM	Energy	Protein	NDF	ADF	DMI	References
Mukota	0.63*	nd	0.67 <sup>a</sup>	0.72 <sup>a</sup>	0.36 <sup>a</sup>	0.28 <sup>a</sup>	nd	Ndindana <i>et al.</i> (2002)
Large White	0.57*	nd	0.51 <sup>b</sup>	0.55 <sup>b</sup>	0.31 <sup>b</sup>	0.21 <sup>b</sup>	nd	
Mong Cai	nd	0.82 <sup>a</sup>	0.81 <sup>a</sup>	0.83 <sup>a</sup>	0.64 <sup>a1</sup>	nd	116 <sup>2</sup>	Ngoc <i>et al.</i> (2013)
Landrace × Yorkshire	nd	0.81 <sup>b</sup>	0.78 <sup>b</sup>	0.79 <sup>b</sup>	0.61 <sup>b1</sup>	nd	82 <sup>2</sup>	
Mong Cai	nd	0.83 <sup>a</sup>	0.80 <sup>a</sup>	0.80 <sup>a</sup>	0.52 <sup>a</sup>	nd	70 <sup>a</sup>	Len <i>et al.</i> (2009a)
Landrace × Yorkshire	nd	0.80 <sup>b</sup>	0.77 <sup>b</sup>	0.78 <sup>b</sup>	0.46 <sup>b</sup>	nd	60 <sup>b</sup>	
Mong Cai	nd	0.87 <sup>a</sup>	nd	0.83 <sup>a</sup>	0.55 <sup>a</sup>	0.43 <sup>a</sup>	85 <sup>a</sup>	Len <i>et al.</i> (2009b)
Landrace × Yorkshire	nd	0.83 <sup>b</sup>	nd	0.80 <sup>b</sup>	0.51 <sup>b</sup>	0.41 <sup>b</sup>	78 <sup>b</sup>	
Mong Cai	0.81	0.82	nd	0.58	0.76	0.55 <sup>a</sup>	34	Khieu <i>et al.</i> (2005)
Landrace × Yorkshire	0.81	0.82	nd	0.60	0.71	0.43 <sup>b</sup>	33	
Rustic Cuban Creole	0.79	0.78	nd	0.75	0.12 <sup>b3</sup>	nd	nd	Macías <i>et al.</i> (2008)
Improved Cuban Creole	0.77	0.76	nd	0.75	0.16 <sup>a3</sup>	nd	nd	

DM = dry matter; OM = organic matter; nd = not determined.

Value with different superscripts for same referenced manuscript within column are significantly different between pair of breeds on the parameter in the considered study ( $P < 0.05$ ).

<sup>1</sup>Fibre is expressed as total non-starch polysaccharides instead of NDF.

<sup>2</sup>Author value was expressed in daily feed intake (g/day) without considering the weight of pigs, which was different.

<sup>3</sup>Fibre is expressed as total crude fibre instead of NDF.

pigs had a lighter and shorter small intestine per kg BW, regardless of age. However, the size of the stomach was significantly larger, between 30 and 80 kg, and turned to be larger in Iberian pigs when the animals weighed 80 kg. Therefore, one can assume that the higher digestive tract development in Iberian pigs weighing 80 kg as opposed to Landrace × Large White pigs weighing 80 kg induces differences that are not observed with younger animals. These observations on Iberian pigs could apply to tropical pig breeds, especially those from Latin America. The high fibre digestibility of native breeds is also explained by a better adaptation to the high fibre content ascribable to high digestive enzyme activity and better adaptation of hindgut microbiota to degrade cell wall constituents of the diet (Freire *et al.*, 1998 and 2003), greater size of the gastrointestinal tract and longer retention time (Ngoc *et al.*, 2013). The ability of indigenous pigs to digest fibrous fractions is more pronounced in high-fibre diets (Len *et al.*, 2009b), which takes place in the hindgut because ileal digestibility of a high-fibre diet is usually similar between breeds in the same trial.

Finally, tropical breeds have a lower average daily gain (ADG) and a poorer feed conversion potential (1.86 v. 1.50 (Len *et al.*, 2009a), 2.27 v. 2.05 (Ngoc *et al.*, 2013) and 4.6 v. 2.9 (Kaensombath and Lindberg, 2013)) than improved ones even on high-fibre diets. As reviewed by Ly (2008) for Cuban and other Creole breeds, indigenous pigs have lower N retention per N intake (e.g. 0.28 v. 0.44 (Khieu *et al.*, 2005), 0.55 v. 0.58 (Ly, 2008)), because of their lower growth rate, inducing low protein-to-energy requirements in their diets as opposed to improved breeds (Barea *et al.*, 2007). The ADG difference is even greater when the protein content of the diet is higher than the protein requirements of the indigenous breeds (Barea *et al.*, 2011). This can be explained by the low selection of indigenous pigs for high growth rate and lean tissue deposition, or for their natural high fat tissue deposition, which is more energy demanding than lean tissue (Renaudeau *et al.*, 2006; Barea *et al.*, 2011). Generally, when indigenous pigs are compared with improved breeds, the dietary CP of trial diets is fixed to meet the requirements of improved breeds.

Nevertheless, trials comparing valorisation by tropical and improved breeds of forage actually used by farmers under field conditions are scarce (Lopez-Bote, 1998), and it is likely that, raised under smallholder conditions, improved breeds will probably not show such a better performance compared with indigenous pigs.

#### Growth performances on forage-based diets

Despite the fact that inclusion of forage reduces digestibility and some inconsistency on the ability of indigenous pigs to digest fibrous feed ingredients, recent studies have shown that a significant proportion of conventional protein concentrates can be replaced by protein-rich forage without affecting either growth performances or carcass quality. Fed for about 100 days with a diet in which soybean meal was substituted on protein basis up to 0.50 with either ensiled *S. guianensis* or *C. esculenta*, growth performance and

carcass traits of local and improved pigs were comparable to those fed the control diet (Kaensombath and Lindberg, 2013, Kaensombath *et al.*, 2013). Similar results were found when fattening pigs were fed a diet containing 0.30 of *Vigna unguiculata* (Sarria *et al.*, 2010). Furthermore, Kaensombath *et al.* (2013) reported that, when *S. guianensis* silage was used, growth performance was two to three times higher than that of the same local breeds fed diets based on locally available agricultural by-products and green plant materials. For this reason, it is essential to select suitable preservation method and forage species with high nutritive value to adequately balance the diet for the breed that is used. Therefore, grasses showing low intake (Sarria *et al.*, 2012) and lower digestibility compared with other plant groups should be avoided even for local breeds (Dung *et al.*, 2006).

#### Inclusion levels

Inclusion rate is of importance when supplementing pigs with forage ingredients because of (1) the presence of PSM, (2) their specific AA profile (3) and their impact on nutrient digestibility of the basal diet, which can be linear or quadratic. For example, the inclusion of *Stylosanthes* at 0.21 improved the ADG (312 v. 205 g/day) for the non-supplemented diet, whereas an inclusion level of 0.37 decreased the ADG to 190 g/day (Phengsavanh and Lindberg, 2013). When pig diets were supplemented with *Acacia karroo*, *Colophospermum mopane* and *Acacia nilotica* at 100, 200 and 300 g/kg, respectively, the increased intake was striking for pigs fed the *A. karroo* diet, especially at 100 and 200 g/kg (1.6 and 1.7 kg/day v. 1.2 kg and 1.4 kg for the two other species), and animals performed better for both inclusion rates with an ADG of 855 and 820 v. 716 and 668 g for *C. mopane* and 604 and 586 g for *A. nilotica* due to phenolic constituents. Therefore, Halimani *et al.* (2005) recommend limiting inclusion level of these legumes to 100 g/kg DM. Leterme *et al.* (2009) advise no more than 150 g/kg DM of aquatic fens in fattening pigs owing to their bulking capacity.

The composition in AA will also influence the optimal inclusion ratio of plants in diets. Hang (1998) fixed the acceptable incorporation limit of ensiled cassava leaves at 0.20 in a diet containing fish meal, which is rich in methionine, resulting in a well-balanced AA profile. In comparison, Phuc *et al.* (1996) established an optimal incorporation level of cassava leaves at 0.15 in a diet containing soybean meal proteins, which are low in methionine but rich in lysine, like cassava leaves. This means that, combined with a methionine-rich source, the inclusion rate of cassava could be revised upwards. Indeed, supplementing *M. esculenta* leaves with 0.2% methionine, a sulphur-containing AA essential among others in the detoxication pathway of HCN, as mentioned previously, increased the ADG of indigenous pigs from 540 to 712 g (Hang *et al.*, 2009; Ly *et al.*, 2012). Daily weight gains were increased from 482 to 536 g when lysine was added to a diet containing *I. batatas* leaves (An *et al.*, 2005).

Moreover, as stated before, PSM in forage can impose stricter limits to the inclusion levels than would the contents in fibre and other nutrients, owing to their anti-nutritive effects or

toxicity. Finally, from a more practical perspective, the optimal inclusion rate varies also according to the time of distribution and whether it is mixed with the basal diet. Dung *et al.* (2006) observed that forage is more consumed when it is offered before a basal diet than after (150 to 330 v. 30 to 150 g/day).

### Implications on the farming system of using forage in the diets of pigs

As shown previously in this review, including forage in well-balanced grain-based diets reduces growth performances of pigs, but, under particular conditions, this detrimental impact is lower for indigenous breeds than for high-performance European or American breeds. However, for regions where the access to balanced diets is difficult for economical or accessibility reasons, forage can improve the quality of the diet, especially by supplying proteins. For example, forage such as *S. guianensis* or *Aeschynomene histrix* was shown to improve growth performances (ADG of 394 and 396 g, respectively) of animals fed traditional poorly balanced diets (ADG of 205 g), especially regarding protein total content and AA profiles (Phengsavanh and Lindberg, 2013). Nonetheless, it is not possible to definitely conclude on the actual positive outcomes of this practice without a proper socio-economic and environmental assessment of the consequences of using forage on the whole production system. Few studies report the actual feeding costs of forage-based diets as opposed to commercial concentrate diets, probably because of the difficulty in calculating opportunity costs of cultivating, collecting and handling forage against concentrate feeds. Heat treatment such as cooking mixed forage with agriculture by-product as practised by many pig smallholders in South-East Asia (Chittavong *et al.*, 2012) efficiently reduces the content of heat-labile anti-nutritive factors and increases feed conversion. However, little is known on how effective this practice is from an environmental and economical perspective. In another example, the inclusion of *Azolla pinnata* as a protein replacer in the concentrate feed at 0%, 10% and 20% in grower and finisher diets significantly reduced the diet cost per kg weight gain by 8% for the 10% forage inclusion level (Cherry *et al.*, 2013). The same trend was found when *M. alba* was included at 25%, 30% and 35% in commercial pig diets. The feeding cost was reduced by 28% for the 30% inclusion rate (Ordóñez, 2010). In contrast, Kaensombath and Lindberg (2013) report similar prices per kg weight gain for concentrate and ensiled forage-based diets, but, as in most studies, the opportunity cost of forage cultivation and silage making on the farm is poorly documented. Preservation seems indeed very important to solve the problems of seasonality of feed availability, but they require knowledge, investment and time especially in low-input smallholder conditions. Silage seems to be ideal during the rainy season when sun-drying becomes difficult to perform.

Moreover, the cost of concentrates strongly varies within the same country or district according to the location of the farms, especially when distance to feed mills increases.

As such, the use of forage might be less interesting in periurban areas than in remote countryside farms. Cultivating forage or using forage by-products of other crops to feed pigs on mixed farms associating pig production to crops has several implications on the use of land, labour and nutrient cycles at the farm level that impact the sustainability of the farm as a whole. Some green plant materials used in pig diets are crop by-products that would be merely left on the fields if they had not been used in the animals' diets. For example, the yield of *M. esculenta* leaves as by-products of cassava root can reach 4.6 tonnes of DM per ha with an average content in protein of 21% DM (Ravindran and Ravindran, 1988). As a defoliation 6 months after planting does not decrease tuber yield (Fasae *et al.*, 2009), feeding cassava leaves to pigs would increase the total amount of product harvested from a field. Legumes used as dual-purpose crops such as cowpea (*V. unguiculata*) or cover crops such as *S. guianensis* to fight erosion decrease the need for N-fertiliser (Husson *et al.*, 2008) and increase the OM content of the soils while they can at the same time produce high amounts of protein-rich forage valuable to a certain extent as feed ingredients for pigs without affecting their beneficial effects on soil fertility. When pigs are fed forage, harvesting shares the highest cost under hand-labour. Mechanisation needs to be developed further because of the diversity of physiognomy between forage species: trees, shrubs or vines. One alternative could be keeping grazing pigs outdoors to let them harvest the forage for themselves on the fields, as studied in tropical conditions in Guadeloupe (Burel *et al.*, 2013). However, this method is challenging in areas where cisticercosis is still a major issue and where African swine fever is endemic. Moreover, some forage species are not accessible to grazing pigs: trees, shrubs or climbing vines and other plants such as *S. guianensis* or *P. scandens* would be destroyed by grazing pigs, impeding several harvests per year.

In order to properly address these questions it is essential to conduct life cycle multi-criteria assessments at farm level to compare social, economical and environmental performances of pigs fed partially with forage as opposed to concentrate-fed animals. Such studies exist for production systems in developed countries (Alig *et al.*, 2012), but unfortunately they are still too scarce in developing countries.

### Conclusion

Forage is an interesting source of proteins, especially for smallholder pig-feeding systems in tropical areas, as protein concentrates are either seldom available or expensive and inaccessible to most farmers. However, using forage for pigs is not obvious as forage plants have numerous disadvantages mainly related to high fibre and low-energy contents and the presence of PSM. Their inappropriate use results in nutritionally unbalanced diets and leads to poor pig performance, both for indigenous and for improved breeds. However, this review showed that including some forage species in the right proportion in the diet allows improvement of the poor nutritional quality of traditional pig diets by

increasing the CP and mineral intake and possibly maintaining the feeding cost at a low level. However, proper assessment of the social, economical and environmental consequences of feeding pigs with forage is required at the farm level to support claims for improved sustainability thanks to this practice as opposed to concentrate-fed pigs.

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