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Alternative plant protein sources for pigs and chickens in the tropics – nutritional value and constraints: a review

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Abstract

In the tropics, a large number of smallholder farms contribute significantly to food security by raising pigs and poultry for domestic consumption and for sale on local markets. The high cost and, sometimes, the lack of availability of commercial protein supplements is one of the main limitations to efficient animal production by smallholders. Locally-grown forages and grain legumes offer ecological benefits such as nitrogen fixation, soil improvement, and erosion control which contribute to improve cropping efficiency. Besides these agronomical assets, they can be used as animal feeds in mixed farming systems. In this paper we review options to include locally-grown forages and grain legumes as alternative protein sources in the diets of pigs and poultry in order to reduce farmers' dependence on externally-purchased protein concentrates. The potential nutritive value of a wide range of forages and grain legumes is presented and discussed. The influence of dietary fibre and plant secondary metabolites contents and their antinutritive consequences on feed intake, digestive processes and animal performances are considered according to the varying composition in those compounds of the different plant species and cultivars covered in this review. Finally, methods to overcome the antinutritive attributes of the plant secondary metabolites using heat, chemical or biological treatment are reviewed regarding their efficiency and their suitability in low input farming systems.

Keywords: tropical forages, pigs, poultry, protein supplementation

Abbreviations:

ANF	–	antinutritional factors,
CP	–	crude protein,
DF	–	Dietary fibre,
DM	–	dry matter,
NSP	–	non-starch polysaccharides,
SCFA	–	short-chain fatty acids,
TIA	–	trypsin-inhibitory activity

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1 Introduction

The demand for animal protein for human nutrition in the developing world is still rising, especially for pork and poultry products (OECD and Food and Agriculture Organization of the United Nations, 2010). This is an opportunity for smallholders with livestock, who make up almost 20 % of the world population (McDermott *et al.*, 2010), to increase household income and improve their livelihoods by connecting with the livestock value chain.

Smallholders often lack access to good quality feed with sufficient energy content and the balanced amino acid profile that is needed to ensure satisfactory animal performance. Soybean meal is widely used as a feed supplement with high energy content and an amino acid profile close to ideal. World soybean production (262 million t in 2010) is dominated by United States (90.6), Brazil (68.5) and Argentina (52.7) (FAOSTAT, 2012). Soybean meal is the residue after the oil is expressed and is dominantly used in highly industrialized production systems of swine and poultry. Globally, however, there is little surplus soybean meal for smallholders. Moreover, the cost of feed concentrates for livestock is increasing (OECD and Food and Agriculture Organization of the United Nations, 2010). Therefore, to meet the nutritive requirements for smallholder swine and poultry, we need to identify alternative low-cost feed resources (Ly, 1990; Lekule & Kyvsgaard, 2003).

The humid and subhumid tropics offer almost year-round growing conditions (Ly, 1990), with seasonal water deficits and excesses, constraints that are usually manageable. Unfortunately, tropical soils are often nitrogen deficient so that production of protein-rich material to supplement the diets of small animals either requires input of nitrogen fertiliser to gramineous crops, or the use of legumes either as the source of the supplement itself or as part of a rotation. Here we focus on the use of legume crops themselves as supplements.

There are about 650 genera of legumes with some 18,000 species, with a large diversity in the tropics and subtropics (NAS, 1979). Many of them have been collected for evaluation as tropical forages with gene banks at the Centro Internacional de Agricultura Tropical (CIAT, over 20,000 accessions, CIAT, 2011), the International Livestock Research Institute (ILRI, 20,000 African forage accessions, Karaimu, 2011), together with the Australian Tropical Crops and Forages Collection and the collection of CENARGEN-EMBRAPA.

We summarize results of research aimed at characterising alternative resources of primary feed for swine and poultry and identify the options of improving smallholder production of monogastric animals in the tropics in terms of their protein needs and forage supply.

2 Digestion and nutrient utilization in pigs and chickens

Pigs and chickens are both single-stomached (monogastric) species as opposed to ruminants, which have several fermentation compartments before the true stomach. Although monogastric mammals and birds show clear differences in their digestive systems, they share similar general feed digestion patterns compared with ruminants. Ingested feed is digested by acid and enzymes in the stomach and soluble components are absorbed in the small intestine. Indigestible components, such as non-starch polysaccharides, resistant starch, protein that underwent Maillard reactions, and some tannin- and fibre-bound proteins reach the cecum and the large intestine (pigs), and the ceca (poultry), where, together with endogenous secretions, they are fermented by the inhabiting microbiota. The fermentation produces short-chain fatty acids (SCFA), which are an important source of energy for the host. For example, in growing pigs and in sows, SCFA can provide 15 % (Dierick, 1989) and 30 % (Varel & Yen, 1997), respectively, of the animals' maintenance energy requirements. In chickens, SCFA can provide up to 8 % of their energy requirements, while ostriches can obtain 75 % of their energy requirements from fermentation in the ceca (Jozefiak *et al.*, 2004). Concentrate-only feeds change the digestion processes in the ceca of domesticated chickens so that its function and physiology are not well understood (Thomas, 1987; Jozefiak *et al.*, 2004). In contrast, there is no indication that modern pig genotypes have less ability to digest fiber (Urriola & Stein, 2012; Ly *et al.*, 2011; von Heimendahl *et al.*, 2010; Ninh *et al.*, 2009).

In contrast to ruminants, little microbially-synthesised amino acids can be absorbed from the large intestine in either pigs or poultry (Bowen, 1996). Therefore, feed protein must be digestible by the enzymes of the stomach to be absorbed in the small intestine. The amino acid profile of the feed protein should correspond to the specific amino acid requirements of the animals. According to the concept of the ideal protein (Wang & Fuller, 1989; Fuller *et al.*, 1989), the profile depends on the composition of body tissue, coat, and products (e.g. eggs) and must suffice for maintenance and growth (Fuller and Chamberlain, 1983 in FAO, 1996a).

3 Constraints for production systems in the tropics

In smallholder systems of monogastric production, lack of essential amino acids is common as diets often consist of cereal grains or part of them (rice, rice bran, maize, or sorghum) or cassava. These only provide 30 % or less of the pigs' requirements of lysine and methionine, which are the most limiting amino acids in pig feeds (Lekule & Kyvsgaard, 2003). Although many smallholders include other feed sources such as local roots or leaves, fruit (papaya) or agricultural by-products such as banana stems, these do little to improve the nutritional status of their pigs.

Farmers often do not understand or know their animals' feed requirements, nor do they know the nutritional value of these alternative feeds. Moreover, the nutritional quality of these alternatives may be low due to fibre-bound nitrogen (Shayo & Uden, 1999) and compounds such as trypsin inhibitors and tannins, which inhibit enzymes or bind to protein and reduce its digestibility. Because smallholders often have such limited choices, they welcome the solution of growing feeds locally specifically for their pigs and poultry, particularly if it also increases their productivity.

Low protein diets can be supplemented with synthetically-produced critical amino acids such as lysine (FAO, 1996a), which increases growth rates and reduces N-excretion (Kirchgessner *et al.*, 1994 in Jeroch *et al.*, 1999). This option is being used in commercial production systems in developing countries, but is rarely available to or affordable for most smallholders. There, it is important to avoid feeding too much protein as the excess is degraded in the animal to urea or uric acid for excretion. This has negative environmental impacts (Aarnink & Verstegen, 2007) and moreover is energy-consuming for the animal (GfE [Ausschuss für Bedarfsnormen der Gesellschaft für Ernährungsphysiologie], 2006).

Within the context of smallholder farms, one has to recognise that fast growth rates, which demand an optimum supply of dietary protein, is not necessarily the most profitable outcome when using locally-grown feeds. Finally, we have to understand the existing smallholder farming and marketing systems well before we attempt to introduce a new feed crop. Cost and profitability are key issues. The understanding also has implications for identifying suitable plant species and processing technologies that will fit within the current agricultural system and its calendar.

4 Tropical forages as protein source

Ideally, feeds should be derived from a crop that is part of an environmentally-sustainable farming system, which optimizes biomass productivity per unit of solar energy, minimizes inputs of agro-chemicals, and maintains (preferably enhances) soil fertility and biodiversity (FAO, 1996b).

Although all these requirements are rarely met at the same time, tropical forages as feed for monogastrics contribute to improved sustainability of animal production within farming systems (Schultze-Kraft & Peters, 1997 and modified according to Savon, 2005):

- High biomass production in environments where other crops cannot compete;
- No or limited competition with human food requirements;
- High levels of protein with a desirable amino acid (AA) profile, especially lysine, methionine and other sulphur-AA, which for monogastrics adequately balances the limitations of cereal proteins (leaf and grain);
- High levels of vitamins and minerals compared to traditional energy-based feed ingredients; and
- Additional benefits from the integration of forages in the farming system such as human food, wood, fibre, gum, tannery, soil improvement, and soil conservation.

4.1 Nutritional value and effect on animal performance

The crude protein content in tropical forage plants varies widely (Table 1), with values up to 360 g/kg of DM, which is similar to soybean grain. Comparing the amino acid profiles to the ideal protein for pigs and for layers (Table 2), the proportion of the sulphur-containing methionine and cystine in the analysed plants is low for chickens. The proportion threonine seems to be quite well balanced and the tryptophane level is within the desired range in half of the species analysed. In general terms, tryptophane is rather high in the green part of the plants and lower in the seeds. Although the amino acid pattern is not optimal for any one plant species, pig and poultry diets are usually mixtures of several ingredients, which when combined should complement each other to meet the nutritional requirements.

The response of monogastric farm animals to supplements made from forage species cannot be generalised as it depends on the ratio of the different components in the overall diet. Thus, to formulate optimal diets for monogastric farm animals, it is important to identify the optimum inclusion level for the available forage species as well as the best administration form in mixed rations. In addition to protein, forage legumes also contain higher amounts of vitamins and minerals compared to most cereals, forage grasses, and some agro-industrial by-products (Lopez & Tapia, 2003; Lajide *et al.*, 2008; Aarti *et al.*, 2005; Mosha *et al.*, 1995; Imungi & Potter, 1983; Garcia *et al.*, 1996; Leterme *et al.*, 2006), which may eliminate the need for premixed industrial supplements.

Forages can have further positive effects when included in diets of monogastrics. Hens' fertility increased when their diet included 14 % grass meal (Davtyan & Manukyan, 1987), while grass and lucerne meal included in the diet of layers decreased cholesterol in their eggs (Rybina & Reshetova, 1981). We do not know whether these effects apply generally nor what the physiological mechanism is.

Table 1: *Crude protein (CP) content of selected legumes [g kg^{-1} DM]*

Plant species	*CP content*				*Digestibility*	*Average Herbage Yield [t/ha] **
	Grain	*Leaf*	*Whole plant*	*Hay*		
Arachis glabrata			150–220 [1]	110 [2]	65 % DM and 66 % CP apparent digestibility (horses)[2]	10 [38]
Arachis pintoi		205 [5]	162–279 [3]	143 [4]	50 % ileal CP digestibility (rabbits) [6] 84 % apparent DM digestibility (horses) [7]	10 [38]
Cajanus cajan	190-219 [8,9], 212-225 [10], 223 [11]		189-214 [12]	167 [12]	50 % apparent CP digestibility of seed meal (pigs)[13] 81 % CP digestibility of seed (broilers)[14]	2-12 [39]
Centrosema molle (*C. pubescens*)			236-253 [12]		73 % CP digestibility of seed meal (broilers)[15]	3-10 [39]
Crotalaria ochroleuca		247-384 [16]	99-388 [17]	185-305 [17]		
Desmanthus virgatus		178 [12]	115 [18]	276 [19] Leaf meal	27 % *in-vitro* enzymatic DM digestiblity and 22 % *in-vitro* enzymatic CP digestibility of leaf meal (pigs) [20]	7 [38]
Lablab purpureus	≤ 120 [21] 252 [25] 230-280 [26]	186 [22] 143-385 [26]	181 [12] 145 [22] 100-250 [23]	167 [12]	51-74 % apparent CP digestibility of seeds (pigs) [24]	4-10 [39]
Mucuna (*pruriens*, *utilis*)	274-286 [25]	–	153-165 [12]	148 [12]	77 % CP digestibility of seed meal (broilers) [25]	5-12 [38]
Psophocarpus tetragonolobus		192-349 [12]			54 % CP digestibility of seed meal (broilers) [26]	
Stylosanthes guianensis		195 [27]	88 (stem) [27] 150-160 [29] 138-166 [30]	167 [12]	31 % *in-vitro* enzymatic DM digestibility [28]	5-10 [38]
Vigna mungo	200 [31] 261-268 [12]		194 [12]			max. 15.6 [40]
Vigna radiata	233-244 [12]	130 [12]				3-7 [39]
Vigna umbellata	233 [12] 182 [32] 174-200 [33]		169 [12]			
Vigna unguiculata	275 [34] 250 [35] 225-249 [12]		102 [29]		57 % apparent DM and 53 % apparent CP digestibility of herbage meal (pigs) [36] 53-59 % true DM digestibility of grains (chickens) [37]	3-8 [39]

[1] Beltranena *et al.*, 1980; [2] Eckert *et al.*, 2010; [3] Villarreal *et al.*, 2005; [4] Ladeira *et al.*, 2002; [5] Nieves *et al.*, 2004; [6] Nieves *et al.*, 2009; [7] Morgado *et al.*, 2009; [8] Amarteifio *et al.*, 2002; [9] Oloyo, 2004; [10] Eneobong & Carnovale, 1992; [11] Apata & Ologhobo, 1994; [12] FAO, 2007; [13] Mekbungwan *et al.*, 2004; [14] Leon *et al.*, 1993; [15] Iyayi *et al.*, 2011; [16] Mkiwa *et al.*, 1990; [17] Sarwatt *et al.*, 1990; [18] Sukkasame & Phaikaew, 1998; [19] Ly & Samkol, 2001; [20] Ly *et al.*, 2001; [21] Lambourne & Wood, 1985; [22] Diaz *et al.*, 2005; [23] Murphy & Colucci, 1999; [24] Laswai *et al.*, 1998; [25] Iyayi *et al.*, 2011; [26] Leon *et al.*, 1993; [27] Phimmmasan *et al.*, 2004; [28] Heinritz *et al.*, 2012b; [29] Guodao & Chakraborty, 2005; [30] Gruben, 2001; [31] Rani & Hira, 1998; [32] Saharan *et al.*, 2002; [33] Sadana *et al.*, 2006; [34] Luis *et al.*, 1993; [35] Ravindran & Blair, 1992; [36] Sarria *et al.*, 2010; [37] Sarmiento-Franco *et al.*, 2011; [38] Cook *et al.*, 2005; [39] Peters *et al.*, 2011; [40] INRA, CIRAD, AFZ and FAO, 2012

Table 2: *Essential amino acid composition relative to lysine content (absolute in g kg^{-1} CP) in forage and legume grains compared to the ideal feed protein, which are given relative to lysine (100).*

Species		*Lysine*	*Methionine*	*Met + Cys*	*Threonine*	*Tryptophane*	*References*
Ideal feed protein	Pigs	100		50	60	18	[1]
Ideal feed protein	Layers	100	44	84–93	74	16	[9; 10; 11; 12; 13]
Cajanus cajan	Grains	5.9–7.0	17–21	34–40	54–59	5–19	[2; 3]
Canavalia ensiformis	Grains	1.3–6.6	23–27	38–41	67–77	15–23	[4; 5; 6; 7]
Glycine max	Grains	6.2	24	50	65	21	[8]
Leucaena leucocephala	Grains	2.9	10	31	66	17	[2; 4]
Vigna mungo	Grains	7.3	15	23	47	n.d.	[4]
Vigna radiata	Grains	8.2	23	32	24	22	[4]
Vigna umbellata	Grains	8.7	14	17	53	9	[4]
Vigna unguiculata	Grains	6.5–6.7	14–18	26–33	57–80	3–19	[4]
Arachis hypogaea	Leaves	5.6	29	46	77	n.d.	[14]
Centrosema molle	Whole plant	3.5	46	74	120	31	[14]
Crotalaria ochroleuca	Leaves	4.7	32				[15]
Ipomoea batatas	Vine	5.4	26	43	78	22	[16]
Leucaena leucocephala	Leaves	5.5–6.7	16–21	29–70	67–69	15–18	[14; 16]
Manihot esculenta	Leaves	5.9	25	46	75	34	[14; 16]
Medicago sativa	Leaf meal	4.6	28	54	83	35	[16]
Stylosanthes guianensis	Hay	3.5	49	83	117	40	[14]
Vigna unguiculata	Straw	3.0	60	90	153	47	[14] [a]

[1] Cole, 1978; [2] Ravindran & Blair, 1992; [3] Eneobong & Carnovale, 1992; [4] FAO, 2007; [5] Vadivel & Janardhanan, 2005; [6] Belmar *et al.*, 1999; [7] Apata & Ologhobo, 1994; [8] INRA, 2004; [9] Kirchgessner *et al.*, 1995; [10] Jais *et al.*, 1995; [11] NRC National Research Council (U.S.) Subcommitee on Poultry Nutrition, 1984; [12] NRC National Research Council (U.S.) Subcommitee on Poultry Nutrition, 1994; [13] Jeroch, 1992; [14] FAO, 2007; [15] Sarwatt *et al.*, 1990; [16] Ravindran & Blair, 1992

[a] Further reading on *V. unguiculata* and other legume herbages' amino acids in Heinritz *et al.* (2012b).

We emphasise that the nutritional value of a feed depends not only on the essential nutrients it contains but also on their digestibility and hence their actual availability. Digestibility can be strongly affected by the content of dietary fiber and by plant-secondary compounds with toxic or antinutritive activities.

4.2 *The effect of fibrous diets on the digestive physiology*

Dietary fibre (DF) is defined as non-starch polysaccharides (NSP), including pectins, cellulose, hemicellulose, β-glucans, fructans, oligosaccharides, lignin, and resistant starch (Bindelle *et al.*, 2008; Chesson, 1995). Fibrous tropical feeds comprise leaves of crops, trees, legumes, and grasses. The chemical composition, the nature, and type of dietary fibre influence the voluntary intake of monogastric animals. Pigs can consume a maximum total amount of only 3.0 kg DM per day of feed (DLG, 2005) or 100 g DM/kg metabolic live weight, but growing pigs need about 16–35 MJ metabolizable energy (ME) per day, i.e. about 13 MJ ME/kg feed. DF lowers the energy value of the diet since its apparent digestibility is only 0.40–0.50, varying widely depending on the fibre source (Close, 1993), while digestibilities of protein, fat, sugars, or starch are above 0.80 (Noblet & Le Goff, 2001).

Intake increases with increasing fibre content to maintain the same amount of digestible energy in the diet (Savon, 2005), but the compensation is limited by gut capacity (Close, 1993). Pigs less than 50 kg liveweight cannot compensate for an energy concentration less than 14 MJ/kg, while pigs over 70 kg liveweight can compensate by increased feed intake if the energy concentration falls to 10 MJ/kg (Black *et al.*, 1986). Young animals, particularly, require diets that are highly digestible. Additionally, increased intake of DF raises the animal's basal temperature from the heat produced in the large intestine by fermentation, which can reduce voluntary feed intake (Ogle, 2006).

DF stimulates peristalsis in the monogastric intestinal tract, which can be used in swine management. For example, feed intake of sows must be restricted during the first 12 weeks of gestation (Reese, 1997; Hackl, 2002; Kirchgessner, 1997; Savon, 2005), which leads to behavioural problems. Adding at least 4 % DF to the diet, which can easily be done by adding forages, promotes peristalsis and appeases the animal's hunger (Jamikorn *et al.*, 2007). Voluntary intake by monogastrics of leafy

Table 3: *The effect of tropical plant species as supplements in feed for monogastric animals.*

Plant species	*Common name(s)*	*Plant part*	*Form*	*Animal*	*Effect**	*Inclusion Level†*	*Country*	*Ref.*
Arachis glabrata	Perennial peanut, florigraze	Leaf	Meal	Broilers	+/–	≤ 20	Cameroon	[1]
Arachis pintoi	Forage peanut	Forage	Dried	Pigs	+	20 % of diet CP	Colombia	[2]
Cajanus cajan	Pigeon pea	Grain	Raw	Chickens	+	30 g/animal	Philippines	[3]
		Grain	Meal	Pigs	+	≤ 30	Australia	[4]
Centrosema molle/pubescens	Centro	Forage	Pellet	Rabbits	+	≤ 75	Indonesia	[5]
Crotalaria ochroleuca	Marejea,	Grain		Rats	–	30	Tanzania	[6]
	Rattlebox	Leaf	Meal	Rats	+/–	≤ 10	Tanzania	[6]
Desmanthus virgatus	Wild tantan	Leaf	Meal	Pigs	–	18	Cambodia	[7]
Lablab purpureus	Lablab	Leaf	Meal	Layers	–	> 10	Nigeria	[8]
		Grain		Rats	–	≤ 12 % of diet CP	Australia	[9]
Mucuna (*pruriens, utilis*)	Mucuna, Velvet bean	Grain	Roasted/ cracked/ soaked	Pigs	+	100 g/d	Benin	[10]
		Grain	Raw/toasting/ cooking/ soaking	Pigs	–	15 % of diet CP	Honduras	[11]
		Grain	Raw/boiled/ toasted	Broilers	–	≥ 10 %	Nigeria	[12]
Stylosanthes guianensis		Forage	Fresh	Pigs	+		Laos	[13]
		Leaves		Pigs	+	≤ 6.4	Laos	[14]
Vigna/Phaseolus mungo, aureous	Mungbean	Grain	Raw	Pigs	+/–	15	India	[15]
Vigna radiata	mongo, gram	Grain coat		Broilers	+	15	Philippines	[16]
Vigna umbellata	Rice bean	Grain	Roasted, meal	Chickens	+	≤ 40	India	[17]
Vigna unguiculata	Cowpea, caupí	Grain	Meal	Broilers	+/–		Philippines	[18]
		Leaf	Meal	Shrimps	+/–	9 % of diet CP	Philippines	[19]‡
Manihot esculenta	Cassava, yuca	Leaf	Fresh	Pigs	+	≤ 50	Cambodia	[20]
Ipomoea batatas	Sweet potato	Leaf	Dried	Broilers	–	Replacing 300 or 200 g/kg maize	Cameroon	[21]
			Meal	Rats	+	10 % of diet CP	USA	[22]
Amaranthus hypochondriacus	Amaranthus, Prince-of-Wales feather	Leaf	Meal	Rats	–	10 % of diet CP	USA	[22]
Chenopodium quinoa	Quinoa	Leaf	Meal	Rats	–	10 % of diet CP	USA	[22]
		Leaf	Meal	Pigs	+	≤ 5	Cuba	[23]
Morus alba	Mulberry	Leaf		Pigs	+	55 % of diet CP	Cambodia	[24]
Trichantera gigantea	Nacedero	Leaf	Meal	Pigs	–	25 % of diet CP	Colombia	[25]
Ipomoea aquatica	Water spinach		Fresh	Pigs	+	15	Vietnam	[26]

n.n. unknown; * effects on animal performance compared to control, † in % of diet dry matter if not indicated differently;
(+) positive, (–) negative, (– –) extremely negative /toxic, (– +) both negative and positive effects, (+/–) neutral compared to control

[1] Teguia *et al.*, 1997; [2] Posada *et al.*, 2006; [3] Yamazaki *et al.*, 1988; [4] Whiteman & Norton, 1981; [5] Prawirodigdo *et al.*, 1989; [6] Mkiwa *et al.*, 1994; [7] Ly *et al.*, 2001; [8] Odunsi, 2003; [9] Lambourne & Wood, 1985; [10] Eteka, 1999; [11] Flores *et al.*, 2002; [12] Emenalom & Udedibie, 1998; [13] Phengsavanh & Stür, 2006; [14] Keoboualapheth & Mikled, 2003; [15] Ravi *et al.*, 1999; [16] Ancheta & Arellano, 1988; [17] Gupta *et al.*, 1992; [18] Luis *et al.*, 1993; [19] Eusebio & Coloso, 1998; [20] Ty *et al.*, 2011; [21] Teguia *et al.*, 1997; [22] Cheeke & Carlsson, 1978; [23] Diaz *et al.*, 1995; [24] Ty *et al.*, 2007; [25] Sarria *et al.*, 1991; [26] Nguyen & Preston, 2011

‡ For pigs refer to Sarria *et al.* (2010).

forage legumes is generally higher than of grasses due to their lower fibre content and higher digestibility. Their retention times in the stomach are therefore shorter so that they are good options to feed for monogastrics. Additionally, pigs and poultry digest hemicellulose better than cellulose, so that forages should be used at an early stage of maturity, before they start to lignify (Kephart *et al.*, 1990).

High levels of DF increases the number and activity of cellulolytic bacteria in the gastrointestinal tract of poultry (Jozefiak *et al.*, 2004) and swine (Bindelle *et al.*, 2010), with the same species found in ruminants (Varel & Yen, 1997). This is an important adaptation to the DF utilization (Rodriguez *et al.*, 2000, 2001). Pigs of > 25 kg live weight need at least 3–5 weeks (Longland *et al.*, 1993) or more (Kephart *et al.*, 1990) adaptation time to maximize the digestion of high-fiber feeds. This needs to be considered when introducing and evaluating forages in the diet.

Non-starch polysaccharides (NSPs) such as polymers of galacturonic acid, galactomannans, xylose, and cellulose have digestibilities in pigs as low as 27–43 % (Gdala & Buraczewska, 1997). They are therefore only secondary in the nutrition of the animal, although xylose and galacturonic acid were much better digested when given at a low rate (4 g/d) to pigs (Yule & Fuller, 1992). Nevertheless, the types and proportions of soluble and insoluble NSPs strongly influence intestinal ecophysiology and health, including the balance between detrimental and health-promoting bacteria species. High levels of fermentable NSPs, such as inulin or beta-glucans, induce a decrease in undesirable enterobacteria in the hindgut by (1) lowering the pH through increased production of short-chain fatty acids; (2) increasing health-promoting bacteria, which impede the access to the receptors on the intestinal epithelium to pathogens; and (3) reducing bacterial proteolysis of undigested protein. (Molist *et al.*, 2009). This is important in freshly-weaned piglets, which are prone to transient inflammation of the gastrointestinal tract (Pie *et al.*, 2007).

Alpha-galactosides or oligosaccharides in legume seeds cannot be directly hydrolysed and absorbed by non-ruminants, which lack α-galactosidase. While microorganisms in the large intestine degrade these sugars, leading to flatulence and gastric discomfort (Trugo *et al.*, 1990), oligosaccharides also have prebiotic effects in chicken (Lan, 2004; Xiang *et al.*, 2008). In broilers, a moderate level of α-galactosides had no effect on animal performance (Veldman *et al.*, 1998). In consequence, a restricted level of legume seeds contributes well to nutrition and health of monogastrics.

4.3 Chemical constraints and antinutritional factors

Plants produce a variety of simple to highly complex compounds, many of which have been identified and characterized. Many of them seem to be defense against biotic and abiotic stresses and more than 1200 classes serve to protect against herbivory. They are not involved in the plant primary biochemical pathways for cell growth and reproduction (Makkar, 2007). The most common major groups are polyphenols, cyanogenic glycosides, alkaloids, saponins, steroids, toxic proteins and amino acids, non-protein amino acids, phytohemagglutinins, triterpenes, and oxalic acid (Kumar, 1992; Liener, 1980), and are either toxic or act as anti-nutritive factors (ANF). ANFs are defined as, "Substances generated in natural feed ingredients by the normal metabolism of [plant] species and [interacting] by different mechanisms, e.g. inactivation of some nutrients, interference with the digestive process or metabolic utilization of feed which exert effects contrary to optimum nutrition. Being an ANF is not an intrinsic characteristic of a compound but depends upon the digestive process of the ingesting animal" (Aganga & Tshwenyane, 2003). Thus, plants that are relatively harmless to humans and other mammals may be, and often are, highly toxic to birds, fish, insects and others (Dobson, 1959; Kumar & D'Mello, 1995). The utility of leaves, pods, and edible twigs of shrubs and trees as animal feed is limited by the presence of ANFs. ANFs are generally not lethal but may cause toxicity during periods of scarcity or confinement when the animals consume large quantities of ANF-rich feed.

In this section, we briefly review a selection of the most common ANFs and the plant species in which they occur.

4.3.1 Lectins

Lectins are sugar-binding glycoproteins, which are classified as toxic (*Phaseolus vulgaris*, *Canavalia ensiformis*), growth inhibitory (*Glycine max*, *Amaranthus cruentus*, *Phaseolus lunatus*, *Dolichos biflorus*) (Grant, 1989), or essentially non-toxic or beneficial (seeds of *Vigna subterranea*, *Vigna umbellata* and *Vigna unguiculata*) (Grant *et al.*, 1995). Lectins occur depending on the development stage and on the part of the plant. Toxic lectins generally coagulate the erythrocytes, which can affect the immune system (Jeroch *et al.*, 1993), or disrupt nutrient absorption in the intestines by shedding the brush border membrane of the enterocytes (Makkar, 2007). Lectin activity can be removed by heat, with moist better than dry.

4.3.2 Polyphenolic compounds

Polyphenols are a major group often related to taste, odour, and colour. Flavanoids (monomeric elements of condensed tannins), cumarine, and lignane are the principal agents. Condensed tannins (CT) are complex heat-stable phenolic compounds and common in many plants, especially shrub legumes such as *Gliricidia sepium*, *Acacia species*, *Leucaena leucocephala* and *Albizia falcataria*.

Tannins bind protein through H-bonds and hydrophobic interactions. By doing so, they reduce the digestibility of protein (Jeroch *et al.*, 1993) and carbohydrates including starch and fibers. Another important property is their bitter and astringent taste, which in many cases reduces palatability, so the animal will not eat it. In pigs and poultry, tannins are associated with poorer feed conversion efficiency (FAO, 1996b). In poultry, tannin levels from 0.5 to 2.0 % in the diet can depress growth and egg production, while levels from 3 to 7 % can cause death. In swine, tannins depress growth rates and protein utilization, damage the mucosal lining of the digestive tract, alter the excretion of certain cations, and increase excretion of proteins and essential amino acids (Cannas, 2008). Pigs fed a tannin-rich extract of the quebracho tree had a lower apparent ileal digestibility of nitrogen, but there was no significant decrease in true ileal nitrogen digestibility (Steendam *et al.*, 1998). Condensed tannins are usually not toxic, but hydrolysable tannins can cause liver and kidney damage, and death (Makkar, 2007). Conversely, tannins are anti-oxidants and can improve resistance to heat stress (Liu *et al.*, 2011).

4.3.3 Toxic amino acids

Non-protein amino acids occur in unconjugated forms in many plants, especially in legumes, with the highest concentration in the seed. For example, *Leucaena leucocephala* contains mimosine, which binds to

Table 4: *Anti-nutritional factors in selected forage plants.*

Plant species	*Plant part*	*ANF type*	*Counter measure*	*Dietary inclusion, pigs*	*Dietary inclusion, poultry*
Amaranthus hypochondriacus	grain	Saponins, TIA	Autoclaving, moist-heating [1], boiling [2]		Up to 400 g/kg [3]
Atriplex hortensis	grain	Saponins	Hot-water extraction [4]	Vitamin supplement [5]	
Cajanus cajan	grain	TIA, phytic acid, condensed tannins	Boiling, roasting [6], soaking+germination [7]		
Chenopodium quinoa	grain	Saponins, phytic acid, tannins, TIA	Washing, polishing [8]	[Forage meal at 5 % of the diet (Diaz *et al.*, 1995)]	Washed grain at 75 % of the diet [8]
Lablab purpureus	grain	Phytic acid	Roasting, soaking [9], boiling ≤ 30 min [10]	9 % inclusion in diet [11]	≤ 50 % inclusion in the diet [10]
Manihot esculenta	leaves, tuber	Cyanogenic glycosides	Ensiling, sun drying [12,13]	Leaves ≤ 50 % of diet [12]	Fermented tuber meal ≤ 75 % of energy supplement [13]
Mucuna (*pruriens, utilis*)	grain	L-DOPA, Phytate, tannins, TIA	Dry heat [14], autoclaving [15], soaking in $NaHCO_3$ + autoclaving [16]	≤ 40 % of the diet with cracking/soaking/ boiling [18]	≤ 40 % of the diet [16]
Psophocarpus tetragonolobus	grain	Lectins, Cyanogenic glycosides, TIA	Roasting, boiling [19], autoclaving [20]		< 75 % of diet protein [20]

[1] Pond *et al.*, 1991; [2] Fadel *et al.*, 1996; [3] Ravindran *et al.*, 1996; [4] Coxworth *et al.*, 1969; [5] Jurubescu *et al.*, 1991; [6] Muangkeow, 1994; [7] Sangronis & Machado, 2007; [8] Improta & Kellems, 2001; [9] Jain *et al.*, 2009; [10] Abeke *et al.*, 2008; [11] Laswai *et al.*, 1998; [12] Ty *et al.*, 2011; [13] Udedibie *et al.*, 2004; [14] Siddhuraju *et al.*, 1996; [15] Vijayakumari *et al.*, 1996a; [16] Vadivel & Pugalenthi, 2008; [17] Vadivel *et al.*, 2011; [18] Emenalom & Udedibie, 1998; [19] Igene *et al.*, 2006; [20] Lumen *et al.*, 1982

minerals and pyridoxalphosphate (Makkar, 1991), decreasing the activity of the enzymes that require them as co-factors, and ultimately inhibiting metabolic pathways. It can disrupt the reproductive process, show teratogenic effects, lead to loss of hair and wool, and even to death (Sastry & Rajendra, 2008; Reis, 1975, 1978; Laswai *et al.*, 1997).

The seeds of *Canavalia* species and other legumes such as *Vicia ervilia* (Sadeghi *et al.*, 2009) and *Medicago sativa* (Nunn *et al.*, 2010) contain canavanine. Canavanine is a potent inhibitor of insect development by competing with the indispensable amino acid arginine. Poultry are much more susceptible to canavanine than mammals due to the antagonism of lysine with arginine in birds. It leads to autoimmune-like diseases affecting the kidneys and skin. Canavaline, found in *Canavalia ensiformis* seeds, is a derivative of canavanine. It is highly toxic and a potent insecticide (Rosenthal, 1983). L-DOPA, which is present in *Mucuna* species, is cytotoxic (Lee *et al.*, 2006) leading to haemolytic anaemia. Lathyrogenic amino acids, like BCNA (β-cyanoalanine), ODAP (β-N-oxalyl-α,β-diaminopropionic acid), DABA (α,γ-diaminobutyric acid) and BAPN (β-aminopropionitrile) are neurotoxic and occur in *Lathyrus* species and in *Vicia sativa* (D'Mello & Walker, 1991).

Selenoamino acids, found in *Lecythis ollaria*, may cause toxic reaction because they replace corresponding sulphur amino acids during protein synthesis (D'Mello & Walker, 1991). As they contribute to the selenium supply in the animal they can act both as micronutrient or as toxin depending on the dose (Kabata-Pendias, 2000).

4.3.4 Saponins

Saponins are found in *Brachiaria decumbens*, *B. brizantha* (Brum *et al.*, 2009), *Amaranthus hypochondriacus*, *Chenopodium quinoa*, *Atriplex hortensis* (Cheeke & Carlsson, 1978), and *Medicago sativa* (Pedersen *et al.*, 1972). They are heat-stable, form a soapy froth when mixed with water, and alter the cell wall permeability, leading to hemolysis and to photosensitization (Brum *et al.*, 2009). They depress growth in chicks (Jeroch *et al.*, 1993), but there are conflicting results in pigs, with a positive effect on both sows and piglets (Hauptli & Lovatto, 2006), compared with fewer stillborn piglets but reduced growth performance (Ilsley & Miller, 2005).

4.3.5 More ANFs

There are heat-labile cyanogens and heat-stable antigenic proteins, amongst others.
Cyanogenic glycosides, such as linamarin and lotaustralin, which are common in cassava (*Manihot esculenta*) and also in *Acacia*, *Phaseolus* and *Psophocarpus*, depress performance and cause cyanide intoxication. If, however, "cyanogen content is below 100 mg HCN equivalent kg^{-1} and the diet is adequately supplemented with proteins, particularly with sulphur-containing amino acids, and iodine", it is safe to feed to livestock (Tewe, 1994).

Alkaloids of legumes such as the bitter-tasting quinolizidine in lupins (Acamovic *et al.*, 2004) reduce the feed intake, may affect the liver, and paralyze respiration (Jeroch *et al.*, 1993).

Isoflavones like the genistein and daidzein of soy have estrogenic effects, which can lead to reduced fertility (Winter *et al.*, 2008), but not always (Wei *et al.*, 2004).

Protease inhibitors like chymotrypsin and trypsin in soybean (Swiech *et al.*, 2004) depress growth, and can cause hypertrophy and hyperplasia of the pancreas. They occur widely in many plants.

Phytate is a major pool of phosphates in plants, with a low availability of the bound phosphorus to non-ruminants. The intestinal apparent digestibility of phytate in pigs varies widely, between 0 and 25 % (Rubio *et al.*, 2006). Moreover, phytate significantly reduces the availability of minerals such as zinc, calcium, and magnesium (Rimbach *et al.*, 2008).

Oxalates, which have similar attributes, occur in concentrations as high as in rhubarb and sorrel (*Rhumex acetosa*) in some tropical legume forages such as *Vigna unguiculata*, *Desmodium velutinum*, and *Lablab purpureus* (Martens, unpublished data) and in grasses such as *Setaria* (Rahman *et al.*, 2011). They limit especially the availability of calcium, magnesium, and iron (Weiss, 2009).

4.4 Processing to improve nutritional value

Forage plants can be processed to enhance palatability, intake, and digestibility, to conserve, detoxify the antinutritional factors above, or concentrate nutrients (Akande *et al.*, 2010; Close, 1993). All this should be achived without decreasing the nutritive value of the feed.

4.4.1 Heat treatments

Heat treatment includes sun- and oven-drying, roasting, autoclaving, and boiling, which usually reduces the content of heat-labile ANFs (see Table 5). Sun-dried cassava leaves (*Manihot esculenta*) had 20 mg/kg hydrogen cyanide in the leaf meal compared with 190 mg/kg in the meal of fresh leaves (Phuc *et al.*, 1995). Laying hens fed sun-dried *Gliricidia sepium* performed better than those fed with the oven-dried legume (Montilla *et al.*, 1974), although it is not clear how the type of drying affects the feeding quality. Drying reduces the volume and increases total dry matter intake, which can more than double in pigs (Leterme *et al.*, 2010) given adequate amounts of water.

Thermal treatment considerably reduced the trypsin-inhibitory activity of seeds of *Glycine max* (Liener, 1994), *Cajanus cajan* (Muangkeow, 1994), *Arachis hypogaea* (Hira & Chopra, 1995), and *Psophocarpus tetragonolobus* (Igene *et al.*, 2006). In the latter, roasting also completely removed haemagglutinin. Roasting or autoclaving seed of *Phaseolus vulgaris* reduced its tannin content by 30–40 %, this was surpassed by dehulling (Borges *et al.*, 1998). Dry heat (Siddhuraju *et al.*, 1996) and autoclaving (Vijayakumari *et al.*, 1996a) significantly reduced the content of L-DOPA in seeds of *Mucuna pruriens*.

Autoclaving gives mixed results. Broilers performed better on autoclaved seed meal of *Psophocarpus tetragonolobus* than on raw meal (Gerpacio & Princesa, 1985), however, it does not remove haemagglutinin, trypsin inhibitors, tannins, or phytins (Igene *et al.*, 2006). Boiling *Canavalia ensiformis* seeds for 60 min gave better broiler performance than either the raw seeds or boiling for 30 min (Aquino *et al.*, 1985), yet it may reduce the mineral content by solubilisation (Igene *et al.*, 2006). Boiling significantly increased apparent and true metabolisable energy of *Cajanus cajan* seeds (Muangkeow, 1994). In contrast, boiling reduced the lysine content of *Vigna radiata* seeds by 43 % (Bhatty *et al.*, 2000), but significantly increased starch digestibility (Antu & Sudesh, 2009). Boiling removes part of water-soluble nutrients and minerals of legume seeds in contrast to autoclaving (Apata & Ologhobo, 1994). Compared with roasting, boiling improved the nutrient availability and utilisation of *Lablab purpureus* beans in pigs (Laswai *et al.*, 1998).

4.4.2 Grinding/ milling

Milling dried forages reduces the volume substantially and is an affordable way to reduce animal selectivity. Also, animals utilize nutrients better from feeds ground to small particle size (Mosenthin & Sauer, 2011; Kim *et al.*, 2009).

4.4.3 Pelleting

Feeding texture determines voluntary feed intake and influences nutritive value. Weaned pigs tend to prefer pellets to meal (Laitat *et al.*, 2004, 2000). Pelleting increases the digestibility in chicks of protein and starch and apparent metabolisable energy values of *Vicia faba* (Lacassagne *et al.*, 1988).

4.4.4 Hulling/husking

Some ANFs such as tannins are mainly concentrated in the seed coat, so that hulling is a simple method to remove them (Vadivel & Janardhanan, 2005). In *Phaseolus vulgaris* seeds, dehulling reduced the tannin content from 22.0 to 5.3 mg/100g (Borges *et al.*, 1998). This method might be an option for farmers, such as coffee growers, who have other uses for a dehulling mill. Other opportunities for small-scale milling are explained by Jonsson *et al.* (1994).

4.4.5 Soaking

Soaking grains in water for 18 h reduced the phytate content of *Mucuna monosperma* by up to one-third of the original content (Vijayakumari *et al.*, 1996b). Farmers in Laos soak *Leucaena leucocephala* leaves for at least three hours, which improves their feeding value for pigs (Tiemann, personal observation). Soaking reduces phytic acid content of *Lablab purpureus* seeds (Jain *et al.*, 2009).

4.4.6 Extraction/chemical treatment (cold)/extrusion cooking/expanding

Extraction of *Canavalia ensiformis* beans with $KHCO_3$ followed by either autoclaving or microwaving reduced canavanine concentration compared with simple soaking (D'Mello & Walker, 1991).

Extrusion cooking inactivated the haemagglutination of *Canavalia ensiformis*, but in feeding chicks other unidentified anti-nutritive factors seemed to be active (Melcion *et al.*, 1994).

Leaf meal of *Leucaena leucocephala* treated with either acetic acid or NaOH raised the rate of nitrogen retention in pigs (Echeverria *et al.*, 2002).

Extraction, extrusion cooking, or chemical treatment are unlikely methods for smallholder farmers, even though urea and sodium hydroxide treatment were adopted for improving roughage quality on-farm in feeding ruminants (Kayouli *et al.*, 1982; Sourabie *et al.*, 1995; Chenost & Kayouli, 1997).

Expanding grains is a hydrothermal process, which like extrusion, can be run at different temperatures. It is important in soybean processing for its cheapness and for conserving lysine (van Zuilichem *et al.*, 1998). Expanding lupin seeds decreased antinutritional factors and significantly improved apparent nutrient digestibility in pigs compared to grinding (Yang *et al.*, 2007).

4.4.7 Fermentation

Under anaerobic conditions microbes ferment carbohydrates into organic acids and/or alcohols. Ensiling is a suitable fermentation method for both grains and whole-crop forage (Table 6).

Lactic acid fermentation reduced trypsin and α-amylase inhibitor activity and tannins in *Sphenostylis stenocarpa* seeds by up to 100 % in contrast to cooking (Azeke *et al.*, 2005), and reduced cyanogenic glycosides and alpha-galactosides by 85 % compared with only 10-20 % by cooking. Fermentation of *Phaseolus vulgaris* grains and grain meal increased *in-vitro* protein digestibility, affected different vitamin fractions, and decreased minerals (Granito *et al.*, 2002), reducing α-galactosides, trypsin inhibitory activity, and tannin content in seed meal. Fermenting *Mucuna* to tempe, a traditional Indonesian food, reduced L-DOPA by 70 % and hydrolysed 33 % of phytic acid (Higasa *et al.*, 1996; Sudarmadji & Markakis, 1977). Solid state fermentation of *Cicer arietinum* gave higher digestibility of lysine and protein, reduced phytic acid content to 10 %, and tannin content to 13 % of raw chickpea flour (Reyes-Moreno *et al.*, 2004).

Ensiling *Leucaena leucocephala* shoots reduced mimosine content from 7 % to 2 % (Liu & Wang, 1990). Ensiled cassava leaves lost 77 % of their hydrogen cyanide and increased digestibility for growing pigs (Borin *et al.*, 2005), although sun-drying was more effective (Bui Huy *et al.*, 2000). Good fermentation management (Niven *et al.*, 2006; Olstorpe *et al.*, 2010; Marcinakova *et al.*, 2008), which is feasible for smallholders, is required to avoid substantial losses of lysine and tryptophane (Blandino *et al.*, 2003), or even benefit from increased lysine content (Gerez *et al.*, 2006). Further information on ensiling and silo types is available in FAO (2000), Heinritz *et al.* (2012a), Reiber *et al.* (2008), and Reiber *et al.* (2009).

4.4.8 Use of enzymes

There have been various attempts to mix different enzymes into feeds to reduce antinutrients (Table 6). The only successes are phytase (Varley *et al.*, 2011) and NSPases (Ao *et al.*, 2010). Enzymes are currently unlikely to be suitable for smallholders due to cost and their limited availability.

4.4.9 Germination

Germination activates endogenous enzymes, which attack most antinutrients (Campbell & van der Poel, 1998) (Table 6) and enhance the nutritional value of grains (Muzquiz *et al.*, 1998). But germination can be difficult to manage as seedlings tend to attract moulds and are easily spoiled. The germinated seeds have to be fed immediately or dried, which increases their cost.

Germination reduces trypsin inhibitors, phytic acid, galactosides, and certain lectins in *Glycine max* (Bau *et al.*, 1997) and, compared to raw seeds, improves the *in-vitro* starch digestibility in *Cicer arietinum*, *Vigna unguiculata* and *Vigna radiata*, similar to the improvement through fermentation and pressure cooking (Urooj & Puttaraj, 1994).

Germination, preceded by soaking, reduced trypsin inhibitory activity of *Phaseolus vulgaris* and *Cajanus cajan* seeds by 26–53 %, phytic acid by 41–53 %, and condensed tannins by 14–36 %, while the *in-vitro* protein digestibility, vitamin C and thiamine content increased significantly, and the mineral composition was modified (Sangronis & Machado, 2007). Germination of *Lupinus albus* for 96 h gave peak phytase activity, while in *Lupinus luteus* it increased until 120 h (Muzquiz *et al.*, 1998).

Table 5: *Reduction of anti-nutritional factors by physical processing.*

Component	*Heat*	*Reference*	*Soaking*	*Reference*
Phytate/ phytic acid	–/+ (autoclaving)	[1;2]	+ (–21-33 %)	[11;46]
Trypsin inhibition	–/+ (autoclaving; boiling, roasting)	[1;2;3;38;40;41;42]	+ (–22 %)	[3;7]
Toxic amino acids/ proteinaceous ANF				
Mimosine	+	[4]	+	[4;12;13]
Canavanine	+ – (roasting)	[35]	+ (combined; $NaHCO_3$; $KHCO_3$)	[33;34;36]
Canaline				
L-DOPA	+ ((pressure-)cooking –14–43 %; dry heat)	[5;45;43]	+ (hot water/ $NaHCO_3$/ $Ca(OH)_2$)	[5;14;15]
Saponins	+ (boiling; pressure cooking)	[6;7]	+ (–34 %)	[7]
Tannins	–/+ (autoclaving; roasting –32 %)	[40;1;44]	–	[16]
Alkaloids			++ (60 °C, 60 min)	[55]
Oxalate	+ (boiling)	[8]	+	[17]
Hydrogen cyanide	+ (sundrying, –33–63 %; steaming, boiling)	[9;39;10]	+	[10]
Oligosaccharides	+ (autoclaving)	[2]	+ (–40 %)	[2]

Table 6: *Reduction of anti-nutritional factors by biological means.*

Component	*Fermentation*	*Reference*	*Enzymes*	*Reference*	*Germination*	*Reference*
Phytate/ phytic acid	+ (–33 %)	[1;2;18;49]	++ (phytase)	[27]	+ (–41–53 %)	[16;52;53;54]
Trypsin inhibition	–/+ (–50 %–99 %)	[3;19,20,18,47]			++	[1;52;53]
Toxic amino acids/ proteinaceous ANF						
Mimosine	+ (–21–90 %)	[32;21;22;23;50]	+ (endogenous)	[28;51]		
Canavanine					–	[37]
Canaline			+	[29]		
L-DOPA	+ (–10–47 %)	[24;49]			–	[5]
Saponins	+				–/+	[30;7]
Tannins	+ (–80 %)	[25;1]			+ (–14–36 %)	[1;53]
Alkaloids	+	[2]				
Oxalate	+	[26]			+	[17]
Hydrogen cyanide	+ (–78-85 %)	[9;47]			+	[16]
Oligosaccharides	+	[2;48]			+	[31;52]

+ reduction; ++ strong reduction; – no effect; –/+ effect variable

[1] Ramachandran & Ray, 2008; [2] Khattab & Arntfield, 2009; [3] Fadahunsi, 2009; [4] Murthy *et al.*, 1994; [5] Bressani *et al.*, 2002; [6] Ejoh *et al.*, 2009; [7] Sinha *et al.*, 2005; [8] Lewu *et al.*, 2009; [9] Borin *et al.*, 2005; [10] Fukuba *et al.*, 1982; [11] Noreen *et al.*, 2009; [12] Vogt, 1990; [13] Tawata *et al.*, 1986; [14] Vadivel & Pugalenthi, 2008; [15] Gurumoorthi *et al.*, 2008; [16] Yasmin *et al.*, 2008; [17] Haritha & Maheswari, 2007; [18] Stodolak & Starzynska-Janiszewska, 2008; [19] Li-Jing & Yu, 2008; [20] Lin *et al.*, 1988; [21] Srinivasulu *et al.*, 2000; [22] Rosas *et al.*, 1980; [23] Angthong *et al.*, 2007; [24] Matenga *et al.*, 2002; [25] Valizadeh *et al.*, 2009; [26] Malavanh *et al.*, 2008; [27] Luo *et al.*, 2009; [28] Lyon, 1985; [29] Rosenthal, 1992; [30] Jyothi *et al.*, 2007; [31] Oboh *et al.*, 2000; [32] Khatta *et al.*, 1987;[33] Sadeghi *et al.*, 2009; [34] Gupta *et al.*, 2001; [35] Viroben & Michelangeli-Vargas, 1997; [36] D'Mello & Walker, 1991; [37] Kasai & Sakamura, 1986; [38] Liener, 1994; [39] Phuc *et al.*, 1995; [40] Igene *et al.*, 2006; [41] Hira & Chopra, 1995; [42] Muangkeow, 1994; [43] Siddhuraju *et al.*, 1996; [44] Borges *et al.*, 1998; [45] Vijayakumari *et al.*, 1996a; [46] Vijayakumari *et al.*, 1996b; [47] Azeke *et al.*, 2005; [48] Granito *et al.*, 2002; [49] Ukachukwu *et al.*, 2002; [50] Liu & Wang, 1990; [51] Ghosh & Samiran, 2007; [52] Bau *et al.*, 1997; [53] Sangronis & Machado, 2007; [54] Muzquiz *et al.*, 1998; [55] Rodriguez & Tecson-Mendoza, 1998

5 Conclusions and outlook

There is a large diversity of tropical forage species as protein options for monogastric farm animals in the tropics. There is also a multitude of choices in terms of agricultural suitability and yields, nutrient contents, and nutritional constraints, which may be partly or fully overcome by appropriate processing methods. Individual decisions at farm level considering ecological conditions, labour and technical requirements, and already-available feed ingredients can achieve good economic returns and reduce the risks of failure.

The available diversity, however, often makes the selection of the best option challenging and requires ample knowledge of agronomic, nutritional, and secondary compound characteristics of forage species. Creative approaches are required to fit forage-based feed solutions for monogastric animals into existing smallholder systems and further systematic research is required to define the actual value of some less-common forage species for different animal species. There are surprisingly large knowledge gaps of the digestibility of total plant or crude protein, and even the direct effects of feeding some of the listed plant species to different farm animals are not documented. In the end, these results have to be dovetailed with agronomic, economic, and sociological studies throughout the tropics to tap the full potential of local plants in swine and poultry feeding for eco-efficient and market-oriented animal production.

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