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Use of cassava in livestock and aquaculture feeding programs

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Foreword

This report reviews and reassesses the present state of knowledge concerning the use of cassava products in livestock and aquaculture feeds. An ultimate objective of summarizing these data is to provide a foundation for establishing reliable and practical guidelines by which more efficient utilization of cassava products and by-products may enhance livestock and aquaculture feeding programs, particularly in West Africa.

Executive summary

On a global scale, cassava (*Manihot esculenta*) represents both an important human food resource and, in many regions, an underutilized animal feed ingredient. Cultivated in tropical/subtropical environments, cassava can be grown on marginal lands; it is relatively drought-hardy, and all parts of the plant can be utilized; and its roots comprise an energy staple in many regions. In recent years, the African continent produced ~60% of the global cassava crop (256 million tonne) through targeted efforts to develop improved varieties; yet only a small fraction is utilized for animal feeding programs throughout Africa. Potential for increased utilization is vast, particularly of unused or underused fractions and residues such as peels.

Specific nutrient imbalances and toxins have been identified in cassava that can limit its feed/food value. The presence of cyanogenic compounds in various cultivars and plant fractions has notably received disproportionate research attention compared with other chemical constituents. Nonetheless, traditional and basic processing methods for minimizing cyanide toxicity including soaking, drying, and fermentation, have been documented effective across species, and can be applied with more advanced technologies for industrial commercialization of safe cassava feed/food ingredients. Improved feeding value resulting from targeted fungal and microbial fermentation have been demonstrated with the capacity to expand cassava root (and by-product) utilization for both applied livestock and human nutrition by minimizing cyanogenic compounds, degrading complex carbohydrates, and improving protein content.

Historically, other nutritional properties of cassava have not been addressed in as much detail; high moisture content and rapid degradation of fresh roots and peels, dustiness of dried fractions, deficiencies in specific amino acids, fatty acids, minerals and vitamins, and a plethora of anti-nutritional factors (apart from cyanide) across various factions are identified and reviewed as limitations of applied feeding programs. Additionally, nutrient composition of cassava and its by-products is affected by factors including growing conditions/climate, maturity, variety, and processing/handling techniques. Data on chemical composition of various cassava fractions, including leaf meal concentrate, leaves (dried, fresh, ensiled), peels, and roots used in livestock feeding, is summarized, with details identified to variety and local/origin where possible. Cassava root and peel fractions represent primary energy sources in feeding programs, whereas leaves provide protein, minerals, and antioxidant vitamins as well as polyphenols. Potential to improve nutritional value (specifically protein and vitamins, also carbohydrates) through selective breeding and/or fermentation processes is described.

Despite recognized nutritional shortcomings, all parts of cassava can be successfully used in livestock and aquaculture feeding programs. Various studies document the replacement value of processed cassava root/peels as an energy ingredient when paired with appropriate nitrogen sources, substituting for maize at up to ~40% of total diets in cattle, 20 to 50% in small herbivores (goats, sheep, rabbits), and up to 100% in swine diets, 10 to 40% in various poultry diets, and 15–30 to >60% in aquaculture diets (depending on species/age). Further, in aquaculture, cassava starch acts as a natural pellet binder. Enzyme treatments improve utilization of cassava peel fractions for monogastrics. Cassava leaf meal can replace other ingredients as a protein source at inclusions of 10 to 20–25% in various species; silages and/or blends of roots/leaves/peels allow somewhat higher inclusion/replacement proportions. Cassava-based feeds require specific nutrient balancing, but offer viable, local alternatives.

Knowledge gaps for improved utilization of cassava in animal feeding programs, including more detailed economics and the need for implementation of existing processing technologies (drying, fermentation, enzyme addition) at commercial scales, are highlighted. Suggestions for future priorities, implemented at national, regional, or global scales, that can result in improved nutritional value, lower feed costs, increased profitability, and mitigation of waste from cassava and its by-products are further detailed. Targeted research building on the long history of cassava use, combined with optimization technologies, pave the way for sustainable development/expansion of currently underutilized feed fractions that can result in improved animal protein production and environmental benefits.

Cassava and its residues as livestock feed: Limitations, processing, and nutritional composition

M. esculenta Crantz (syn. *M. utilissima* Pold) (Euphorbiaceae) (also known as cassava, manihoc, tapioca, Brazilian arrowroot or yuca) originated from tropical America and was first introduced to the Congo basin, Africa, by the Portuguese around 1558 (Akoroda and Ikpi 1992). It is an herbaceous shrub, 2–4 m tall, with palmate 3–7 lobed leaves. Cassava is extensively cultivated as an annual crop in tropical and subtropical regions for its edible underground tuberous root, recognized as one of the highest yielders of starch and the third largest source of food carbohydrates in the tropics, following rice and maize. Cassava is a major staple food in the developing world, providing a basic diet for over 800 million people (Lebot 2009; Ecocrop 2011), important as a drought-tolerant crop capable of growing on marginal soils. A targeted focus on improved varieties in Nigeria, resulting in higher yields, earlier maturation, and improved drought- and disease resistance, increased cassava production by ~150% between 1998 and 2008 (for varietal details, see Appendix 1).

Over the past 5 years (2008–2012 inclusive), cassava production on the African continent (~54% of global production) as a whole has been growing at a faster rate (~4%) compared with other major regions (worldwide average growth rate, +1.2%). African cassava production surpassed 145 million tonne in 2011, approximately 57% of the global crop that year (256 million tonne, FAOStat 2013). Nigeria alone contributed 36% of all African production, which is approximately 52 million tonne (FAOStat 2013). In contrast to Latin America (~14% of global production, mainly from Brazil) and Southeast Asia (~32% of global production from Thailand and Indonesia), where the majority of cassava is exported for industrial purposes or animal feed, ~70 to 80% of cassava produced in Nigeria is utilized for human consumption (Dada et al. 2010). While many food products are based on cassava tubers in Nigeria, and roots provide starch for ethanol production (Kuiper et al. 2007), only a reported 5% of cassava is currently used as livestock feed (Apata and Babalola 2012). Increased cassava productivity offers further opportunities to intensify the utilization of cassava, particularly unused or underused fractions and residues, within applied animal feeding programs.

As an example, a recent study of a single starch-producing factory in Nigeria, processing 120 t of tubers into starch daily, resulted in quantification of five waste product streams: cassava starch residues or pomace (17 t/day), cassava peels (5 t/day), cassava effluent (15.4 t/day), cassava stumps (8 t/day) and cassava whey (1.51 t/day) (Aro et al. 2010). Given appropriate handling and technologies, much or all of the by-product from this primary production of starches or fermented cassava-based foods may be effectively and sustainably incorporated into livestock feeding programs.

Cassava by-products

Various parts of the cassava plant, defined as outlined in Table 1, can be successfully incorporated into diets of multiple species, with by-products readily available in the vicinity of factories where cassava tubers are processed into starch or flour. In general, the biotechnology to harness these residues from cassava processing for economic use in livestock or fish production, though available, has not been fully realized due to limitations in research and/or development. Numerous fractions represent differing nutrient profiles; leaves and green fractions are considered protein sources, whereas the remaining constituents provide primarily energy.

Table 1. Defined fractions of cassava (*Manihot esculenta*) plant utilized in livestock feeding programs

Cassava leaf	Fresh or wilted leaves, chopped or intact, may or may not be inclusive of petiole
Cassava leaf meal	Dried leaf fractions, chopped or ground; may or may not be inclusive of petiole
Cassava leaf protein concentrate	Protein precipitate from leaves, processed using heat and/or acid
Cassava hay	Includes leaf, petiole, and stems generally > 40 cm from soil surface
Cassava pomace	Also called starch residue, pulp, bagassse; solid fibrous residue remaining after starch extracted from root. Up to 17% of tuber. Quality and appearance varies with age, time after harvest, and industrial equipment
Cassava peels	Can represent 5–15% of tuber weight; obtained after water-cleaning and peeling
Cassava chips	Root fraction, cut chunks of varying size; may or may not contain both pulp and peel
Dried cassava pulp	Dried root tissue
Cassava stumps	Ends trimmed off the tubers while prepared for washing and peeling
Cassava pellets	
	Various fractions processed into pellets
Cassava whey	Liquid pressed out of the tuber after it has been crushed mechanically. Whey and pomace can be mixed to form slurry or effluent.
Cassava discards	Tubers that fail to meet quality standards for processing. May be mixed with stumps, often higher fibre content
Cassava retting	
Cassava sievate	By-product of production of garri (garri, gary). Tubers peeled, crushed, fermented, sieved and roasted. Sievate 15–17% of root weight.
Cassava dregs	
Cassava starch	Purified starch extracted from cassava tuber pulp
Composite cassava Pellet	Includes flour made from whole root (with peel), leaves and petioles

Sources: Balagopalan et al. 1988; Cereda et al. 1996; Boscolo et al. 2002a; 2002b; Nwokoro et al. 2005; Scapinello et al. 2005; Ukachukwu 2005; Modesti 2007; Aro 2010.

Although leaves comprise only ~6% of the cassava plant (Devendra 1977 cited in Smith 1988), they can be harvested above ground without damage during root development from 3 to 4 months of age in 60–75 days cycles (Ravidran 1992; Phengvilaysouk and Wanapat 2008), or trimmed with the stems to 40 cm prior to tuber harvest, and chopped by hand or in a stationary forage chopper. As such, leaves and stems (40% of plant wet weight) constitute a substantial amount of potential green feed—fresh or dried—in cassava regions.

While tubers are primarily harvested (in western Africa) for human starch consumption, assorted discarded tuber fractions, as well as fermentation end-products, and even flour deemed unsuitable for human consumption, are available for incorporation into animal feeding programs. Further, with peels comprising 10–15% of the whole cassava plant (Devendra 1977 cited in Smith 1988), and up to 35% of the tuber weight (depending on how they are processed; Obadina et al. 2006), the potential quantity of cassava peel as a by-product feed ingredient in Nigeria alone—conservatively estimated at 10% of production—totals 5.2 million tonne per annum (FAOStat 2013).

Identified limitations of cassava in livestock feeding programs

As has been well-documented in the scientific literature, widespread utilization of cassava as a primary feed ingredient in livestock feeding programs has been limited due to presence of toxic cyanogenic compounds in various fractions and cultivars, high fibre and ash levels in peels (Asaolu et al. 2012), and deficiencies of specific nutrients other than energy (amino acids (particularly Met and Tryp), fatty acids, minerals, and vitamins (reviewed in Montagnac et al. 2009a). High moisture content, concomitant rapid rates of deterioration in wet fractions, and dustiness of dried materials are also practical considerations in transport, storage, handling and utilization (Garcia and Dale 1999; Apata and Babalola 2012). As such, cassava peels and tubers should be processed rapidly following harvest to reduce cyanogenic potential and to preserve nutritive quality through drying, soaking, fermentation and/or combinations of these treatments.

Much literature concentrates on the cyanide content of cassava, often measured as hydrocyanic acid or HCN. In the whole unbruised plant, the cyanogenic glucoside remains intact as linamarin and lotaustralin (Nartley 1968) in a ratio of 93:7 (Butler and Kennedy 1965). When the cellular structure is disrupted, the intracellular glucoside becomes exposed to the extracellular enzyme linamarase (Butler and Kennedy 1965). Hydrogen cyanide (HCN) is then produced. The reaction proceeds in two steps (Nartley 1978) viz: cyanogenic glucoside is degraded to sugar and cyanohydrin (x-hydroxynitrile); cyanohydrin then dissociates to ketone and hydrocyanic acid. Thus, for linamarin the glucoside is first hydrolysed by linamarase to produce B-D-glucopyranose and 2-hydroxyisolentyronotrite or acetone—cyanohydrin, after which the latter is degraded to acetone and HCN (Tewe et al. 1980; Mahungu et al. 1987).

Cyanohydrin produced as a result of linamarin activity is stable only under moderately acidic condition (pH 4.0); in neutral or alkaline condition it undergoes spontaneous hydrolysis to yield HCN (Cooke et al. 1978). In spite of the relative instability of cyanohydrin, it coexists with intact glucoside and HCN in differently processed cassava products (Fomunyan et al. 1985). Thus the cyanide in cassava products exists in three forms: (i) the glucosides (linamarin and lotaustralin), (ii) the cyanohydrin and (iii) the free HCN. However, the quantitative estimation of cyanide by various methods has produced varied and unreliable results, and in many cases a gross underestimation, largely arising from quantification of free HCN alone in the reports of earlier investigators.

HCN in cassava is affected by variety, maturity of plants, environmental conditions, and nutritional status of the plants. Cassava varieties are usually divided into two groups: Bitter, with roots containing 0.02–0.03% HCN (DM basis) and leaves containing up to 0.2% HCN, or Sweet varieties containing <0.01% CND and leaves 0.1% or less, although there is a continuum of cyanide concentration among varieties (Peroni et al. 2007). Cassava varieties containing HCN levels >100 mg/kg are considered very toxic; 50–100 mg/kg moderately toxic, with those containing <50 mg/kg preferred due to lower toxicity risk. In ruminants, cyanide can be toxic at 2 to 4 mg/kg body weight; growth and other production traits of monogastrics appear satisfactory if diets contain less than 100 mg/kg HCN.

HCN levels, as well as bitterness in plants, has been shown to decrease with plant maturity (references in Borin et al. 2005), as well as with fertilization; significant effects of fertilizer type have been recently demonstrated. Organic fertilizer resulted in lower cyanide content in both leaves and tubers of 2 cassava varieties compared with inorganic fertilization (Faezah et al. 2013), and is an area requiring further study to improve nutritional aspects of cassava as a feedstuff.

Cassava's cyanogenic glucosides were initially thought to be of little consequence to mammalian health as long as the hydrolytic enzyme had been inactivated. However, the ingestion of high concentrations of cyanogenic glucosides via fresh cassava roots and leaves is lethal in numerous livestock. This was because the possibility of hydrolysis during digestion was not adequately understood, despite early reports that oral doses of pure linamarin produced physiological and biochemical changes in rats and chick embryos even in the absence of linamarase activity (Philbrick et al. 1977; Maduagwu and Umoh 1988). The subject is now better understood. Following excess consumption of unprocessed cassava, enzymatic breakdown of the glucoside occurs, releasing HCN and thereby causing poisoning. Cassava toxicity may be acute and/or chronic.

Acute toxicity results from ingestion of a lethal dose of cyanide, and death is caused by the inhibition of cytochrome oxidase of the respiratory chain. This has been reported in goats ingesting cassava leaves (Obioha 1972; 1977), and also in non-ruminants like pigs, when fed fresh uncooked tubers. The level of total HCN varies widely in cassava tubers, and death has been more common with the 'bitter' varieties containing >500 ppm of HCN (Tewe and Iyayi 1989). Where sublethal doses of cyanide are consumed, the inhibition of cellular respiration can be reversed by the removal of HCN by respiratory exchange or the detoxification process. The latter proceeds via many pathways, though probably the most important is the reaction of cyanide with thiosulphate to form thiocyanate and sulphite. The cyanide is initially trapped in the erythrocyte fraction of the blood and later converted to the less toxic thiocyanate (Nwokoro et al. 2000).

Chronic cyanide toxicity in animals can affect both the growth and reproductive phases of development. While the lethal dose has been estimated at 0.5–3.5 mg/kg body weight or 30–210 mg for 60 kg adult human, the lethal dosage for various livestock species has not been firmly established. Bolhuis (1954; 1966) classified the toxicity of cassava cultivars as innocuous: <50 ppm fresh peeled tuber; moderately poisonous: 50–100 ppm fresh peeled tuber; dangerously poisonous: >100 ppm fresh peeled tuber.

The ingestion of fresh or processed cassava-based diets causes reduced growth rates in rats, pigs, African giant rats, sheep and goats (Tewe et al. 1977; Tewe and Maner 1981; Tewe 1983). The animals also have increased serum and urinary levels of thiocyanate, which is a continuous cause of depletion of sulphur-containing amino acids. The thiocyanate also inhibits the intra-thyroidal uptake of iodine, causes an increase in secretion of thyroid stimulating hormone (TSH) and causes a reduction in thyroxine level which is necessary for growth. It is thus a goitrogenic factor, which was demonstrated by Tewe (1984), who reported a significant reduction in serum thyroxine levels in growing pigs fed cassava peel diets containing 96 ppm total cyanide.

In rats and pigs consuming inadequate amounts of protein and sulphur amino acids, the serum thiocyanate concentration decreases, as the animals become unable to adequately detoxify cyanide. This condition can also aggravate deficiencies in selenium, zinc, copper and vitamin A. Even with sufficient protein intake, consumption of cassava flour-based rations can result in parakeratosis in pigs, attributable to zinc deficiency, aggravated by the cyanide in cassava diets. Other features include paralysis of the hind limbs and muscular weakness. In poultry, there are scant reports of toxicity due to cassava cyanide. However, depression in growth rates of broilers consuming cassava diets is common, and especially when a significant amount of the grain is replaced without proper protein supplementation. This observation is ascribed to a lower protein content in cassava and the extra need for sulphur amino acids. However, the performance of poultry on cassava diets is satisfactory as long as the total HCN content in the final ration does not exceed 100 ppm. Such rations must, however be nutritionally balanced, and in particular contain sufficient sulphur containing amino acids.

Chronic cyanide toxicity appears to pose more problems with breeding stock, as they remain on farms longer than growing animals. However, very few studies have been conducted in this area. Studies conducted with gestating pigs (Tewe and Maner 1981) showed that, when fed fresh cassava containing 0, 250 and 500 ppm HCN, maternal and foetal serum thiocyanate levels only increased in those receiving the 500 ppm HCN diet. A slight

increase in the thyroid weight with increasing levels of cyanide was only observed in pigs fed the two lower levels of HCN, with definite pathological changes noted in the thyroids of those fed the 500 ppm HCN diet. Although the consumption of the cassava diet during gestation did not affect performance during lactation, milk thiocyanate and colostrum iodine concentrations were significantly higher ($P>0.05$) in the animals fed diets containing the highest level of HCN. Otherwise, the size of litters and weights of the young produced from pregnant rats and pigs fed on the various cassava diets were essentially normal.

Maner (1972) reported that a fresh cassava-based diet had an identical nutritional value to a corn-based diet fed gestating pigs. However, in this study the cassava-fed sows, also maintained on pasture, had an increased still-birth rate and slightly inferior weight gains in post-lactation. Studies have also been carried out on the reproductive performance of rabbits fed cassava-based diets over three breeding periods Results demonstrated that the performance of pregnant and lactating does did not differ significantly from those receiving non-cassava diets, in terms of litter size and birth and weaning weight of offspring (Omole and Onwudike 1982).

In summary, studies conducted with small ruminants (goats and sheep), pigs and rodents, high cyanide diets affect growth through sulfur amino acid metabolism in particular, as well as through interference with iodine uptake and thyroid function, and interactions with Se, Zn, Cu and vitamin A. Less direct effects on reproduction have been seen in controlled studies with rabbits, poultry, and swine. It is also possible that dietary palm oil has direct physio-chemical effects on minimizing the effects of cyanide in animals consuming cassava-based diets (Tewe 1991; Ty et al. 2003). Thus multiple nutritional considerations and interactions with HCN must be considered regarding the consumption of cassava, and has directed the focus of research for many years. However, relatively simple and effective semi-industrialized methods are available that, in combination with use of low-cyanide varieties, can yield a low-toxicity product for application to cassava as a feedstuff.

Processing techniques for cassava

Fresh cassava tubers, particularly high-quality ones, are highly perishable. They deteriorate within two or three days of harvest and must be processed quickly (Müller et al. 1975; Tewe 1992). Tubers intended for industrial livestock feeding are sliced and dried, and then usually ground or pelletized. The technologies used at different scales of chip and pellet production are similar, and cassava chips can be produced by simple techniques in the household or village as well as on a large mechanized scale. The selection of a technology depends on the amount of cassava to be processed, the availability of capital and labour cost, as well as the availability of relatively cheap energy (Hahn et al. 1992).

The first step is usually washing, followed by peeling. The roots are then sliced, either by hand or mechanically. Cassava chips may have different sizes and shapes (rectangular, cube, thick slice) depending on the slicing and drying methods. Drying may be natural or artificial. Sun-drying is done on concrete floors or on trays. Sun-drying is a very labour intensive operation, requiring about 35–40 labourers/ha of drying floor. Chips dried on trays are better-looking and more uniformly dried than those dried on concrete floors. Artificial drying is done using static or moving bed dryers, or rotary dryers.

Cassava chips can be sold directly, ground into cassava meal, or pelletized. During pelletizing, chips are heated and moistened and then forced into continuous die presses. Pelletizing may result in a product that is 25–40% denser, more uniform, more durable, less dusty and easier to handle (Hahn et al. 1992). Because peeling operations require time, alternative methods to produce chips and pellets without peeling have been developed. One such method consists in grating and chopping unpeeled tubers, mixing them with cassava foliage in a 4:1 ratio and passing the mixture through a pelletizer (Tewe 2004). In humid places where sun-drying is not easy, cassava roots can be ensiled alone (clean cassava roots+0.5% salt) or in mixture with rice straw or cassava leaves (Premkumar et al. 2001; Ngoan et al. 2002; Kavana et al. 2005).

Thus cassava tubers are traditionally processed by methods which decrease toxicity and improve palatability and stability; however, these methods can also contribute to rapid deterioration of other nutrients. Nonetheless, HCN reduction in cassava feed fractions remains a primary goal and processes developed for tubers are also generally applicable to peels. Reported efficacy differs considerably due to analytical methods, combination of methods and extent to which the process(es) is (are) carried out (Etejere and Bhat 1985). Summary effects of processing methods have been previously reviewed by Tewe (1991) and more recently by Montagnac et al. (2009b):

Peeling: Peeling can be an effective way to reduce cyanide content by at least 50% in cassava tubers. Peels, in general, contain higher cyanide concentrations than pulp, thus peeling lowers the potential toxic principle. In sweet varieties, the cyanide is found primarily in the peel and cortex, thus tubers can be safely consumed by simple processing whereas bitter varieties have distribution of HCN throughout the tuber. Glucosidase enzyme levels (which release the free cyanide) are higher in pulp tissues compared with the storage glucosides that are higher in peel fractions. Macerating the two fractions together (pulp plus peel) thus may influence the release and breakdown of HCN more than either fraction processed separately.

Grating: Depending on whether the peels are included in the grated product, cyanides can be more evenly distributed, but also the intrinsic glycosidases can certainly affect overall levels, as enzyme activity is dependent on time and temperatures. Grating provides greater surface area for fermentation of pulp, and removal of HCN through enzyme breakdown.

Soaking of cassava roots normally precedes cooking or fermentation. It provides a suitably larger medium for fermentation, and allows for greater extraction of the soluble cyanide into the soaking water. The process removes about 20% of the free cyanide in fresh root chips after 4 hours, although bound cyanide is only negligibly reduced. Bound cyanide begins to decrease only after the onset of fermentation (Cooke 1978; Cooke and Madunagwu 1978). A very significant reduction in total cyanide is achieved if the soaking water is routinely changed over a period of 3–5 days. A variation to the soaking technique is known as retting (similarly used in processing of jute) (Ayenor 1985), which involves prolonged soaking of cassava roots in water to remove soluble starches and extraction of the starchy mass. A simulation of retting, followed by sun drying, resulted in removal of ~100% of initial cyanide content (Tewe 1992).

Boiling removes ~90% free cyanide within 15 minutes compared with 55% of bound cyanide after 25 minutes (Cooke and Madunagwu 1978). Prolonged cooking, on the other hand, destroys the linamerase enzyme at 72°C, thus keeping the glycoside(s) and HCN intact.

Dehydration is accomplished through solar radiation (sun drying) and/or mechanical means (electric or fuel driers), depending on economic viability. The process removes much of the soluble cyanide compounds, with sun drying on sloped trays more effective due to slower breakdown, and less denaturation of the linamerase enzyme that destroys the cyanogenic glycosides of cassava (Gomez et al. 1984a). While solar drying may result in reduction of >85% of free cyanide (Gomez et al. 1984b), bound cyanide (which is less volatile and less frequently measured), can be a greater contributor to cyanide toxicity in sun dried products than free HCN. The solar drying process is clearly dependent on physical and environmental conditions (temperature, sunlight, wind) and may result in higher microbial contamination than oven-drying.

Sun drying cassava:

- results in a greater loss of total cyanide compared to oven-drying at 60°C for 48 hours. Oven drying apparently affects the stability of linamarase which decomposes at 72°C.
- produces greater loss of bound cyanide due to slower drying rate relative to oven drying.

- allows a longer contact period between the glucosidase and the glucoside in the aqueous medium. The effectiveness of enzyme/substrate interaction depends on the particle size and environmental factors (ambient temperature, insulation, relative humidity, wind velocity). Thus proper sun drying is achieved in 1–3 days in the dry season and up to 8 days in the rainy season.
- facilitates the continuation of the fermentation process.
- is cost effective, but slow and often encourages the growth of mould and other microorganisms including *Aspergillus flavus* (pathogenic), *A. fumigatus, A. cherahen, A. teirenus, A. flaripes, A. japonicus, A. niger, A. ochracuss,* and *Penicillium rubrum* (Clerk and Caurie 1968; Oke 1978). This microbial growth exposes the consuming animal to aflatoxicosis and/or mycotoxic infection.

As a result of the poor microbiological properties of sun-dried cassava products, there is a need for quicker drying methods which will reduce or eliminate microbial proliferation and ensure optimal cyanide detoxification (Knowles 1976; Okafor and Ejiofor 1986). Development of solar/hybrid drying systems is a promising technology to alleviate much of the delay inherent with weather conditions, and consequent potential deterioration of cassava products/by-products. Hybrid driers may be particularly sustainable if biofuels are utilized (Sanni et al. 2012).

The two most widely used processing methods are sun drying and ensiling. In the humid tropics, especially in the wet season, sun drying is difficult and may result in the production of low quality product with severe Aspergillus and aflatoxin contamination.

Ensiling: The ensiling process causes disintegration of intact glucoside via marked cell disruption, a drop in pH of the ensiled medium, and intense heat generation. Ensiling cassava tuber pulp fractions, peels, and/or leaves breaks down glucosides, lowers pH and generates heat—if maintained anaerobically, molding of substrate is less problematic. Gomez and Valdivieso (1988) reported that ensiling cassava chips reduced HCN content to 36% of the initial value after ensiling for 26 weeks, whereas Tewe (1992) documented ~ 98% of the free cyanide lost by ensiling cassava roots with poultry litter for 8 weeks. Ensilation of milled cassava pomace can be accomplished through the addition of either 0.5% salt (fresh weight basis) or rapidly fermentable carbohydrates such as milled maize or molasses before being placement under anaerobic conditions (in pits or plastic bags). The addition of urea and other minerals is also possible, with the intention of increased nutritional value to the ensiled products (Ubalua 2007). Mixing silage components (cassava pulp/chips/ peels) with adequate nitrogen sources (i.e. poultry litter, Tewe 1991; or leaves Kavana et al. 2005) to support continuing microbial growth diminishes cyanide to safe feeding levels for using the high starch by-products of cassava.

Good quality silage can be obtained from peels after chopping the peels to lengths of about 2 cm for easy compaction, and wilting for two days to reduce moisture content from 70–75 to about 40%. Under these conditions, cassava peel silage after 21 days had light brown colour, firm texture and a pleasant odour. The pH was 4.4, and no fungal growth was observed (Asaolu 1988; Smith 1988). Solid fermentation of a mixture of cassava peels and waste water from fermented cassava pulp with *Saccharomyces cerevisiae* and *Lactobacillus* spp resulted in a product with a higher protein content, lower cyanogenic glycosides and lower phytate content (Oboh 2006; Ubalua 2007).

Silage fermentation has also been shown effective in decreasing cyanide compounds in cassava leaves to provide a roughage product for feeding during periods of forage shortage. Similar to other cassava fractions, ensiling leaves entails chopping into small pieces (2–3 cm), then mixing with additives (urea and salt at 0.5%) and storage in sealed plastic bags for 2 months. Ensilation reduced HCN content by up to 80% of the original concentrations, compared to a sun drying treatment (30–60% decrease) on the same sample (Borin et al. 2005).

Fermentation: Most marketed cassava food products in Africa (‘garri’, ‘fufu’, ‘pupuru’, ‘apu’) are obtained through fermentation, a critical step for reducing the cyanogenic glucosides to relatively insignificant levels. Unlike

alcoholic fermentation, the biochemistry and microbiology is not fully understood, but it is believed that some cyanidrophilic/cyanide tolerant microorganisms may effect breakdown of the cyanogenic glucoside (Fomunyan et al. 1984). The higher the retention of starch in grated cassava, and longer the fermentation, the better the detoxification process and the lower the residual cyanide content (Tewe 1992; AgriPinoy.net 2011). Onabowale (1988) developed a combined acid hydrolysis and fermentation process which achieved an approximate 98% reduction in total HCN after dehydration of the cassava flour. In general, fermented cassava products store better.

More recently, treatment with tuber liquor ferment containing *A. niger, A. flavus,* and *Lactobacillus* spp has been shown to increase the feeding value of cassava peels (Oboh 2006; Adamafio et al. 2010), decreasing the HCN content by 88% and raising N levels. Cattle microbes also have demonstrated ability to break down HCN in cassava leaves; fermentation of bitter cassava varieties (both peel and leaves in a ratio 3:1) using 6% *A. niger* in a 2-stage fermentation was examined, with varying levels of cattle rumen inoculum added after 4 days. HCN concentration dropped approximately 34% just from wilting of leaves, and 64% from initial levels (197.8 mg/kg) following the 2 stage fermentation; crude protein in the leaves increased from 28 to 34% of DM, and *in vitro* DMD was improved (Prayitno et al. 2011). The development of targeted fermentation technologies and microbial cultures, optimized for various feed fractions, holds solid promise for expansion of cassava utilization in both livestock feed programs and for human nutrition products (Boonnop 2009; Ferriera et al. 2013).

Nutritional composition of cassava feed fractions

The composition of cassava can be affected by factors such as growing conditions, maturity, variety, rootstock and climate; nutrient content of cassava by-product feeds is also influenced by variety as well as processing/handling. The chemical composition of various cassava fractions, including leaf meal concentrate, leaves (dried, fresh, ensiled), peels, and tubers used in livestock feeding is summarized in Tables 2 through 8; details identified to variety and locale where possible can be found in Appendix Tables A1–A5).

Table 2. Nutritional composition of cassava (*M. esculenta*) by-products used in livestock feeding programs

Cassava fraction/ nutrient	Leaf meal conc	Foliage dehy	Foliage fresh	Foliage ensiled and/or wilted	Peels dry	Peels fresh	Tubers dehy	Tubers fresh	Tubers peeled fresh	Pomace dehy	Pomace fresh	Sievate dehy
DM, %		90.0 **89.6**	22.1 **22.5**	42.2 **24.4**	90.1 **87.4**	**28.2**	92.7 **87.6**	**37.8**	**28.5**	**89.2**	**13.1**	**86.8**
Crude protein, %	47.2	27.0 **25.5**	27.8 **24.9**	22.0 **23.8**	7.1 **5.2**	**4.8**	3.9 **2.9**	**2.6**	**2.2**	**2.2**	**1.7**	**1.1**
Sol protein, %		28.5	30.4	47.8	79.0		63.7					
Crude fat or EE, %	20.1	7.4 **7.0**	**6.8**	10.0 **8.3**	2.0 **1.4**	**1.3**	0.7 0.7	**0.8**	**0.6**	**0.6**	**1.3**	**0.7**
Crude fiber, %	1.6	14.5 **17.1**	**17.7**	16.6 **17.9**	15.3 **14.0**	**21**	18.8 3.9	**3.7**	**1**	**16.7**	**17.7**	**2.4**
NDF, %		34.4 **42.2**	49.1 **42.3**	37.8 **42.5**	24.0 **51.4**	**19.6**	18.1 **8.0**	**7.8**	**3.7**	**36.7**		**29**
ADF, %		26.4 **31**	31.8 **27.2**	29.8 **30.3**	15.7 **37.4**	**17.1**	9.9 5.4	**5.3**	**1.6**	**19.3**		**2.1**
Acid lignin, %		7.8	12.1 **9.4**	8.1 **8.4**	2.3 **8.4**	**7.2**	1.5 1.7	**1.6**	**0**	**3.6**		
NFC, %		39.9			66.4		82.0					
Starch, %		**1.7**					**80.4**	**80.8**		**52.3**		**72.5**
Total sugars, %		**4.9**					**2.4**			**3.3**		
NFE, %	19.0	42.9		41.8	70.9		59.2					
Ash, %	6.0	6.8 **8.4**	6.7 **7.4**	8.5 **7.9**	7.1 **5.8**	**5.7**	3.6 3.9	**2.8**	**3.8**	**4.3**	**3.7**	**1.2**

Bold numbers from Heuzé (2012). All nutrients except dry matter (DM) on a DM basis. Details in Appendix Table A1.

Table 3. Protein and energy digestibilty of cassava (*M. esculenta*) by-products used in livestock feeding programs

Cassava fraction	Foliage dehy	Foliage fresh	Foliage ensiled	Foliage wilted	Peels dry	Peels fresh	Tubers dehy	Tubers fresh	Tubers peeled fresh	Pomace dehy	Pomace fresh	Sievate dehy
Ruminant nutritive values												
OM digest, %	68.2	63.9	62.7		56.1*		88.8	89.1	93.7			
Energy digest, %	66.8	62.6	61.5				84.5	85	89.2			
DE rum, MJ/kg DM	13.2	12.4	12.3		9.5*		14.2	14.5	14.9			
ME rum, MJ/kg DM	10.4	9.9	9.8		8.3*		12.2	12.4	12.8			
N digest, %	75	72.3	74			59.7	35.3	31.4	33.8			
Swine nutritive values												
Energy digest, %	63.2	62.3	62	73.1	68.1	57.2	90.2	92.1	95.6	63.9		86.3
DE, MJ/kg DM	12.5	12.4	12.4	15.2	13.2	10.1	15.3	15.7	16	10.4		14.8
ME, MJ/kg DM	11.6						15	15.4	15.7	10	11.1	11.8
NE, MJ/kg DM	7.5						12.2	12.6	12.8	7.6		
N digest, %	51		46				52.3		78.2	66.7	67	
Poultry nutritive values	7.8											
AME broiler, MJ/kg DM							15.1	15.2				
AME cockerel, MJ/kg DM							15.1	15.2				
Rabbit nutritive values												
Energy digest, %										91.9		
DE, MJ/kg DM										14.9		
ME, MJ/kg DM										14.7		
N Digest, %										80.1		

Summarized from Heuzé (2012).

*Tram and Preston (2004).

All values on a dry matter basis.

Table 4. Amino acids in various cassava (*M. esculenta*) fractions

Fraction	Locale	N	Asp	Thr	Ser	Glu	Gly	Ala	Cys	Val	Met	Iso	Leu	Tyr	Phe	Lys	His	Arg	Pro	Reference
			Amino acids expressed as % of crude protein (or g/16 g N)																	
Leaf meal concentrate	Nigeria	4	7.9	5.0	5.1	5.5	5.9	6.3	1.3	6.3	2.5	5.6	9.6	4.8	6.3	6.8	2.8	6.1		Fasuyi and Aletor (2005)
Leaf meal concentrate	Nigeria	1	9.6	4.5	4.5	11.0	5.2	5.7	1.3	5.8	2.1	5.1	9.2	4.3	5.9	6.3	2.3	5.6		Eggum (1970)
	Average		8.8	4.8	4.8	8.3	5.6	6.0	1.3	6.1	2.3	5.4	9.4	4.6	6.1	6.6	2.6	5.9		
Leaf*	Global	4 to 6	9.5	4.2	3.9	10.2	4.7	6.3	0.8	5.2	1.3	4.5	8.3	4.2	5.6	5.1	1.9	6.3	4.0	Heuzé (2012)
Leaf	Nigeria	3 varieties	10.4	4.5	4.8	12.5	5.0	5.9	1.5	5.7	1.9	4.5	8.4	4.0	5.4	6.0	2.3	5.5		Eggum (1970)
Leaf	Vietnam		8.4	4.1	4.0	12.0	5.0	5.3		4.1	2.1	5.1	7.6	3.0	4.2	4.2	1.8	5.6	4.6	Nguyen et al. (2012)
	Average		9.4	4.3	4.2	11.6	4.9	5.8	1.2	5.0	1.8	4.7	8.1	3.7	5.1	5.1	2.0	5.8	4.3	
Peel	Global	1	5.6	2.2	1.8	7.2	2.6	3.9	0.7	3.5	0.6	2.3	4.5	2.2	2.7	2.3	1.8	3.4	1.7	Heuzé (2012)
	Puerto Rico	4	5.6	2.3	2.3	10.2	2.3	2.3	1.1	2.3	1.1	2.3	3.4	1.1	2.3	3.4	2.3	20.3	2.3	Mutayoba et al. (2012)
	Average		5.6	2.2	2.0	8.7	2.4	3.1	0.9	2.9	0.9	2.3	3.9	1.7	2.5	2.8	2.0	11.9	2.0	
Tuber**	Global	3 to 27	6.6	3.4	3.2	12.5	3.4	5.3	1.6	4.5	1.1	4.0	5.4	1.7	3.2	5.1	2.6	6.4	3.3	Heuzé (2012)
	Brazil	20	5.3	2.3	3.2	24.2	5.9	6.0	2.7	2.0	1.6	1.6	1.2	1.2	2.2	3.1	7.2	15.0	2.3	Gomes and Nassar (2013)
	Puerto Rico	4	3.8	1.6	1.8	11.1	1.4	2.4	0.6	1.8	0.6	1.4	2.2	0.8	1.4	2.6	1.0	11.1	1.2	Mutayoba et al. (2012)
	Thailand		6.6	3.8	4.6	4.2	3.9	7.0	0.0	4.1	0.9	3.3	5.3	2.3	3.0	5.3	0.7	3.1	4.8	Khempaka et al. (2009)
	Average		5.6	2.8	3.2	13.0	3.7	5.2	1.2	3.1	1.1	2.6	3.5	1.5	2.4	4.0	2.9	8.9	2.9	
Ensiled	Vietnam		9.2	3.5	4.7	20.9	2.1	4.2		2.5	0.6	2.1	3.5	2.7	2.8	6.0.	3.2	10.1	0.9	Nguyen et al. (2012)

Note: 2 Brazilian hybrids VERY high in CYS removed from summary as outlier.

See Table A2 for details of hybrids.

* Combined data from dehydrated, ensiled and fresh foliage.

** Combined data from dehydrated and fresh tubers.

Table 5. Comparison of ideal amino acid ratios (relative to lysine) in various fractions of cassava (*M. esculenta*) used in livestock feeding

Ideal amino acid ratios	Reqts. layer	Reqts. broiler 0–21 day	Reqts. broiler 21–42 days	Reqts. swine	Leaf protein conc	Leaf meal	Peel	Tuber
				% relative to Lys				
Lys	100	100	100	100	100	100	100	100
Met	43	45	38		35	35	31	26
Met and Cys	84	82	72	60	55	57	63	57
Thr	68	73	74	65	73	83	78	69
Try	23	16	16	18			20	31
Val	101	82	82	70	92	98	100	78
Iso	94	73	73	60	82	92	80	64
Arg		114	110	42	89	114	426	221
Leu		109	109	100	89	159	137	87
His		37	37	38	39	39	71	71
Phe and Tyr		100	100	95	229	173	144	98

Red indicates limiting for both poultry and swine; blue, limiting for some.

Source: Baker and Czarnecki-Maulden (1991).

Table 6. Minerals in cassava (*M. esculenta*) by-products used in livestock feeding programs

Cassava fraction/ nutrient	Leaf meal conc*	Foliage dehy	Foliage fresh	Foliage ensiled and/ or wilted**	Peels dry	Peels fresh	Tubers dehy	Tubers fresh	Tubers peeled fresh	Pomace dehy	Pomace fresh	Sievate dehy
Macrominerals, %												
Calcium	1.12 (0.4–1.16)	1.84 0.6–2.6)	1.19 (0.7–1.8)	1.45 (2.5–2.6)	0.56 (0.3–1.3)	0.17 (0.01–0.3)	0.17 (0.1–0.8)	0.16 (0.1–0.2)	0.1	0.74 (0.4–1.2)	0.56 0.01–1.1)	0.14 (0.1–0.2)
Phosphorus	0.18 (0.1–0.3)	0.31 (0.2–0.4)	0.37 (0.2–0.6)	0.32 (0.31–0.33)	0.14 (0.1–0.4)	0.21 (0.1–0.3)	0.10 (0.02–0.2)	0.12 (0.02–0.2)	0.04	0.04 (0.02–0.09)	0.14 (0.06–0.2)	0.02 (0.02–0.03)
Sodium	0.15	0.06 (0.001–0.14)	0.06 (0.05–0.07)		0.03 (0.01–0.04)	0.03	0.04 (0.02–0.07)				0.01	0.04 (0.02–0.06)
Magnesium	0.20 (0.04–0.4)	0.59 (0.2–0.8)	0.73 (0.3–1.0)	0.86	0.13 (0.06–0.2)	0.06 (0.02–0.1)	0.10 (0.05–1.4)	0.11 (0.08–0.15)		0.12	0.01	0.07 (0.03–0.17)
Potassium	0.33 (0.1–0.5)	1.43 (1.0–1.7)	1.25 (0.9–2.2)	0.86	0.76 (0.05–1.5)	0.06 (0.03–1.3)	1.08 (0.5–3.0)	0.77 (0.5–1.2)			0.01	0.1 (0.07–0.13)
Sulfur		0.34 (0.1–0.4)			0.22 (0.1–0.3)		0.03 (0.02–0.04)					
Trace minerals, mg/kg												
Copper	8.9 (4.2–16.1)	18.5 (4.1–29.1)	29	31	3.7 (2–6)	0	4.2 (2–7)			0	11	
Iron	110.1 (47.9–188.5)	323.8 (224–500)			57 (44–66)	15	17.5 (6–57)			559	6	
Manganese	232.0 (27–444)	95.7 (51–190)			53.8 (12–97)	0	18.6 (7–43)					
Zinc	85.0 (40–111)	38.9 (20.3–67.1)	25 (20–29)	33 (30–36)	19.3 (20–40)		20.2 (7–116)			102		

* Summary includes both concentrate and concentrate residues.

** Ensiled and wilted data combined.

Data are summarized as means and (ranges); all data on a dry matter basis. See Table A3 for details.

Table 7. Vitamin C, ß-carotene, and polyphenols reported in various cassava (*M. esculenta*) cultivars

	Vitamin C mg/100 g	ß-carotene mg/100 g	Polyphenols mg/g
Leaf meal	50–569	7–137	29–106
Peels	91–95	<0.01–0.5	
Tuber	10–97	<0.1–4	661

All values are on a dry matter (DM) basis; for details of variables associated with samples, see Table A4.

Table 8. Secondary metabolite concentrations reported in various cassava (*M. esculenta*) cultivars

	Cyanide mg/kg	Condensed tannins, %	Tannins (tannic acid eqiv), g/kg	Nitrate mg/10	Oxalate g/100 g	Phytate mg/100 g
Leaf meal, dry	16–1934	1–5	0.1	43–89	1.4–2.9	
Leaf, fresh	2650–7200		26–156			
Peels, dry	33–1081	4			33	705–1044
Peels, fresh	1300–2250	0.6	2–4			
Peels, fermented	6–23					
Tuber, dry	4–173	0.1				
Tuber, fresh	233–1150					62,400

All values are on a dry matter (DM) basis; for details of variables associated with samples, see Table A5.

Anti-nutritional factors and plant secondary metabolites in cassava

Anti-nutrients are potentially harmful and pose a genuine concern for human and animal health as they prevent digestion and absorption of nutrients. They may be toxic and can reduce the nutritional value of a plant by causing a deficiency in essential nutrients or preventing thorough digestion when consumed (Prathibha et al. 1995; Francis et al. 2011). Alkaloids, flavonoids, tannins, cardiac glycosides, anthraquinone, phlobatinnins, saponins and anthrocyanosides have been reported in aqueous and ethanolic extracts of raw cassava tubers, peels and leaves (Ebuehi et al. 2005), as have oxalates, nitrate, and phytates, the latter at concentrations summarized in Table 8. Dunstan et al. (1996) also reported the occurrence of phaseolunatin in cassava (*M. aipi* and *M. utilissima*).

The most commonly known anti-nutritional factors in cassava roots and tubers are cyanogenic glycosides (Montgomery 1980), which must be inactivated/removed through processing before they are suitable for livestock or aquaculture nutrition (Falaye 1992; Ebuehi et al. 2005; Agbor-Egbe and Mbome 2006). Effects of dietary cyanides and processing techniques have been previously discussed in this report. Cyanide inhibits several enzyme systems including metalloenzymes (Enneking and Wink 2000) through cytochrome oxidase, depresses growth through interference with certain essential amino acids, and impacts utilization of associated nutrients (Tewe and Egbunike 1992; Okafor 2004). Chronic exposure to cyanide due to the consumption of non-detoxified cassava products is associated with a number of diseases including goitre, dwarfism and the tropical ataxic neuropathy. It is particularly a problem in the regions where cassava is the major source of calories (Oke 1980; Tewe 1984; Umoh et al. 1985; Balagopalan et al. 1988). Other diseases associated with dietary cyanide intake include konzo (Mlingi et al. 1991; Cliff et al. 1997), a paralytic disease; tropical ataxic neuropathy (TAN) (Onabolu et al. 2001), a nerve-damaging disorder that renders a person unsteady and uncoordinated; goitre and cretinism (Delange et al. 1994).

Nutritional characteristics of specific cassava fractions

Cassava Leaf Protein Concentrate (CLPC) isolated from leaf flours/meals either through heat or acid precipitation (Fasuyi and Alator 2005; Modesti et al. 2007) resulted in increased crude protein (to 50–54% of DM) and crude fat (17–23% of DM), with a decrease in crude fibre from 21% of DM to almost zero in the concentrates, hence enhanced energy content and DM digestibility. Protein digestibility (measured *in vitro*) doubled in the concentrate from 28 to ~55%. Amino acid (AA) ratios, however, were not enhanced by the concentration of protein precipitates (Table 5) and in fact, relative to Lys, CLPC provides the least balanced overall amino acid profile of the cassava fractions summarized. As has been previously reported, the SAA (Met and Cys) appears limiting for optimal non-ruminant nutrition (Fasuyi and Aletor 2005), an others (Arg, Leu, Iso, Val) may be marginal depending on the species and production traits. There appears to be a change in Nigerian CLPC AA data over the past 3 decades (Table 4a), particularly regarding Glu values (Eggum 1970; Fasuyi and Aletor 2005); differences in AA profiles may be due to varietal or processing differences among the cassava leaves utilized. Interestingly, in a recent more extensive survey of AA profiles in Brazilian cassava hybrid tubers (Table A2), Glu values are highly variable across cultivars, but correlations (predictive or otherwise) between AA profiles in tubers and other plant fractions were not found. Macromineral concentrations of CLPC, with the exception of S, in general decreased, while processing effects on trace elements were variable. Essentially no data were found on vitamin or anti-nutrient factors in CLPC.

Cassava leaves. Dried cassava leaves processed for food or feed (Cassava Leaf Meal or CLM; also called cassava leaf powder) has been analysed in detail as a potential source of dietary protein and other nutrients. Average leaves contain about 70% water, whereas the dried meal is approximately 9–10% moisture (Wobeto et al. 2006). Energy content (Table 3) in leaves is high for both ruminants and swine, with digestibility ranging from 62–73%, and DE (MJ/kg DM) values of 12.3–13.2, slightly higher (15.2) measured in wilted forage fed to growing pigs. Energy values are considerably lower for poultry (apparent ME 7.8 MJ/kg DM for broilers), due to high fibre levels in leaves. Fibre content increases with maturity; both NDF (20–30% of DM, up to 60% in some reports) and CF (8–20%) fractions are not insignificant. It is unclear if leaf meals analysed in the literature included petioles or not, which would increase fibre content. Crude protein, with highest levels in leaves approximately 12 month of age, is reported to vary from ~17 to 40% of DM (Wobeto et al. 2006), averaging ~21%; current summary data (Table 2) average slightly higher (25–28%). Almost 85% of the crude protein fraction is true protein according to Eggum (1970); he and subsequent others (i.e. see Montagnac et al. 2009 a review) report that cassava leaf protein is deficient in methionine but high in lysine. These observations are confirmed in Table 4a; when compared with an ideal AA profile relative to Lys (Table 5), CLM appears lacking in SAA for poultry (and possibly marginal in Iso for layers) but otherwise provides a good AA balance for swine, only marginally low in Met and Cys. Phuc and Lindberg (2001) reported that the AA composition for cassava and leucaena (*Leucaena leucocephala*) leaf meals were similar to that of soybean meal, but their apparent ileal digestibilities were lower. This confirmed the hypothesis that the value of the protein source is not only determined by the composition of AA but also by their availability. Interactions between cysteine and cysteine with hydrogen cyanide were reported by Nassar and Souza (2007), whereby increases in detoxification of cyanide led to a reduction in sulphur containing AAs. Thus interactions amongst total protein, AAs, and potential anti-nutritional factors such as HCN and/or phenolics must be considered when evaluating N availability.

Cassava leaves are a good source of minerals, particularly Ca, Mg, Fe, Mn and Zn (Ravindran and Ravindran 1988). Macromineral ranges (DM%) previously reported from CLM include: Ca (0.04–1.63), K (0.8–1.69), Mg (0.26–0.97), P (0.07–0.35) and S (0.28–041),whereas trace elements (mg/kg DM) ranged from 6–50 for Cu, 62–270 for Fe, 50–263 for Mn, and 30–64 for Zn (summary data in Wobeto et al. 2006). Current data summaries (Table 6) fall within these ranges. Differences in cultivars (genetics), stages of plant maturation, and soil growing conditions, including fertilization, underlie variability observed.

Concentrations of antioxidant nutrients in cassava leaves, including vitamin C (149–568 mg/100 g)) and polyphenols (16–56 mg/g), increased with plant age (maximum vitamin C at 17 months) in a recent study comparing four Brazilian varieties (Simão et al. 2013) whereas ß-carotene (50–73 mg/100 g) declined slightly in the oldest leaves.). ß-carotene concentrations were reported highest if dried rapidly in an oven at 30°C, decreasing with longer exposure to oxidation if slowly air-dried in the shade. Values for ß-carotene, polyphenolics, and vitamin C differed than previously published values for the same nutrients from a different location (Corrêa 2004; Wobeto et al. 2006), likely due to differences in growing conditions as well as analytical and handling techniques. Nonetheless, cassava leaves are relatively high in vitamin C (50–450 mg/100 g DM), polyphenolics, and ß-carotene (~10–137 mg/100 g DM; Table 7) concentrations—the latter presumably providing a good source of vitamin A through carotenoid conversion, giving them excellent antioxidant properties similar to ranges that might be found in fresh produce and/or green teas. Leaves also contain significant amounts of riboflavin and flavonoid activity, indicating they are a likely source of B vitamins; considerable losses of vitamins, particularly of ascorbic acid, occur during processing (Ravindran 1992). Polyphenolic compounds reported in cassava leaves may have beneficial properties as antioxidants, or may in fact reflect tannin compounds that bind proteins and lead to rumen bypass, hence improving protein quality of CLM in ruminants.

A number of antinutrients have been examined in CLM (Table 8), including tannins (both condensed and hydrolysable; Reed et al. 1982; Wanapat 2003), oxalates (range 1.4–3 g/100 g), nitrates (~40–90 mg/100 g), which decrease with plant maturity, trypsin inhibitors (0.6–3.3 ITU/mg DM), hemaglutanins, saponins (1.7–4.7 g/100 g), polyphenols—which increase with plant maturity (2–120 mg/100 g)— and particularly cyanide (range from about 2 to 200 mg/100 g DM), which also increases with leaf maturity (Wobeto et al. 2006). With the exception of cyanide, these antinutrient levels are within typical ranges found in other agricultural crops, and negative effects can be minimized by processing or low inclusion rates in diets. Processes for minimizing cyanide content in CLM for safe incorporation into livestock diets, similar to those utilized with cassava tubers (i.e. drying, ensiling/fermentation), have been a predominant focus of research. As with tubers, growing conditions and varietal differences contribute significantly to baseline cyanide content in cassava leaves; organic fertilizers resulted in a 17% decrease in cyanogenic glycoside content in leaves from 2 cultivars grown in Malaysia (Faezah et al. 2013). Murugesrawi et al. (2006) confirmed positive effects of processing (wilting, drying, ensiling) on decreasing HCN concentrations in 2 varieties of cassava in India, with significant differences quantified between the varieties used. Similar to other reports (Borin et al. 2005), ensiling cassava leaves for 3 month resulted in a reduction of free cyanogens from 289 to 20 mg/kg in a study in Tanzania (Kavana et al. 2005), and was found to be a suitable forage for lactating dairy cattle, particularly during dry season feeding. In direct comparisons, ensiling/fermentation was found to be more effective than sun drying in decreasing cyanide levels in cassava leaves.

Cassava peels and tubers. From a nutrition perspective and at the current time, these feed fractions must considered jointly as energy sources in animal feeding programs; with the exception of cyanide content, both peels and various tuber fractions are low in other nutrient concentrations compared with cassava leaves. Approximately 80% of the carbohydrates produced in tubers is starch (Gil and Buitrago 2002 cited in Montagnac 2009); 83% is amylopectin, 17% amylose, with smaller levels of sucrose, glucose, fructose, and maltose (Rawel and Kroll 2003; Tewe and Lutaladio 2004 both cited in Montagnac 2009), thus tuber chips and cassava flour energy content can replace cereal grains in animal diets. A comprehensive description of peel polysaccharides was not found, but due to its overall higher fibre content, peels are lower in energy density and digestibility than tubers, thus of less feeding value to monogastrics without prior modification. Fermentation technologies have been developed, however, that result in the conversion of cellulose in cassava peels to soluble carbohydrates (Ofuya and Obilor 1993; Iyayi and Losel 2001) and also add protein content to peels to increase feeding value for poultry. These treatments allowed inclusion of fermented cassava peel as a 100% maize replacement (30% of the diet) that resulted in increased digestibility, growth, and reduced mortality in broilers (Ofuya and Obilor 1993). More recent fermentations have been shown to increase crude protein in peels from <2% to 13 to 26% of DM,

while lowering crude fibre values by one-half (Obadina et al. 2006; Adamafio et al. 2010), thus further enhancing potential feeding values.

While low in overall protein content, peels in general contain higher concentrations of protein (Table 2) than roots, but possibly a different AA profile (Table 3). Gil and Buitrago (2002, cited in Montagnac et al. 2009) reported that tubers contain an excess of Arg, Glu and Asp, with about 50% of the crude protein in the roots consisting of whole protein and the other 50% free amino acids (predominantly Glu and Asp), along with non-protein components such as nitrite, nitrate, and cyanogenic compounds. Only a single small sample set (Mutayoba et al. 2012) compares AA profiles in both peels and tubers from the same plants. In that dataset (n = 4 varieties), values were highly correlated (r = 0.93), thus may be predictive but larger, controlled studies are required to verify. Further, in looking at the ideal AA ratios in peels compared to tubers (Table 5), the overall average AA profile for peels is better balanced than in tubers, with Met still the first limiting AA. Given the more recent targeted genetics studies seeking to enhance the nutritional properties of specific cassava cultivars (and, possibly concurrently in peels associated with those tubers), including increased protein content and lower cyanide levels, general summary data may no longer provide adequate information to optimize diets for feeding livestock.

For example, Ceballos et al. (2006) analysed crude protein content in 149 cassava tuber clones from 19 countries, including both improved and unimproved cultivars. They reported a wide range in mean crude protein content in original root stock across these samples (calculated at N × 5.31), ranging from 2.3 to 4.6% of oven DM, with an overall average of 3.2% (and 8–52% CV, depending on the sample set). Had authors used the conventional conversion factor of 6.25, the CP range would have been 2.7 to 5.4%. The highest crude protein level recorded was 6.42% from Colombia, and the lowest, in a variety from Thailand at 0.95%. Central American samples tended to show the highest crude protein values, and Asian varieties the lowest. Samples were, in this case, opportunistic rather than representative of any specific region; the study was conducted to evaluate the variability in this nutrient across samples as preliminary data to investigate the potential scope for altering this parameter with applied breeding programs. Results suggested that select improved cassava cultivars—perhaps developed for yield rather than nutrient continent—may actually result in dilution of certain nutrients such as crude protein. Dry matter content in tubers averaged 36.1%, ranging from 25.7 to 44.0%, and was negatively correlated (r = –0.37) with crude protein content, i.e. clones with higher protein tended to have lower levels of dry matter content. Although cassava is considered primarily an energy source, interactions among various nutrients, as well as anti-nutrients, must be recognized, with resulting potential impact on both quantity and quality parameters. This is particularly important for maximizing both primary and secondary (by-products) in combined human and livestock applied nutrition programs.

A more recent study by Gomes and Nassar (2013) of cassava hybrids developed from a common and popular Brazilian cultivar (530) reported an even wider range in crude protein content across 20 plant lines, ranging from 1.8 to 5.8% crude protein on a DM basis. These authors calculated crude protein using total nitrogen determined through both Kjeldahl and ammonium ion content procedures multiplied by 3.24 as a more accurately determined constant for use in cassava roots. Not only did their data suggest high overall CP relative to average values reported for cassava root pulp (2.6–2.9% of DM; Heuzé 2012), but recalculating CP based on the more standard conversion of total N × 6.25 results in an overall range of 3.5 to 11.2% crude protein in these tuber samples (with presumably even higher protein levels in peel fractions). Clearly there is scope and capability for raising overall protein levels in cassava roots (and presumably other feed-targeted fractions) through applied plant breeding programs. Similar data were not available for leaf or peel fractions at the time of this review.

Gomes and Nassar (2013) further examined amino acid profiles in the 20 hybrid (with wild relative *M. oligantha*) samples in their study, and isolated breeding crosses that resulted in high sulfur amino acid concentrations, in addition to low total cyanide (20 to 173 mg/kg) levels (data in Tables A2 and A4). Both Met (previously identified as a limiting EAA for use of cassava in animal feeding programs) and Cys (known to be involved in *in vivo* detoxification mechanisms for cyanogenic glycosides) showed relative 7 to 20-fold increases in specific hybrids within this sample set. Additionally, hybrids that resulted in high Lys concentrations (again 8–10-fold relative increases) were also identified. These high Lys hybrids, however, resulted in lines that would appear even further limiting with respect to SAA and ideal AA ratios for monogastric feeding program. Nonetheless, results suggest that improvements in protein biological value and AA balance can be achieved through directed breeding/selection programs. Indeed, 76% (13/19) of these samples showed adequate Met:Lys ratios for meeting needs for broilers or layers, and almost 90% resulted in more than adequate SAA (Met+Cys): Lys ratios. Similar studies have not been conducted on cassava leaves or peel fractions to date.

Cassava peels and tubers are not particularly rich sources of minerals and have been shown to contain high levels of phytic acid in some samples, up to 1% of DM, which can result in low bioavailability of phosphorus in non-ruminant species (Oboh 2006; Aro et al. 2010; Apata and Babalola 2012), hence dietary minerals must be supplemented. Microbial fermentation reduces the phytate content of cassava peels (Oboh 2006).

Tubers contain carotenoid levels considerably lower than found in leaves (by 1–2 magnitudes, even compared on a dry basis), but research focused on genetic modifications to increase the ß-carotene content of cassava tubers as a critical source of pre-vitamin A activity for human consumers has identified cultivar differences (Nassar et al. 2005), as well as promising genetic stock from wild cassava lineages containing high levels of both ß-carotene and lycopene (Nassar et al. 2007). Tubers from three high ß-carotene cultivars sourced in Nigeria were examined to evaluate effects of processing on nutrient stability. Reported analytical concentrations from that study, converted to comparable units, were considerably lower than other literature values (Thakkar et al. 2009). It is unknown if differences are due to cultivar or analytical procedures at this time. Antioxidant and pre-vitamin A properties of these carotenoids may increase not only nutritional value, but also assist with shelf life/slow the rapid deterioration inherent in harvested cassava (Chavez et al. 2000). Further research is needed; pilot studies suggest that peels may contain ß-carotene concentrations intermediate to leaves and tubers of the same plants (Mutayoba et al. 2012). Expanded carotenoid profiles of the various cassava fractions may reveal additional pigments of interest in health and applied feed/food programs.

In addition to the green leaf fraction, cassava tubers also contain significant vitamin C levels, and limited evidence suggests that peels may reflect values seen in tubers (approximately 100 mg/100 g DM) (Table 7). It is possible that increased antioxidant activity from vitamin C, ß-carotene, and possibly even polyphenolic compounds in cassava peels may contribute to stability/extended storage-life of the intact tuber, but has not been investigated. Increasingly, nutritional sciences recognize beneficial properties of the diverse polyphenolics: they may function to bind protein and contribute to improved protein utilization in ruminants (Wanapat 2003), and /or may also provide anti-parasitical/antibiotic (Sokerya et al. 2004) activity in addition to antioxidant status. A dearth of information exists concerning quantification or contribution of polyphenolics in cassava peel fractions for applied feeding programs.

A majority of the literature on secondary metabolites of cassava focuses on the cyanide content of tubers and methods for detoxification which have been previously discussed (Montagnac 2009b). Much variability exists regarding cyanide content in cassava peels and tubers, both across varieties within locales as well as within specific cultivars. Various hybrids from a common Brazilian cultivar (530) considered to contain non-toxic HCN levels (~51 mg/kg fresh pulp) resulted in strains with HCN content ranging from ~20 to 173 mg/kg DM in fresh pulp (Gomes and Nassar 2013). The 20 samples examined in their study resulted in an almost equal distribution of tubers classified non-toxic (30%; <50 mg/kg cyanide), low toxicity (20%; 50–80 mg/kg cyanide), toxic (30%; 80–100 mg/kg cyanide) and highly toxic (20%; >100 mg/kg cyanide.

Ruminants are more susceptible to cyanide toxicity than non-ruminants due to microbial fermentation breaking the glycosidic bond to release free HCN. Since cassava peels contain higher concentrations of cyanogens than the pulp (Cardoso et al. 2005), detoxification must be undertaken prior to feeding to all hoofstock. Tweyongyere and Katongole (2002) examined ranges of cyanide equivalents in peels from 14 cultivars of cassava from Uganda, as well as pooled samples from local markets. They reported a wide range of values among these samples (253–1081 mg HCN eq/kg DM); all peels contained potentially toxic levels (>100 mg/kg), with bitter local varieties exceptionally high. They further examined 3 methods of detoxifying the peel fractions: sun drying, heap fermentation, or soaking in water, and evaluated HCN levels at time intervals over 5 days. All methods were successful; by 48 hours, sun drying reduced HCN by more than 82%, heap fermentation lowered levels by 48%, and soaking by 27% (Tweyongyere and Katongole 2002). By 72 hours, residual cyanogenic compounds were reduced to <50 mg/kg sun-dried or heap fermented peels; soaking required 120 hour to reach safe levels. While sun drying resulted in the most rapid decline in cyanogenic glycosides in this study, heap fermentation actually achieved the lowest residual level (5 mg HCN eq/kg DM) after 120 hours.

By-product slurries or liquids from fermentation processes used in production of human-grade cassava-based foods (i.e. gari, fufu) might be applied further to livestock feeding programs as a targeted fermentation culture for other industry waste products such as cassava peels. Pure cultures of *Aspergillus* spp, *Saccharomyces* spp, *Lactobacillus* spp have been shown effective in decreasing cyanogenic glycoside and phytic acid concentrations in peels (Oboh 2006), as well as increasing protein content, but may have limited practical application at the farm level. Applying these concepts further, Adamafio et al. (2010) utilized fermented (3 days) cassava pulp juice containing identified naturally-occurring *A. niger, A. flavus,* and *Lactobacillus* spp, as a low-tech, practical addition to sun-dried (3 days) peel meal, and fermented a further 1 to 7 days to determine effect on cyanogenic glycoside content. Although control/sterile fermentation treatments also showed a decline in cyanogen content (34–43% of initial starting concentrations), the pulp juice inoculum treatment resulted in a decline to only 12.3% of HCN levels (~54 mg/kg DM) relative to untreated peels (352 mg/kg). Additionally, crude protein content in the peels was increased through the addition of the pulp fermentation inoculum—from <1% of DM to >5%, likely due to the contribution of microbial mass and microbial enzymes. Fibre content was not altered through treatment (crude fibre ~7% DM), thus potentially fermentable CHO utilized by ruminants were preserved through this treatment. Non-structural carbohydrates (starches and sugars), however, declined through the fermentation process from about 2.5 to 1.5% of DM, serving as energy substrates for the microbes.

Despite improvements in nutrient content, the remaining fibre in fermented cassava peels can still limit its utilization by monogastrics. In other studies, pure fungal cultures of *A. niger, Rhizoctonia solani,* and *Phanerochaete velutina* were shown to degrade cellulose in cassava peels to starches and soluble sugars (Iyayi and Losel 2001) over 10–14 days fermentations. Such fermentation end products may have an application in monogastric feeding programs, not only in lowering fibre content, but increasing available energy content, amino acid quantity and quality, and likely vitamin levels. Thus several methods are available for initial preparation of cassava peels for safely feeding livestock, but must nonetheless be considered a mandatory initial step. Furthermore, different processes and directed cultures may be necessary for different species' applications.

Applications of cassava and cassava residues as livestock feed

Cattle

Various cassava fractions have been investigated as both energy and protein sources in feeding hoofstock. Although dried cassava tuber chips and/or peels can be used as an energy source replacing grain and/or high proportions of the concentrate in ruminant diets, carbohydrates are degraded rapidly, displaying >80% disappearance in 48 hours. Thus animals must also have access to slower-degrading nitrogen sources to support rumen microbial growth.

Dairy

Wachirapakorn et al. (2001) developed and tested a dairy concentrate (20–21% crude protein) containing cassava root chips at levels of 25, 35, 45, and 55%, fed to crossbred Holstein–Friesian cattle in an *ad libitum* ration consisting of roughage (dried Ruzi grass, *Brachiaria ruziziensis*; (6% CP)) and concentrate at a ratio of 30:70. Level of cassava root chips in this study did not affect rumen pH (6.6–6.7), and had no effect on total dry matter intake, digestion, or milk components; cows produced 8.4 to 10 kg milk/day. Contrary to earlier suggestions limiting inclusion rates at 20–30% of the diet for dairy cattle (Smith 1988), cassava root chips were used as an energy source in lactating cow diets at quite high levels (55% in concentrate or 38% of total diet), without affecting feed intake, milk production and milk composition.

Slow-release N sources (urea with calcium chloride or calcium sulfate) developed and tested with dairy cattle fed diets containing a high level of cassava chips (70% of the concentrate; ~42% inclusion in total diet) and rice straw (Cherdthong et al. 2011) demonstrated improvements in intake of OM and ME and digestibility (OM and NDF) associated with the added N supplement. Rumen parameters, including cellulolytic microbial populations, were improved with the urea-calcium sulfate product, and milk yield increased from 10.7 to 14.7 kg/day (3.5% FCM) compared to control cows with added normal urea (not slow release products) added to the diet.

Cassava hay has also been added to dairy rations to improve bypass protein, resulting in increased milk production (Wanapat 2003). Studies to maximize nutritional value of cassava leaves and stems by harvesting at 2–3 months' growth, chopping and sun drying demonstrated elimination of hydrocyanic acid (HCN), increased palatability, storage stability, and better protein:energy ratios. Cassava leaves and hay harvested at 3–4 month growth (with 2 month recutting intervals) showed protein and amino acid profiles comparable to soybean meal and/or alfalfa (Wanapat 2003). Cassava hay proved higher in Met compared to SBM or alfalfa in these studies; further, condensed tannins (<4% of DM), were at levels known not to reduce palatability in ruminants, and actually may prove beneficial by increasing rumen bypass protein, N recycling, and possibly added antiparasitical action. High-quality cassava hay replaced concentrate in diets for lactating dairy cows with no reduction in milk yield, and improved feed conversion as well as milk fat and protein components. The concentrate, in these studies, comprised 95% cassava chips, 3% urea, 1% S and 1% mineral mix; a 42% reduction in concentrate

was possible with the feeding of cassava hay. Numerous other studies incorporating cassava hay as a roughage component in high quality feed blocks fed to lactating dairy cows maintained on urea-treated rice straw also demonstrated similar improvements in milk production and nutrient components (cited in Wanapat 2003).

Cassava leaf (sweet variety) silage increased milk production and milk fat (7.6 to 9.9 L/day; 3.3 to 4.0%, respectively) in a pilot study conducted with Friesian × Boran cattle (n = 5) in the Tanga region of Tanzania (Kavana et al. 2005), likely due to bypass protein provided by the silage as measured by ADF-bound protein fractions. Harvested leaves were wilted for at least 12 hours; silage was produced by mixing chopped leaves with cassava chips in a 1:4 ratio, packing and sealing the mixture into polyethylene bags for fermentation (90 days). Cows were fed a variety of local unimproved grasses, 2 kg maize bran during milking, and offered 10–12 kg silage overnight during feeding/milking trials; average silage intake in this study was 3.7 kg DM.

Beef

In order to provide supplemental substitution energy to a local grass and rice-straw based diet consumed by Laisind cattle in Vietnam, Ba et al. (2008) fed graded levels of cassava powder (0, 0.3, 0.7, 1.3 and 2.0% of LW) with 2% added urea in 2 days meals to 150 kg animals over 88 days. The basal diet comprised chopped elephant grass at 1.25% LW and untreated rice straw (also chopped) offered *ad libitum*, with a hard salt block containing 3% urea, 5% cottonseed meal, 5% molasses and a mineral premix available. Intakes of cassava powder increased linearly, except at the highest level where cattle refused feed, and rice straw decreased. Highest daily gains (0.59 kg/d) were seen on the highest cassava + urea intakes (~1.3% LW), with accompanying lower fibre digestibility (NDF from 62 to 41%) and possible subacute rumen acidosis due to the rapidly fermenting characteristics of cassava starch. Supplementation rate of this highly digestible starch is thus suggested at 0.7 to 1% of LW and/or lower amounts mixed with other energy supplements such as maize or rice bran may be more suitable. Nonetheless, digestible energy intakes increased with increasing cassava intake, as did weight gain.

ADGs of 0.54 to 0.81 kg have been reported for cattle consuming, respectively, 50 to 60% cassava root by-product in the concentrate (Umiyasih et al. cited in Antari et al. 2013). In a follow up study, finishing cattle in Thailand were offered diets comprising untreated rice straw (10–20%) and concentrate (80–90%) that contained 40 to 50% cassava powder (34 to 42% dietary inclusion) and varying levels of rice bran, copra meal, and palm kernel cake, fed *ad libitum* (> 3.5% DMI) for 28 weeks. Total diets contained about 10% CP; animals gained 0.74 to 0.8 kg/day, and performance and carcass traits were not affected by diet treatments, thus demonstrating inclusion rates of up to 40% dried cassava can be profitably fed (Antari et al. 2013).

In an attempt to modify the rumen environment to optimize pH and N metabolism, dairy steers fed a basal diet comprising a high-cassava concentrate (65% cassava chips, 17% SBM, 5% molasses, 2.5% palm kernel meal, 4% coconut oil, 3% urea, and 3% minerals (S, salt, and trace minerals) and local forage (1% and 1.5–1.8% DMI, respectively) were offered a feed block containing 30% cassava hay or rice bran, at 0.5% DMI, with malate added at 500 or 1000 g (Sittisak et al. 2009). Addition of the cassava hay (with malate) to the overall diet had no effect on DMI, but significantly increased ruminal bacterial concentrations and lowered fungal and protozoal populations, thus demonstrating potential for further improved rumen efficiency by adding malate on high-cassava diets.

Native cattle in Cambodia were fed 0, 0.25, 0.5, 0.75, or 1% of BW in dried cassava foliage as a supplement to untreated *ad libitum* rice straw, with a rumen supplement fed at 0.25% BW (comprising urea, S, salt, minerals) in an on-farm trial (Sath et al. 2008). Over 3 months, cattle weight gain doubled (201 to 402 g/day) with increasing intake of dried cassava foliage (90% intake of leaves, 45% of petioles), and feed conversion improved with added nitrogen from the cassava hay.

Small herbivores

All parts of the cassava plant are successfully utilized in feeding small ruminants, as well as rabbits, particularly by the smallholder farmer. Cassava sievate included at up to 18–20% in rabbit grower diets (replacing the corresponding amount of maize grain) resulted, for all inclusion rates, in growth performance similar to or slightly better than that obtained with the maize-based control diet (Ngodigha et al. 1995; Ekwe et al. 2011). A higher inclusion level (40%) reduced growth rate by 9% in comparison with the maize-based control diet, but the unit cost of feed to weight gain remained in favour of sievate utilization (Ngodigha et al. 1995). Yousef et al. (2007) found dried cassava leaves superior to locally sourced Leucaena or Gliricidia leaf meals provided at ~1% of BW as a nitrogen supplement to growing goats consuming poor quality *Panicum maximum* hay *ad libitum*; animals gained ~290 g/day. While dried meals can be fed, wilted and even fresh cassava leaves appear acceptable for feeding goats. Goats are often fed fresh cassava foliage in Vietnam and Cambodia, with little to no risk of toxicity, provided animals are gradually adapted to the forage.

A production goat concentrate was developed in North Vietnam containing 25% dried cassava foliage, 25% dried flemingia (*Flemingia macrophylla*) foliage, 11% rice bran, 11% cassava root meal and 28% molasses (Van et al. 2001). Intake at 613 g resulted in weight gains of 101 g/day for goats weighing ~33 kg. Grazing studies with local Para grass in an 80:20 (concentrate:grass) ratio resulted in further daily gains of 58 g, and proved most economic. An additional study feeding a combination of cassava and jackfruit foliage, in addition to sugar cane, rice bran, cassava root, and molasses urea block, resulted in the optimal doe and kid performance when compared with other local forage mixtures or single browses.

Dried cassava peels, with poultry litter as the N source, replaced maize in goat diets at 0, 50, or 100% substitution in a trial conducted by Akinsoyinu (1992) as a supplement to grass (*Cynodon nlemfluensis*). No effect on DMI (5.5% of BW) was noted across diet treatments, but digestibility parameters were reduced with increasing inclusion rates. Results support the value of cassava peels as a dry season feed resource.

Although fresh (Onwuka 1992) and dried (Lakpini et al. 1997; Ukanwoko et al. 2009, Asaolu et al. 2012) materials have been utilized successfully as roughage in various feeding trials with various protein supplement sources (cottonseed or groundnut cake, SBM, brewer's grains, urea-molasses blocks, local browses/shrubs), ensiled cassava peels have also shown excellent promise as a practical feed ingredient for small ruminants. Not only does ensiling minimize cyanogenic compounds in the peels, but recent studies with goats confirm the efficacy of cassava peels as a high starch additive to improve fermentation and moisture-holding capacity in grass silages (Olorunnisomo et al. 2012). After wilting elephant grass (*Pennisetum purpureum*) and cassava peels for 6 hours, various silage blends were tested with the addition of 10, 30, or 50% wet cassava peels to the mixtures. Following a 21-day fermentation, silages were fed to goats *ad libitum*, along with concentrate at 0.5% DMI; higher inclusion rates of peels increased fermentation characteristics, palatability, animal intakes, and plasma glucose, and clearly could be fed without problem at 50% inclusion.

Okoruwa et al. 2012 conducted a trial with 15 growing West African dwarf sheep, replacing 70% of guinea grass diets with dried cassava peels and rice husk in differing ratios (60:10 and 55:15). DMD was not affected by the dietary treatments, and metabolizable energy $BW^{0.75}$ was highest on the 55:15 diet, suggesting that blends of cassava peels and rice husks may successfully replace guinea grass in diets.

Other studies with sheep fed cassava peels demonstrated increased gains with ensiling vs. feeding dry peels (59 vs. 81 g/day; Asaolu and Odeyinka 2006), and linear improvements in weight gains (45 to 107 to 225 g/day) with addition of cottonseed cake as a protein supplement to a grass (*Pennisetum* spp) and dry cassava peel diet (Formunyan and Meffeja 1987).

Swine

Cassava roots and/or peels can be fed fresh, boiled or as dried meal in swine diets, as an energy replacement for maize in pelleted or mixed diets. Apata and Babalola (2012) referenced studies incorporating 60 to 100% replacement of maize in supplemented diets for growing/finishing swine with cassava root and/or peels, demonstrating no negative impacts upon production or health parameters. Other studies successfully relied on cassava root meal fed *ad libitum* as the primary energy source for growing pigs, with protein and other essential nutrients provided as a dietary supplement. On a practical basis, properly formulated supplements for diets based on fermented by product cassava peels (to minimize cyanogenic potential) as an inexpensive energy source may prove most economical for both the smallholder as well as commercial pig farmer.

Ekwe et al. (2011) evaluated efficacy of inclusion rates of sun-dried cassava peel supplementation on the performance of weaner pigs, with alternating ratios of cassava peel (50, 40, 30, 20%) and maize (0, 10, 20, 30%). Other diet ingredients included SBM and fishmeal for protein, palm kernel cake and wheat bran for energy, and minerals and vitamins. No differences were determined in feed efficiency or growth performance across the 4 treatments, with pigs consuming 1.3 to 1.5 kg and gaining about 500 g/day. The best economics of production were realized at inclusion levels of 30% for cassava peels, and 20% maize in the diet. Inclusion of dried cassava peel at 50% was not detrimental to performance, but resulted in poorer profitability due to high feed cost.

The use of enzyme supplementation is an important technique for enhancing the efficiency of cassava by-product utilization in livestock nutrition (Akinfala and Tewe 2004). Adesehinwa et al. (2011) conducted a study with growing pigs in Nigeria, replacing 100% of maize in the diet (30% total inclusion) with sun-dried, ground cassava peels, with and without addition of an enzyme cocktail. Remainder of diet ingredients included palm kernel cake, wheat bran, groundnut, fishmeal, minerals and a vitamin premix. The enzyme blend (protease, fungal xylanase, fungal *β*-gluconase, endo β-gluconase, α-amylase, β-gluconase (pH 7.5–30°C), β-gluconase (pH 5–30°C), hemicellulose, pentozanase, pectinase) was designed to degrade the suite of carbohydrates in cassava peels, and resulted in a 23–34% reduction in feed cost/kg gain, enhanced feed utilization, and comparable performance.

Cassava leaf silage and/or wilted leaves have been successfully used as a nitrogen source for growing pigs in Asia (Hang 1998; Ty et al. 2003; Nguyen et al. 2012) and Africa (see Apata and Babalola 2012), with young leaves (2 months) containing higher nutritive value compared with those harvested at a later stage of maturity (5 months) (Ty et al. 2003). Management of the plants as a forage crop, with added fertilizer inputs, is necessary to maintain high nutritive quality over multiple harvests for this application. In early studies of cassava leaf use in swine diets, leaves were wilted and ensiled in plastic bags with molasses and rice bran; after 7 days, HCN levels had decreased >50% in all treatments. Ensiled cassava leaves successfully replaced up to 20% of fish meal in swine diets before intakes appeared limited when energy was supplied by ensiled cassava roots (Hang 1998). In this study, overall DMI did not change, but apparent digestibility tended to decrease, and nitrogen retention diminished with increasing levels of cassava leaf silage replacement. Nonetheless, the combination of fish meal and cassava meal supported growth of piglets. Although wilting or ensiling was suggested as a necessity to reduce potential cyanogenic toxins in cassava leaves, later studies also demonstrated the utility of feeding fresh leaves at up to 25% of the diet (Tram and Preston 2004) as a sole supplement with broken rice (as the energy source) fed to pigs, with no advantage associated with wilting (Norachack et al. 2004). In general, positive response to cassava leaf meal in swine diets at levels of 15–25% of the ration is supported; lower gains and feed efficiency have been reported at 30% inclusion (Apata and Babalola 2012).

Indigenous pigs of several breeds appear better able to utilize fibre in cassava leaf meal (CLM) and/or silages (CLS) compared with improved breeds (Borin et al. 2005), possibly due to better fibre digestion abilities. In a study comparing CLM and CLS from different varieties, cassava leaves supplied the sole nitrogen source (20–30 g DM per kg live weight); the diet comprised cassava leaves, sugar palm syrup, crude palm oil, salt, and a pre-mix

(Borin et al. 2005), offered *ad libitum* 4× daily. Total DM, CP, OM, and fibre intakes were higher in CLM diets than CLS, but variety had no effect on nutrient intakes; CLS resulted in better nutrient digestibilities compared with CLM. While CLM resulted in greater N intakes, N utilization was higher on the CLS diets; both processes result in suitable nitrogen sources in energy-rich diets for swine.

Utilization of various combined parts of the cassava plant were explored by Akinfala and Tewe (2004), on diets comprising 60% cassava in a ratio of 4:1:1 (root flour:peel:leaves/stems (the latter 75%:25%); DM basis). Dietary treatments tested included baker's yeast, antibiotics, and a protease enzyme, with greatest gains and fibre digestibility response due to the yeast additive; pigs demonstrated feed:gain of approximately 2 on this cassava-based diet, with a daily gain of ~0.5 kg/day (on treatment diets). The positive effect of the yeast additive was attributed to enhanced microbial environment, added vitamins, and/or amino acid/protein enhancement. The first and second limiting amino acids for swine fed diets with protein based on either cassava leaf meal, or cassava leaf silage, continue to be confirmed as methionine + cysteine, and lysine (Nguyen et al. 2009).

Poultry

Substitution of maize in poultry diets with cassava root meal or cassava starch has been explored in numerous studies over the past 3 decades (see, for example Garcia and Dale 1999; Akinfala et al. 2002; Salami and Odunsi 2003). Some studies with broiler chickens have shown that performance declines progressively as the amount of cassava root meal is increased in the diet (Ojewola et al. 2006; Khempaka et al. 2009). Although earlier studies suggested lower inclusion rates (8–10%) must be maintained, more recent studies with broilers suggest that a substantial proportion (as much as 50 to 75–80%; Olugbeme et al. 2010; Kana et al. 2012) of energy ingredients can be replaced with cassava chips or flour with no decrease in production, provided diets are balanced with regard to other nutrients, cyanide levels are <141 mg/kg, and diet is not overly dusty (Apata and Babalola 2012). Addition of palm oil (3%) and cocoa husk (1%) to cassava meal was shown to improve broiler diet texture and palatability (Kana et al. 2012).

The use of palm oil has been shown to be of other benefits when feeding cassava based diets. Hew and Hutagalung (1972) and Maner (1974) reported that there were added advantages in combining palm oil and methionine as detoxification agents of residual cyanide in cassava-based diets for poultry and pigs. Aniebo (2012) examined the performance of broilers placed on composite cassava root meal-based broiler starter diets supplemented with palm oil, methionine or palm oil plus methionine. The results indicate that palm oil complemented DL-methionine as a cyanide detoxification agent in cassava root meal-based broiler diets but was apparently ineffective as the sole detoxification agent at 4% or lower inclusion levels. Chou et al. (1976), Odukwe and Obioha (2000) and Omole and Onwudike (1983) noted that supplementation of palm oil and methionine to cassava-based diets improved the performance of chickens. However, on the whole, inclusion of methionine supported better overall performance than palm oil inclusion. This was probably due to better amino acid balance at appropriate levels of supplementation (Adegbola 1977). Enriquez and Ross (1967) noted that the addition of 3.7% soybean oil of the methionine-supplemented diets further improved poultry performances, suggesting that energy was a second limiting factor.

Cassava peels (Nwokoro and Ekhosuehi 2005) and fermented cassava peels have also been demonstrated to be a viable ingredient at up to 15% inclusion in diets fed to broilers, with a variety of locally available protein sources (i.e. groundnut cake, cashew nut meal) utilized to meet amino acid requirements. Inclusion of 40% cassava flour or 20% cassava peels in blended diets supports egg production in layers. Midau et al. (2011) investigated the performance of broiler chicken fed varying levels of cassava peel meal supplemented with Maxigrain® enzyme (at 100 g/tonne of feed) to replace maize and its cost benefit and the feed intake, feed conversion ratio and daily weight gain showed significant differences. Enzyme addition reduced the anti-nutritional effect of HCN. Enzyme

addition improved weight gain, feed intake, feed utilization, nutrient digestibility and absorption of nutrients. Feed cost/kg of feed, cost of feed/kg gained also decreased with increasing levels of enzyme supplemented cassava peel meal. Supplementing cassava peel meal with Maxigrain enzyme at 50% inclusion level gave the best result.

The quantity and quality of protein supplementation in cassava based diets is critical, and especially with regard to the content of sulphur containing amino acids. Methionine supplementation has been reported to significantly improve protein utilization in rabbits, pigs and poultry (Job 1975; Wyllie and Kinabo 1980; Omole and Sonaiya 1981; Gomez et al. 1984c). Phuah and Hutagalung (1978) reported that up to 40% cassava meal had no adverse effect on broiler performance when the diet was supplemented with methionine, lysine and palm oil. The requirement for sulphur-containing amino acids is in part for use in the rhodanase detoxification pathway. Enriquez and Ross (1967) noted that supplementation of 0.15–0.20% methionine in 50% cassava root meal-based diets could help overcome HCN toxicity and restore poultry performance to normal levels. Similarly, Olson et al. (1969a; 1969b) and Hutagalung (1977) showed that the supplementation of 0.40% cysteine in 45% cassava root meal-based diet gave comparable results to the 0.20% supplemented methionine. Palm oil, methionine or a combination of the two have been used as a detoxification agent in cassava based chicken rations (Obioha et al. 1984; Gomez et al. 1987). These detoxification agents are now very expensive and their use at arbitrary levels may not be justified unless their efficacy and the cost-effectiveness of their use are determined. Nutritional fortification of cassava flour with fresh blood or cashewnut reject meal or soybean meal has shown promising results in poultry (Manukure 2001; Sogunle et al. 2007; Banjoko et al. 2008).

Combinations of cassava root fractions and leaves may also prove an economic and practical combination that can substitute for maize in diets to support both growth and egg production; one study (Eruvbetine et al. 2003) demonstrated that a blend of 50:50 leaves and tubers before drying resulted in the best texture, lowest HCN content, and highest protein content. Early trials with a composite cassava pellet (Ukachukwu 2005; proportions of various fractions not stated) showed promise, but require fine tuning the concept. Cassava leaf protein concentrate has been shown able to substitute for up to 60% of fish meal in broiler starter diets (Fasuyi and Aletor 2005). Typically, inclusion of cassava leaf meal as a protein source has been limited to ~10% of broiler diets due to fibre levels and amino acid imbalances (Tewe and Egbunike 1988).

More recently, a blend of CLM and blood meal (1.5:1) has been shown to provide a better amino acid balance, and can be included as a protein ingredient at up to 20% of the diet, substituting for 50% of soybean meal, with no decrease in production parameters (Adeyemi et al. 2013); inclusion of exogenous NSP enzymes further improved weight gains and F:G conversions. Other local leaf meals (i.e. *Moringa oleifera*) have been examined as economic protein substitutes in broiler diets that also include cassava energy sources (Olugbeme et al. 2010); additional benefits pigments in the green leaf meal diets were noted. A combination of both energy and protein sources, based on cassava by-products, may prove most beneficial for increased sustainable poultry production.

Limited data on the use of cassava leaf meal and cassava foliage meal in poultry diets indicate that these products might be used, at low inclusion levels, as pigment agents, or, at higher levels, as partial substitutes for the conventional feedstuffs. Cassava leaf meal could be included up to 20% in broiler diets whereas the inclusion levels of cassava foliage meal were slightly lower (Khieu 2005). This, as expected, is attributable to the higher content of crude fibre in the foliage meal than in the leaf meal. The limiting factors with both meals are the HCN content, low energy, bulkiness and possibility of tannin content (Ravindran et al. 1986). Normal supplementation of high cassava leaf meal and cassava foliage meal inclusion rations are 0.15–0.25% methionine and 3% fat. However, the economic value needs to be carefully assessed.

Palatability of cassava-based ration is a factor limiting feed intake of poultry. Physical properties such as dustiness and bulkiness are closely related to palatability and limit feed intake. Further processing of cassava-based diets including pelleting, addition of molasses or fat to eliminate dust and improve diet texture, supported significantly better poultry chick performance (Khajarern and Khajarern 1992). Although the feed efficiency of poultry chicks fed the fat supplemented cassava-based diets was significantly better than in those fed the unsupplemented diets, the use of fat supplementation could not be economically justified.

Cassava Leaf Protein Concentrate (CLPC) was evaluated as equi-protein replacement of fish meal protein in layer diets by Fasuyi (2006). Six isonitrogenous and isocaloric diets containing 5% fish meal (control) in which were formulated with various replacement levels of 20, 40, 60, 80 and 100% CLPC, corresponding to 1.61, 3.22, 4.82, 6.43 and 8.04% inclusion levels of CLPC, respectively. Total feed intake and daily feed intake were similar ($P = 0.05$). There was no mortality and no significant difference ($P = 0.05$) occurred in the weight changes and hen day production indices among the 6 diet treatments. Among the haematological indices, only the erythrocyte sedimentation rate (ESR) was significantly different ($P = 0.05$). The serum constituents showed no consistent relationship with the dietary treatments and were not significantly different ($P = 0.05$). It was concluded that CLPC can replace fish meal at about 8.04% inclusion in layers diet without any adverse effects on health status and performance characteristics particularly in reference to egg production. However, CLPC is of limited significance due to its high labour requirements and high costs of processing.

Use of cassava and its by-products in aquaculture feeds

Shortage of cereals has recently been a serious issue in several regions of the world; in many areas, the use of cereal products as energy feedstuffs and oilseed meals as protein feedstuffs in livestock and aquaculture feeds is increasingly unjustified in economic terms. Non-conventional dietary energy and protein sources, especially from plant origin, need to be evaluated to replace expensive cereals and oilseed meals for sustainable livestock and aquaculture production. Cassava and its by-products are appropriate for this purpose.

The cost of nutritionally complete aquaculture feeds represents about 60–75% of the cost of intensively reared fish (Fagbenro and Adebayo 2005). Feeds for warmwater omnivorous fish such as tilapias (*Oreochromis* spp, *Sarotherodon* spp, *Tilapia* spp) and African catfishes (*Clarias* spp, *Heterobranchus* spp and their hybrids) are generally compounded from soybean meal and maize (Tacon 1993; Fagbenro and Adebayo 2005). Increasing pressure on the use of these crops by both the increasing human population and by livestock feed millers is making use of these products increasingly expensive. This, in turn, is stimulating the use of alternative feedstuff sources that are locally and widely available (Fagbenro et al. 2005), such as cassava, which is commonly available in many areas of the humid tropics. In addition, cassava by-products, such as peels and leaves, are non-competitive feedstuffs that can perhaps be developed as components of aquaculture feeds.

Tilapias and Clariid catfishes are major aquaculture species in Africa, Europe and southern Asia because of their ready marketability, fast growth, disease resistance, and amenability to high density culture (Balarin and Hatton 1979; Jauncey and Ross 1982; Hogendoorn 1983; Hecht and Lublinkhof 1985; Viveen et al. 1985; Huisman and Richter 1987; Hecht et al. 1988; Haylor 1989; Haylor 1992; Salami et al. 1993; Williams et al. 2007; Fagbenro et al. 2010; Fitzsimmons et al. 2011; Munguti et al. 2012). Nutrient requirements (protein, essential amino acids, lipid, energy, micronutrients) of tilapias (Jauncey 1998; 2000) and catfishes (Wilson and Moreau 1996) have been established, as well as their ability to digest various protein and energy feedstuffs (Fagbenro 1996; 1998a; 1998b; 2001). Based on these, standard diets were developed for both tilapias and African catfish species by Fagbenro and Adebayo (2005) (Table 9).

Table 9. Standard diets for tilapias and African catfishes

Ingredients (g/kg weight)	African catfish feeds (40% protein)		Tilapia feed (30% protein)
	Grower	Broodstock	
Fish meal (65% crude protein)	250	250	150
Soybean meal (45% crude protein)	350	350	450
Maize (10% crude protein)	150	100	250
Blood meal (85% crude protein)	100	100	–
Fish oil	60	90	40
Vegetable oil	40	60	60
Mineral–vitamin premix	30	30	30
Starch (binder)	20	20	20

Source: Fagbenro and Adebayo (2005).

The aquaculture industry in sub-Saharan Africa is based mainly on herbivorous/omnivorous tilapias and omnivorous/carnivorous catfishes, cultivated under intensive (commercial) and semi-intensive (artisanal) production systems. Both indigenous and introduced species are cultivated in ponds, reservoirs and cages. Tilapias (*Oreochromis niloticus, O. aureus, Sarotherodon galilaeus, S. melanotheron, Tilapia zillii, T. guineensis*), Clariid catfishes (*Clarias gariepinus, C. anguillaris, C. isheriensis, H. bidorsalis, H. longifilis*) and the mirror carp (*Cyprinus carpio*) are the most widely cultured fish in Africa and are suited to low-technology farming systems (Hogendoorn 1983; Fagbenro and Sydenham 1988; Fagbenro et al. 1993; Haylor and Muir 1998; Fitzsimmons et al. 2011). This is because of their popularity in the market, fast growth rate, efficient use of natural aquatic foods, propensity to consume a variety of supplementary feeds, omnivorous food habits, resistance to disease and handling, ease of reproduction in captivity and tolerance to wide ranges of environmental conditions (Fagbenro 2002; Williams et al. 2007).

Formulated feeds constitute significant portions of the operating cost of aquaculture enterprises, of which protein is the most expensive component. Fish meal (the conventional protein source) supports good fish growth, because of its protein quality and palatability (Tacon 1993). Good quality fish meal is scarce, and when available, it is very expensive (Fagbenro 2005). Hence, there is a compelling need to explore the use of alternative protein sources in combating the problem of escalating cost of aquaculture feeds. The use of plant-based feedstuffs in aquaculture feeds is desirable due to their low prices and regular availability.

Although cassava roots/tubers and leaves are cheap sources of dietary energy and protein, the extent of their practical use in aquaculture feeds has been limited. In particular, there is dearth of information on the use of cassava products as feedstuff in aquaculture feeds as replacements for maize and soybean meal. Maize and soybean meal are the conventional dietary energy and plant protein sources in aquaculture feeds, respectively. The increased interest in cassava production and the need to increase its use has made it more compelling to find alternative uses for its residues, especially in aquaculture feeds. Oresegun and Alegbeleye (2002) indicated that cassava meal can replace the conventional energy feedstuffs such as maize, broken rice and sorghum, which are commonly used in aquaculture feeds in Africa.

Nutritive value of cassava root meal for aquaculture species

Intensive use of cassava roots in aquaculture feeding is possible after removal of the cyanogenic glucosides through processing methods (drying, cooking, ensiling) described previously in this report, with sun drying appearing more efficient than oven-drying (60°C) (Panigrahi et al. 1992; Tewe 1992). Addition of 15% cassava root meal to a concentrate feed has also been reported to improve resistance to pests (Göhl 1982). Summarized nutritional composition of cassava roots/tubers is presented in Tables 2 through 8, with detailed information in Appendix Tables A1 through A5).

The high starch content of cassava root makes this ingredient an excellent aquafeed binder (57.7% water stability), with comparable values to corn grain starch (56.85% water stability) when incorporated at 12% level in 25% crude protein pellets after 50 minutes in water. These are higher than the values reported for other cereal grain starches (wheat, millet, guinea corn) (Solomon et al. 2011). Importantly, cassava starch has excellent binding properties which are very useful when pelleting feed and hence eliminates the need for expensive artificial binders (Adebayo et al. 2003). Cassava root meal has been used as the main dietary energy source for fish and the various recommended inclusion levels were 45% for mirror carp; 30% for rainbow trout (Ufodike and Matty 1984) and 60% for Nile tilapia (Wee and Ng 1986).

Cassava sievate has been evaluated in feeds for cockerel (Nwokoro et al. 2000) broilers (Onwujiariri et al. 2000) and rabbits (Ekwe et al. 2011) but not in aquaculture feeds.

Tilapias

Maize has been the major dietary energy source for aquaculture species and represents about 10–40% by weight in most aquaculture feeds. The high cost and scarcity of maize in formulated feeds has led to the use of underutilized energy sources such as cassava root meal. Digestibility and energy values of cassava chips reported in literature are highly variable. Apparent dry matter digestibility of 70–78%, apparent protein digestibility of 88–90% and digestible energy (DE) values of 6.7–13.2 MJ/kg DM were reported by Pezzato et al. (2004) and Campeche et al. (2011). Cassava flour unfit for human consumption is highly digestible (91% for DM, 97% for protein) with a much higher DE value (15.4 MJ/kg DM) (Boscolo et al. 2002a). Cassava root meal is suitable for replacing 50% of maize grain in diets of young Nile tilapia (El-Baki et al. 1999). Discarded cassava flour fed to Nile tilapia fingerlings up to 24% inclusion level, wholly replacing maize grain, resulted in no decrease in performance (Boscolo et al. 2002b). Ty et al. (2010) fed tilapias at 5% of their body weight/day with mixtures of 76–80% fresh or sun-dried sweet variety cassava leaves, 12–16% rice bran and 5% cassava roots for 100 days. No fish mortality occurred and there was no evidence of HCN-related mortality. Daily weight gain by fish did not differ among treatments.

Pereira-da-Silva et al. (2000) reported that cassava root meal was less palatable to tilapias than sunflower meal and cottonseed meal. Increasing the amount of cassava root meal affected palatability negatively. This led to low feed intake in Nile tilapia (Faturoti and Akinbote 1986). Wee and Ng (1986) reported that there were no significant differences in feed conversion ratio, protein efficiency ratio or apparent net protein utilization in Nile tilapia fed diets containing 15–60% cassava root meal and no related pathology was observed in fish fed high cassava root meal levels. However, increased incorporation of cassava led to an increase in carcass fat content in Nile tilapia. Viola et al. (1986) reported that cassava root meal at levels of 20 and 30% produced growth performances equal to a commercial diet, while a 40% inclusion level slightly reduced growth in Nile tilapia. Jauncey (1998) recommended a maximum dietary inclusion level of 30% for tilapias, the limiting constraints being costs and carbohydrate content.

Madalla (2008) evaluated the suitability of cassava root meal in Nile tilapia diets. Cassava root was processed to remove the most significant antinutritional factor, and juvenile tilapia were fed isonitrogenous (300 g/kg), isolipidic (100 g/kg) and isoenergetic (18 kJ/g) diets containing graded cassava root meal levels to apparent satiation (<10% of their body weight) for 8 weeks. Processing led to the removal of 90% of HCN. Cassava root meal had a digestible energy content of 13.5 kJ g-1. Cassava root meal replaced up to 75% of wheat meal in the diet without significantly affecting performance. The suitability of cassava root meal as a dietary energy (carbohydrate) source will depend on the availability of cost effective protein sources due to its low protein content. Dada et al. (2013) reported that cassava root meal included at 24% as energy source (replacing maize) in diets fed to Nile tilapia over 56 days performed poorly in daily growth (1.61 g/day) compared with a control diet (2.44 g/day).

Catfishes

Cassava by-products have been evaluated in many African Clariid catfishes as dietary protein or energy sources. In African catfish, *C. gariepinus* fingerlings, replacement of 33–100% of maize grain by cassava flour resulted in lower performance (Akegbejo-Samsons 1999). However, an economic analysis showed that cassava root meal could profitably replace maize in the diet of hybrid catfish (*H. bidorsalis* × *C. gariepinus* fingerlings (4.35–4.63 g), up to 100% inclusion level with the optimal performance at 66% level of inclusion (Abu et al. 2009; 2010a). HCN content increased with the level of cassava in the diet (4.25–11.94 % of diet) but was always within tolerable range for the normal metabolism of the fish (Abu et al. 2010c).

Jinyasatapon et al. (2000) reported the best profit margin in African catfish fed with 100% of cassava root meal in replacement for maize. However, increasing the amount of cassava root meal affected palatability negatively leading to low feed intake; similarly reported for African catfish fingerlings (Olurin et al. 2006) and advance fry (Olukunle et al. 2006) fed diets in which cassava root meal replaced maize up to 50%; and hybrid catfish fed diets containing cassava root meal replaced maize up to 66% (Abu et al. 2010b). Chalorklany et al. (2002) observed similar economic advantage in the American channel catfish (*Ictalurus punctatus*) fed with varying levels of cassava root meal as replacement for maize. For African catfish, apparent digestibility coefficient of dry matter (DM) was 89.07%, crude protein was 91.61%, carbohydrate was 88.78%, lipid was 88.90% and gross energy was 69.96% (digestible energy (DE) values of 12.1 MJ/kg DM) of cassava root meal (Udo and Umoren 2011).

Carps

In grass carp (*Ctenopharyngodon idella*) fingerlings, cassava root meal replaced up to 100% maize grain (30% inclusion level of the diet) with no detrimental effect on the final weight, final length, feed conversion ratio, condition index and survival (Lacerda et al. 2005). In mirror carp (*Cyprinus carpio*) a diet containing 47% cassava root meal had a slightly lower energy digestibility (87%) than diets containing maize or wheat starch (90%). Growth and feed conversion efficiency were not influenced by starch source. The DM, fat and energy content in carp given cassava meal was significantly lower than those given maize or wheat starch (Schwarz et al. 1993). Ufodike and Matty (1983) found cassava carbohydrate digestibility in fish was comparable to that of rice reaching up to 86 to 87%. They concluded that cassava could be substituted for rice as an energy source in carp diet. Increasing the dietary cassava root meal level affected palatability negatively, which led to low feed intake in mirror carp (Ufodike and Matty 1983; Viola et al. 1988).

Characids

In South American Characids, black pacu (tambaqui) *Colossoma macropomum* and red pacu *Piaractus brachypomus*, cassava root, plantain fruit and peach-palm fruit (*Bactris gasipaes*) gave better growth performance than wheat bran and wheat middlings in diets containing 30% of the test ingredient (Lochmann et al. 2009). Sun-dried, milled cassava chips could be fed to *Colossoma macropomum* at 5% of body weight daily, along with commercial chicken feed given at 1% of body weight (Souza et al. 1998).

European eel

Garcia et al. (1994) compared the utilization of four carbohydrate sources (raw wheat starch, corn malto-dextrins, manioc (*M. dulcis*) meal, pre-gelatinized corn starch in European eel (*Anguilla anguilla*) isoenergetic extruded diets (28.5% protein, 8% fat, 40% carbohydrate DM) and evaluated feed acceptance, growth, feed efficiency, digestibility, dietary protein utilization, and effects on body composition. All diets were well utilized and promoted similar growth rates, irrespective of the origin and nature of the carbohydrate source. The diet containing raw wheat starch resulted in tougher pellets and was poorly accepted by the eels; besides, digestibility was clearly lower, so growth rate and feed conversion were the poorest. Results confirm the ability of eels to use high dietary carbohydrate levels from cassava starch.

Salmonids

Increasing the dietary level of cassava root meal affected palatability negatively which led to low feed intake, poor growth and inefficient feed utilization in coho salmon, *Oncorhynchus kisutch* (Mantando 1977) and rainbow trout *Oncorhynchus mykiss* (syn. *Salmo gairdneri*) (Ufodike and Matty 1984).

Prawns

Cassava root meal totally substituted for wheat flour in extruded diets for white shrimp (*Litopenaeus vannamei*) without any adverse effects on growth performance. It also improved the development of the immune system of the shrimp (Songluk et al. 2010). In giant tiger prawns (*Penaeus monodon*) fed with diets comprising cooked meat of golden snails and cooked cassava chips (60:40, fresh weight) yielded the highest net income than with maize alone and helped address the problem of snail infestation in rice fields (Bombeo-Tuburan et al. 1995). Cassava root meal replaced 100% of maize grain (51% of total diet) in the Malaysian prawns (*Macrobrachium rosenbergii*) diets without detrimental effects (Correira et al. 1996; Gomes et al. 1996). DM, protein and energy digestibility in that species were 47–54%, 74–77% and 44–45%, respectively, with heated cassava being slightly more digestible than dried cassava (Gomes et al. 1997).

Mud crab

Truong et al. (2009) incorporated local plant-based feed ingredients (defatted soybean meal, rice bran, cassava meal and corn flour) into diets formulated for the mud crab species, *Scylla paramamosain*, at 30% or 45% inclusion levels in a fishmeal-based reference diet and conducted nutrient digestibility trials. Generally, high apparent digestibility coefficients (ADC) values were obtained using diets containing 30% soybean meal or rice bran. By contrast, the lowest ADC values were obtained for the diet containing 45% cassava meal [70.9% for dry matter (ADMD); 77.1% for crude protein (ACPD) and 80.2% for gross energy (AGED)]. Specifically, the highest ADCI values were obtained for soybean meal when used at a 30% inclusion level (87.6% ADMD; 98.4% ACPD, 95.6% AGED) while the lowest ADC values were obtained using cassava meal at 45% inclusion level (53.8% ADMD; 60.2% ACPD, 67.3% AGED).

Nutritive value of cassava peels for aquaculture species

A comprehensive summary of cassava peel nutrient composition is presented in Tables 2 through 8; a comparison with other peels and fibrous feedstuffs used in aquaculture feeds is found in Table 10. Peels in general display a higher HCN and protein content than other root fractions, and a higher and variable fibre content (10–30% DM). The phytate content can range up to 1% DM, resulting in low dietary P availability in livestock (Ubalua 2007); fermentation slightly reduces phytate content (down to 0.7%) (Oboh 2006).

Table 10. Nutritional composition (g/kg DM) of cassava peels compared with other peels and fibrous feedstuffs used in aquaculture feeds

	Dry matter	Crude protein	Crude lipid	Crude fibre	Ash
Cassava peels	27.9	5.6	1.4	10.3	4.4
Yam peels	17.7	11.2	1.2	9.5	9.8
Plantain peels	18.4	9.1	5.6	6.4	17.2
Maize chaff	88.0	10.9	4.8	10.2	3.4

Source: Fagbenro and Arowosoge (1991a).

Tilapias

Cassava peel meal fed at dietary inclusion levels up to 30% to young Nile tilapia decreased performance (lower weight gain, productive protein value, feed efficiency and feed intake), and a maximum inclusion rate of 10% was recommended for feeding tilapia (Omoregie et al. 1991a; 1991b; Ugwu et al. 2004). The toxicity of cassava peel limited its inclusion in diets of juvenile Nile tilapia to a maximum of 10% (Mgbenka et al. 2004). Oresegun and Alegbeleye (2001) reported that the supplementation of 0.2% DL-methionine improved feed conversion

ratio (FCR) and protein efficiency ratio (PER) of Nile tilapia fed diet containing 20% sun-dried cassava peels as replacement for corn meal, but no improvement in FCR and PER were recorded in tilapia fed diets containing DL-methionine supplemented 30% cassava peels. Contrastingly, Adewale (2013) obtained good growth of Nile tilapia fed sun-dried cassava peels up to 15% dietary inclusion as total replacement for maize. Cassava peels have been fermented with palm wine in order to prepare a protein-enriched diet that could replace fishmeal and soybean meal in Nile tilapia fingerlings diets. This feed resulted in a lower performance than with soybean meal, but higher than with fish meal. Using cheap cassava peels for protein production through fermentation might be a profitable way of feeding tilapia fingerlings (Ubalua et al. 2008).

Solomon et al. (2005) investigated the value of cassava peels as an energy source in the diet of Nile tilapia fry (mean weight, 0.32 g). Three levels of cassava peel-based diets and a control diet (100% yellow maize in the carbohydrate mixture) were fed to fry for 70 days at 10% biomass. Diet 3 (97% cassava peels and 3% yellow maize) in the carbohydrate mixture gave the best growth performance. The fry fed this diet gained mean weight of 1.18 g over 70 days. The poorest growth performance was obtained with fry fed the control diet (100 % yellow maize in the carbohydrate mixture) which gained mean weight of 0.80 g. Analysis of the various growth indices such as specific growth rate (SGR), PER, FCR and net protein utilization (NPU) shows that Diet 3 was the overall best diet with an SGR value of 2.40 and FCR of 43.83. However, Diet 1 (70% cassava peels and 30% yellow maize) gave the poorest SGR of 1.61 and FCR of 67.58. The difference in weight gain among the fry fed the three dietary levels of cassava peels and the control diet was not statistically significant different ($P>0.05$).

Ubalua and Ezeronye (2008) fermented cassava peels with palm wine in order to prepare a protein-enriched diet that could replace fish meal and soybean meal in tilapia fingerlings diets, which resulted in a lower performance than with soybean meal, but higher than with fish meal. They concluded that using cheap cassava peels for protein production through fermentation might be a profitable way of feeding tilapia fingerlings. El-Qusairi (2011) evaluated the quality and digestibility of cassava peel, rubber seed, copra, cottonseed, and palm kernel meal fermented by *Saccharomyces cerevisiae* in juvenile of Nile tilapia (mean weight, 16.26±2.43 g), with diets fed to satiation, three times a day. The results showed that fermentation by *S. cerevisiae* increased fish carcass protein around 16.85%–31.11%, decreased crude fibre around 2.6%–31.65%, increased protein digestibility around 0.25%–11.7%, increased energy digestibility around 4.29%–11.17% (except for digestibility in the cassava peel) and also increased the dry matter digestibility of the test feedstuffs around 1.37%–61.19%.

Adriani et al. (2012) determined the quality improvement in the nutritional value of cassava peels through the fermentation process by cellulolytic microbial consortium of *Aspergillus tamari, Bacillus megaterium* and *B. mycoides*, and used the product as herbivorous fish feed material. The results showed that the enzymatic activity of fermentation with 5% of microbial consortium of *A. tamari, B. megaterium* and *B. mycoides* in the fermentation process improved the quality of the nutritional value of cassava peel. There was an increase in crude protein, gross energy and glucose contents from 4.63%, 3510 kcal and 7.36 ppm to 10.91%, 4015 kcal and 10.59 ppm, respectively. Meanwhile, the enzymatic process of the microbes decreased the content of crude fat, water, ash, HCN, starch, lignin, cellulose, and hemicelluloses. The HCN content of cassava peel significantly reduced from 265.142 to 5.49 mg/kg. The fermented product was therefore recommended as having a better biological value than the unfermented peel as a feedstuff in diets for herbivorous fishes. Dada et al. (2013) reported that cassava peel meal included at 24% as replacement for maize (energy source) in diets fed to Nile tilapia over 56 days performed similarly in daily growth (2.11 g/day) compared with a control diet (2.44 g/day).

African catfishes

Fagbenro and Arowosoge (1991a) evaluated the replacement value of fibrous feedstuffs peels of cassava, yam and plantain, and maize chaff, as substitutes for maize as energy feedstuff in low-cost diets for the dwarf African catfish, *C. isheriensis*, fingerlings (mean weight, 34.72 g) were fed for 84 days with 37% crude-protein diets containing each of the energy substitutes at 25% inclusion level. The maize chaff diet produced the greatest

body weight increases and best growth performance as well as the best feed utilization. This was followed by yam peel, plantain peel and cassava peel diets in decreasing order. Apparent nutrient digestibility coefficients of the experimental diets followed a similar trend. Only the maize chaff diet compared favourably with the control (yellow maize) diet with regard to nutrient utilization and digestibility. As with cassava peel, similar results were obtained with coffee pulp in *C. isheriensis* diets (Fagbenro and Arowosoge 1991b).

Nutritive value of cassava leaf meal for aquaculture species

The nutritional composition of cassava leaf meal is summarized in Tables 2 through 8, and compared with other leaf/foliage meals used in aquaculture feeds in Table 11.

Table 11. Nutritional composition (g/kg DM) of cassava leaf meal compared with other leaf/foliage meals used in aquaculture feeds

	Crude protein	Crude lipid	Crude fibre	Ash	References
Cassava leaf meal	29.0	2.4	10.2	6.0	Madalla (2008)
Leucaena leaf meal	29.1	6.2	12.6	9.1	Wee and Wang (1987)
Alfalfa leaf meal	21.7	3.4	20.1	17.0	Olvera-Novoa et al. (1990)
Gliciridia leaf meal	30.9	13.9	8.4	11.4	Nnaji et al. (2010)
Stylosanthes leaf meal	19.5	10.5	24.4	9.6	Chiayvareesajja et al. (1990)
Moringa leaf meal	31.1	4.5	5.9	5.5	Francis et al. (2001)
Azolla meal	25.3	3.8	9.3	24.0	Almazzan et al. (1986)
Duckweed	20.9	4.1	13.2	13.6	Gaigher et al. (1984)
Hornwort/coontail	16.2	1.5	8.3	19.7	Chiayvareesajja et al. (1990)
Water hyacinth	16.6	3.3	25.7	24.8	Klinnavee et al. (1990)

In aquatic animals, some studies have reported good performance in Nile tilapia (Nieves and Barro 1996) and milkfish (Borlongan and Coloso 1994) when cassava leaf meal did not exceed 15% of the diet. In other studies, higher inclusion levels caused poor growth in Nile tilapia (Ng and Wee 1989) and pacu, *P. mesopotamicus* (Padua et al. 1998), low protein digestibility in Asian sea bass, *Lates calcarifer* (Eusebio and Coloso 2000) and increased susceptibility to diseases in African catfish, *Clarias gariepinus* (Bureau et al. 1995). The poor growth observed in Nile tilapia by Ng and Wee (1989) was partly due to high dietary crude fibre content (16.7%) in diets with high inclusion levels of cassava leaf meal.

Tilapias

Cassava leaf meal included at 10% in Nile tilapia fingerling (2.40–2.54 g) diets gave the best growth, feed conversion ratio and survival compared to the control diet and other test diets (leaf meals of *Gliricidia sepium* and *Stylosanthes humilis*) (Nnaji et al. 2010). When tilapia fingerlings were fed with diets where soaked and/or sun-dried cassava leaves replaced 20–100% of the dietary protein, depression of growth performance and feed utilization efficiency occurred with increasing dietary levels of cassava leaves. No mortality or morphological abnormalities were observed. Supplementation of the 100% cassava protein diet with 0.1% methionine has improved growth performance slightly (Ng and Wee 1989). Fresh or sun-dried cassava leaves from a sweet variety could be included at 76–83% in tilapia fingerlings (6 g) diets. Survival was 100% on all diets and growth parameters were identical for fresh and dried cassava leaves, even though fresh leaves contained more HCN

(333 vs. 50 mg/kg DM) (Ty et al. 2010). The apparent dry matter digestibility of cassava leaf meal (50%) was similar to that of cottonseed meal and lower than that of palm kernel meal (48% and 56%, respectively). Crude protein digestibility was 50% while energy digestibility was very low (29%) (Braga et al. 2010). Higher digestibility values have also been reported (63 and 72% for DM and protein digestibility, respectively) (Tram et al. 2011). Jauncey (1998) recommended a maximum dietary inclusion level of 20% for tilapias, the limiting constraints being antinutritional factors (HCN toxicity) and nutrient value.

Madalla (2008) evaluated the suitability of Moringa leaf meal and cassava leaf meal protein feedstuffs in Nile tilapia diets. Both meals were processed to remove the most significant antinutritional factor. Juvenile tilapia were fed isonitrogenous (300 g/kg), isolipidic (100 g/kg) and isoenergetic (18 kJ/g) diets containing graded levels of Moringa leaf meal and cassava leaf meal to their apparent appetite (<10% of their body weight) for 8 weeks. Processing led to the removal of 0.3% of saponin from Moringa leaf meal and 60% of HCN from cassava leaf meal. The contents of other inherent antinutritional factors such as phenols, tannins and phytic acid were little affected. Digestible protein and digestible energy was higher in MLM (257.1 g/kg, 15.44 kJ/g) than in cassava leaf meal (127.1 g/kg, 9.16 kJ/g). Inclusion of either of the leaf meals, even at the lowest level of 15 g 100 g-1 of total dietary protein, led to a significant reduction in feed intake, growth and feed utilization. Liver and small intestine did not show any histopathological changes which could be linked to dietary treatment. The performance of leaf meals was marginally improved by a combination of blending and feeding stimulants, whereby a blend containing 1 part MLM and 2 parts cassava leaf meal could provide up to 200 g/kg of dietary protein without significantly reducing performance. Biological and economic performance of practical diets containing 300–500 g/kg of dietary protein from Moringa and cassava leaf blends with feeding stimulants was significantly lower than a fishmeal-based diet but comparable to a soybean meal-based diet. The suitability of cassava leaf meal as novel protein sources in Nile tilapia diets will depend on improving reduction/removal of inherent antinutritional factors as well as improving digestibility.

Sena et al. (2012) incorporated mesquite bean bran (*Prosopis juliflora*) and cassava leaf bran in Nile tilapia (85.22 $\pm$ 3.13 g) diets in a 2 $\times$ 4 factorial scheme for two sources of oil and four levels of bran (0, 5, 10 and 20%). After 60 days, growth performance (feed intake, weight gain, feed conversion, fish survival), fish body composition, and density of villi were not affected ($p > 0.05$) by the source and level of inclusion of bran. However, there was a significant effect of the level of inclusion of bran on villi height, with a linear trend, indicating that the higher the inclusion levels of bran, the lower the height of the villi. They concluded that cassava leaf bran studied can be used up to 20% without compromising growth performance and body composition change, but the presence of these by-products can result in a deleterious effect on fish villi.

Catfishes

Dry matter and protein digestibility values reported for cassava leaf meal in hybrid catfish (*C. macrocephalus* × *C. gariepinus*) are relatively high (76–79%), but lower than the digestibilities of groundnut meal and soybean meal (94–94%) (Tram et al. 2011). In African catfish fingerlings (12.57 g) fed isoenergetic and isonitrogenous diets where cassava leaves substituted for 0 to 100% maize grain (0–30% by weight of diet), the best growth response was at the 66.7% substitution level (20% of the total diet) (Bichi and Ahmad 2010). Full substitution (40% by weight of diet) depressed growth in hybrid catfish (*C. gariepinus* × *H. longifilis*) fingerlings (15 g) (Ekanem et al. 2010) and was caused by poor binding ability of the feed due to high fibre content, which resulted in leaching of nutrients in addition to poor palatability and hence reduced feed intake.

Bureau et al. (1995) incorporated cassava leaves and peanut vines in diets for African catfish in a 10-week experiment. Two groups of diets were used: one group used cassava chips as the main energy ingredient and cassava leaves as the crop residue, the other used corn as the energy ingredient and peanut vines as the crop residue. Each group had diets with 0% (control), 10 or 20% crop residue incorporation. Comparison of the two control diets (cassava-based or corn-based) showed that the cassava-based diet resulted in a significantly lower biomass and final weight ($P<0.01$) and higher FCR. There was no significant difference of biomass yield and final weight for the fish fed diets with 0, 10, and 20% cassava leaf meal-based diets. Fish fed 20% cassava leaf appeared to be more sensitive to diseases. Their mortality and FCR were significantly higher ($P < 0.01$) than those of the control. The results showed that a maximum of 10% cassava leaf meal can be incorporated in a cassava-chip diet.

Sutriana (2007) evaluated the effect of graded dietary levels of cassava leaf meal with varying cyanide content on growth performance of African catfish fry. There were four treatments namely, a control diet (0 mg HCN/kg diet) with fish meal and soybean meal as protein source (30% CP). Treatments 2, 3 and 4 were fed graded levels of cassava leaf meal to replace 10, 20, and 30% of the total diet at the expense of soybean meal which contained 4.19, 7.47 and 11.96 mg HCN/ kg diet, respectively. After 12 weeks, fish fed with increasing level of cassava leaf meal showed a significant growth depression and poor feed utilization compared to those fed with the control diet. Apparent dry matter digestibility (ADMD) and apparent protein digestibility (APD) were also significantly ($P<0.05$) affected by cassava leaf meal inclusion, with the best values were found in catfish fed the control diet (52.26+0.24% and 83.11+1.17% for ADMD and APD respectively). Body composition of fish fed higher cassava leaf meal tended to have less protein and fat but more ash. The poor methionine availability as a result of low protein digestibility and the presence of cyanide content limited the use of cassava leaf meal in African catfish fry diet.

Anyanwu et al. (2012) fed African catfish fingerlings (mean weight, 0.87 g) with 35% crude protein diets containing 0% (control) 10%, 20% and 30% inclusion levels of cassava leaf meal at 5% body weight for 56 days. Mortality ranged between 20 and 24%, the least observed in the control treatment while 20 and 30% were the highest. Daily feed intake and protein intake were not significantly ($p>0.05$) different. The control diet gave the highest body weight gain, followed by 20, 30 and 10%. Specific growth rate, feed conversion ratio and protein efficiency ratio for the control were significantly ($p<0.05$) better than other treatments.

Milkfish

Borlongan and Coloso (1994) fed milkfish (*Chanos chanos*) (mean weight, 0.3 g) for 12 weeks with isoproteic, isolipidic and isocaloric (40% crude protein, 10% crude lipid, 375 kcal/100 g) diets containing leaf meals derived from cassava, ipil-ipil (*L. lecocephala*), sweet potato (*Ipomea batata*) or swamp cabbage (*I. reptans*) replacing 15% of fish meal component in a control diet. Growth, feed conversion ratio, protein efficiency ratio and fish survival were not significantly different from those of fish fed with the control diet, and the best performance indices were recorded in the cassava leaf meal-based diet treatment. They opined that the leaf meals can partially replace fish meal in milkfish diets provided the dietary requirements for essential amino acids are met.

Pacu

Pacu (*P. mesopotamicus*) fed with diets containing increasing levels of cassava foliage meal in pond showed a progressive reduction in growth performance on the basis of final weight gain and specific growth rate (Padua et al. 1998).

Asian sea bass

Cassava leaf meal included at 13–18% in the diet Asian sea bass (*L. calcarifer*) gave lower growth than the control diet (Eusebio and Coloso 2000).

Prawns

In Indian prawns (*Fenneropenaeus indicus*, syn. *Penaeus indicus*) fed a soybean meal-based diet where cassava leaf meal replaced 9% of the protein, the test diet resulted in a non-significantly lower weight gain and growth rate and a significantly lower survival than the control diet (Eusebio and Coloso 1998).

Nutritive value of cassava leaf protein concentrate (CLPC) for aquaculture species

Bohnenberger (2008) evaluated the chemical composition and the apparent digestibility coefficients (ADC) from the dry matter (DM), gross energy (GE) and crude protein (CP) of cassava leaf protein concentrate (CPLC) for Nile Tilapia (mean weight, 86.92±36.70 g). The ADC from for DM, CP and GE were 32.49, 66.57 and 30.05, showing digestible protein and energy values of 32.23% and 1661.13 Kcal/kg. They suggested that Nile Tilapia used the protein of CLPC in an efficient way; however, while there was low efficiency in the use of energy. Data on the use of CLPC in livestock feeding are limited (Agbede 2006; Aletor 2010). Currently, least-cost cassava leaf meal-based and CPLC-based pelleted diets (cassava varieties: TME 419, TMS 98/0505, TMS 92/0326, TMS 30572 and TME 01/1368) are being formulated, characterized and are evaluated in Nigeria using tilapias (*T. guineensis, T. zillii, S. melanotheron, O. niloticus*) and catfishes (*C. gariepinus, C. anguillaris, H. bidorsalis, H. longifilis*) in nutritional trials using growth and economic performance, feed utilization, nutrient digestibility, with reports on the effects on haematology, physiopathology and histopathology of the fishes (Fagbenro et al. 2013).

Conclusions and recommendations

Summary of feed attributes of cassava and its by-products

The literature on the nutritive value of cassava products and by-products display a wide variation in the published values, often linked with inaccurate definition and characterization of the products evaluated. Results obtained from biological evaluation studies show that cassava from different origins, with regard to varieties, ages at harvest, edaphic and ecological conditions of plant growth, and processing methods, contain widely varying levels of nutrients, energy values and HCN content. Animal nutrition scientists need to more explicitly define the feed products used in studies to support realistic evaluations and comparisons. It is clear, from a variety of inputs, that cassava-based feeds require some care in balancing of nutrients, but particularly energy, sulphur-containing amino acids, phosphorus, zinc, iodine and vitamin B12 (for non-ruminants). Nonetheless, it is also undoubtedly clear that, depending on the quality and starch content, cassava root/tuber meal, with an energy value 85–93% that of maize grain, can replace cereals as an energy source for livestock or aquaculture feeding in Africa, provided it is supplemented with a nitrogen source. Cassava root meal may be included as a feed binder up to 30% level (DM) to improve the physical properties (pellet hardness, water stability) of feeds. Peels, with proper processing, may also provide energy feed ingredient substitute, as well as a better protein and amino acid profile compared with roots. Cassava leaves, in contrast, are a good source of protein, high in lysine but deficient in methionine and tryptophan, and are rich in vitamins and minerals (Ravidran 1991; Fasuyi 2000; Heuzé and Tran 2012). HCN content in any of these fractions may or may not be a problem, depending on the variety, process and livestock species. The use of a combination cassava residue for energy, with leafy material from the same plant, could produce a blend of nutrients that could largely substitute for cereals. The lower protein content of the residues could also be compensated for by better utilization of locally produced protein sources such as agro-industrial by-products (grain legumes, oilseed cakes). Protein quality can be improved by further processing cassava leaves into leaf protein concentrate. The processing of cassava residues into useful feedstuffs will further ameliorate the negative issues posed to the environment, as well as reduce human and public health hazards around cassava processing locations.

In spite of the considerable literature on the use of cassava for livestock feeding, limited information is available on the economic advantage resulting from its use. This is surprising because economic considerations are of paramount importance, since cereals can be replaced by cassava only if the nutritionally equivalent mixture of cassava with protein feedstuffs is cheaper than feed prepared with cereals (Müller and Chou 1974). Tiemoko (1992) showed that under the economic conditions in Cote d'Ivoire, the price of cassava must not exceed 75% of that of maize used as a reference, if it is to compete successfully with maize. If market prices of cassava in Cote d'Ivoire are considered, this condition is rarely met. The price paid for cassava is generally high and often greater than the price of maize. It seems that the opportunity cost of cassava for human consumption exceeds its value for livestock and fish feeding, at least among the rural populations of Africa. However, cassava is still a subsistence crop rather than a competitive commercial commodity because of the limited size of farms, the poor productivity of the crop (average of 6.5 t/ha), and the lack of facilities for efficient processing and distribution. The future utilization of cassava by-products in animal feeds depends very much upon the development of improved processing technologies and improved products.

Knowledge gaps

Recently, cassava has transformed from being a 'poor man's' crop to now a cash crop and an industrial crop, as cassava is being processed to products such as starch, flour, glucose and ethanol. While this transition has placed demands on cassava production, it is imperative that the growth continues. A major stimulus to continue that momentum would be an improvement in the cassava value chain. It is anticipated that with more complete use of all parts of a cassava stand through the reduction, recycling and reuse of cassava processing residues, cassava-growing regions and nations will benefit through increased production of cassava, as well poverty reduction through an increased income derived from cassava cultivation.

Complete utilization of the cassava plant in animal feeds will increase its cultivation and its economic importance; this will fill a gap in the value chain of this plant. In particular, improved incorporation of peel and root by-products, and/or further development of cassava products as commercial ingredient energy sources for livestock and fishes, in cassava producing areas, would relieve pressure on demand for available cereal grains. Further advancement of cassava leaf meal as a protein source for livestock, and especially cassava leaf protein concentrate for aquaculture, will reduce considerably the amount of fish meal inclusion in feeds for monogastric species. A reduction in the use of fishmeal will reduce the unit cost of feeds, and consequently result in higher profit margins, leading to increased animal production.

Although available, the biotechnology(ies) to harness the residues from cassava processing for economic use in livestock and aquaculture feed production has not been fully exploited due to inadequate implementation of research results and lack of development. Considering the substantial quantities of cassava peels and leaves currently being generated as by-product from primary cassava production (which is expected to increase in the years ahead), it has become imperative to evolve sustainable, easily adaptable, cheap and environmentally friendly modes for economic utilization of these fractions. Integrated systems of cassava waste disposal have been previously outlined (i.e. Okafor 1998), some aspects of which may have value in feed applications currently under consideration, and warrant re-examination. Sustainable drying techniques (i.e. Sanni et al. 2012), fermentation (Iyayi and Losel 1999; Boonnop et al. 2009) and more recent enzyme-based methods (Adesehinwa et al. 2011; Midau et al. 2011), leading to improved nutritional properties and utilization of cassava by products, have yet to be feasibility-tested at a commercial scale. Locally adaptable and cost-effective technologies that will enhance cassava residues, and increase their use in livestock and aquaculture feeds, will lead to reduction in the overall cost of feeds, and increase the affordability of animal protein with attendant reduction in protein undernutrition in human populations (Munguti et al. 2012).Apart from being a potential source of alternative feed ingredients, development of residue utilization has the immediate potential for employment generation, and environmental contaminant mitigation.

Three major areas of focus are identified to advance more comprehensive utilization of cassava and its by-products into improved animal feeding programs, encompassing a wide range of implementation time frames and complexity, as well as anticipated outcome/progress:

- Targeted processing technologies for economically harvesting and/or improving cassava by-products for integration into animal feeding programs
- Continued animal nutrition studies to ensure enhanced utilization
- Improved agronomic traits to optimize cassava productivity, considering yield as well as nutritional value.

Areas of future research potential and advocacy

Processing technologies

Technologies described below have, in general, already been developed and tested (for cassava or other by-products), thus offer rapid options for further targeted implementation/ development with cassava and its by-products.

- Fermentation treatments to alter nutrient content of cassava by-products (peels, root pomace) as feed ingredients should be conducted at various scales (local and/or commercial), as an add-on technology at gari, flour and/or starch processing plants. Appropriate and effective microbial/fungal cultures have been demonstrated to detoxify HCN, decompose cellulose and hemicellulose in cassava, as well as increase amino acids and vitamin content of various residues for use in livestock feeding programs. Standardized microbial blends, protocols for use, and feeding instructions for end product application should be developed and made available to farmer groups (smallholders) as well as feed millers.
- Enhanced, economic and sustainable solar/hybrid drying technologies for use with by-product fractions should be implemented within both small- and intermediate-scale cassava processing facilities, and encouraged at a commercial scale. Effective drying technologies have been developed and tested; drying will ensure improved stability and nutritive value of by-products for applied feeding programs, and enhances ease of transport and storage.
- In combination with fermentation (as described above), respiration biogases could be captured and utilized as sustainable fuel in solar/hybrid drying facilities.
- If cassava peels are not further utilized for animal feeding, residues should be mixed with lime, packaged, and marketed as soil amendment/fertilizer.
- Improved mechanized harvest of cassava leaves, integrated with drying technologies, might encourage further development of the use of dried leaf fractions as well as leaf meal concentrate, as protein sources in livestock and aquaculture feeds, particularly if standardized drying techniques are shown to minimize cyanogenic and trypsin inhibitor potentials.
- On an industrial scale, development of fungal-based refineries may be linked to improved cassava by-product utilization through fermentation, but also have broader capacity beyond immediate applied livestock feeding programs including production of amylases, cellulases, phytases, and proteases as feed ingredients, biomass production in the form of single cell proteins (feed ingredients high in amino acids, lipids, and chitosan), biodiesel production, corticosteroid drugs, and industrial metabolites such as lactic and fumaric acid and ethanol (Ferreira et al. 2013).

Animal nutrition studies

Based on existing literature information, a number of commercial products could be successfully formulated and/ or marketed in support of cassava-based livestock and /or aquaculture feeding programs.

- Cassava root by-products can clearly substitute for grain as an energy source, and leaves as a partial protein replacement in animal agriculture; a goal would be to economically obtain and incorporate processed (detoxified, dried) quantities of standardized by-products of known quality and detailed nutritional profiles into on-farm or commercial feed production operations.

    - Although detoxified cassava products and by-products can be safely used in feeds, it is difficult to establish a maximum level of usage due to inconsistencies in variables such as definition of product types and test conditions. Standardization of ingredient descriptions and nutrient composition must become an immediate priority.
    - Cassava residues that require further evaluation and validation in aquaculture nutrition research include starch (feed/pellet binder), root meal (energy source), peels (carbohydrate and energy sources), leaf meal and leaf protein concentrate (protein sources). The harmonization of current analytical and presentation methods is therefore strongly recommended; analytical data would apply for other livestock species as well.
    - Inclusion of cassava by-products depends on price and availability of energy and protein sources, synthetic amino acids, and pigments.
    - Sulphur amino acid supplementation may need to be increased to provide a readily available source of labile sulphur for cyanide detoxification, and to provide a margin of safety for these amino acids.
    - The level of inclusion of cassava root meal is dependent on the quality of supplemental protein. Particularly for aquaculture, animal proteins are good sources of methionine and vitamin B12, which serve as independent pathway for cyanide detoxification.
- Composite pellets, comprising both leaf and root/peel fractions for nitrogen and energy, respectively, properly balanced with trace minerals, sulphur amino acids (specifically Met) and tryptophan, as well as oil (palm oil 3%) and cocoa husk and/or rice bran (1%) has been demonstrated successful in feeding poultry and swine.
    - Pelleting decreases the bulkiness of cassava-based diets by about a third, overcomes the problem of dustiness, and ensures an optimum feed intake. Feed attractants or oils can be added to improve palatability and feed consumption.
- Use of feed enzyme additives (either cocktail or solitary products/blends including phytase, carbohydrases, amylase, and protease) should be economically available to the farmer to encourage improved on-farm digestion/utilization of cassava by-products, particularly applicable for swine and poultry.
- Similarly, appropriate fermentation cultures and technologies for on-farm application to produce optimal silage from cassava by-product(s) should be developed for feeding hoofstock.
- For on-farm usage, slow-release urea (with calcium sulphate) appears to be a promising technology to complement rapidly-fermenting carbohydrates from cassava peels and/or root fractions for ruminant diets. Field testing in Africa should commence.
- Standardization of evaluation parameters and methodologies for nutritional studies using local/native aquaculture and livestock species of commercial importance in different regions of Africa is recommended.
    - The research will provide reliable data on nutritional performance (growth, feed utilization), nutrient (protein, energy) digestibility, economic performance, and examine the effects on physiology, pathology and haematology of test species. This is followed by conduct of field trials and wide dissemination of results through regional, national and local workshops.

Improved agronomic traits

Advances in cassava cultivation should maintain focus on both yield and nutritional parameters as targets of emphasis. Integration of these characteristics will provide benefits to animal health and productivity, thus indirectly as well as directly impacting human populations that rely on cassava as a staple food. These actions/activities may take longer to develop, but have the capacity for extended, sustainable impact.

- Put in place policies such that production in excess of direct human consumption, and by-product residues, will become prioritized and available for livestock and aquaculture feeding in Africa.
- Establish plantations of current cassava cultivars that result in optimum animal production (growth, feed utilization, nutrient digestibility and economic performance) with emphasis on the expanded program of cassava and many high yielding varieties of cassava that have been developed and released through the improvement efforts of IITA, CIAT and other collaborating institutions (see Appendix 1).
- Develop new improved varieties to boost regular supply of cassava products and residues to meet the increasing demand.
    - Identify, designate and brand cultivars that generate high volumes/quantities of products and residues, with sustainable and environmentally friendly cultivation techniques, including possible impact of organic or inorganic fertilizers.
    - Continuous breeding of such improved new varieties will stabilize production, processing and marketing of cassava products. These efforts will impact rural employment and establish a virile cassava industrial sector.
- Targeted plant breeding programs for productivity, disease, and drought-resistance traits in cassava should clearly continue; results, however, should be evaluated with respect to overall nutritional and antinutrient content (Mahungu 1994) as well as harvest volumes. The scope for genetic diversity is high, and targeting specific nutrients (i.e. protein) to better compete with grains (for animal feeding) and improve protein overall (for human nutrition) is an important consideration.

Further exploration of genetic pathways between HCN and Sulfur AAs is needed.

- Towards the above objective, global biotechnologies/genetic modification efforts for nutrient biofortification (increased ß-carotene, protein, minerals; Stupak et al. 2006) and lower cyanide levels in cassava should ensure that other nutrients are not simultaneously compromised. It might further be important to:
    - Evaluate efficacy of biofortified carotenoid cassava(s) in depositing pigment in eggs, milk, meat of livestock, and transfer to human health effects through the food chain.
    - Examine influence of ß-carotene isomer formation during processing on later utilization/efficacy.
    - Evaluate means of altering mineral content, particularly zinc, through cultivation and/or organic or inorganic fertilization treatment.

Cassava analysis

In support of the focus areas suggested above (process technologies, animal nutrition studies, and improved agronomic traits), we recommend:

- Periodic inventory of national cassava production and volume of residues available from processing industries should be undertaken in order to ascertain year-round availability.
- Establishment of national cassava residue banks/collection centres.
- Development of a centralized global database of cassava nutritional and production characteristics to allow meta-analysis as a discrimination tool of most promising cultivars for rapid implementation/ adaptation into animal feeding programs. Specifically, more detailed information is required concerning:

  - Cultivar and seasonal variations in feed attributes of cassava by-products (both peels and foliage)
  - Standardized methodology for assessment of cyanide in cassava (incorporating both free and bound HCN)—possibly through near infra-red spectroscopy (NIRS)
  - Amino acid composition in peels and/or correlation with pulp data as a predictive tool
  - Specific soluble and insoluble carbohydrate constituents in cassava peels as substrate for optimized fermentation / enzyme technologies
  - Standardization of conversion of N to crude protein in cassava and its various fractions
- Lastly, post-harvest storage issues could be addressed by examining the impact of elevated endogenous antioxidants in cassava (ß-carotene, polyphenolics) on product stability/shelf life; both raw ingredients and processed end products may be affected by these constituents, in both animal feeds and human foods.

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Appendix 1 Improvements in cassava (*M. esculenta*) variety and productivity in Nigeria

Over the last decade, cassava has evolved in Nigeria from a mere food security crop to a cash and industrial crop, with a strong focus on agronomic traits. The impact of improved cassava varieties, in comparison to traditional varieties, can be assessed against four broad parameters: yields; resistance to drought and disease; the maturation period, and household levels of consumption. Over 7000 cassava varieties exist, which can be divided into two main groups; 1) bitter and 2) sweet varieties. Roots of the bitter varieties contain 0.02–0.03% hydrogen cyanide/hydrocyanic acid (HCN) on dry matter (DM) basis, and leaves contain up to 0.2% DM on a fresh weight basis. Farmers often prefer the bitter varieties because they deter pests, animals, and thieves. Sweet varieties have roots containing <0.01% HCN and leaves containing about 0.1% HCN; most commercial varieties belong to this latter group. Scientists at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria, pioneered the development of improved cassava varieties which are disease- and pest-resistant, low in HCN content, drought-resistant, early maturing, and high yielding. Disease-resistant varieties give sustainable yields of about 50% more than local varieties.

In January 2011, the Nigerian government released four improved cassava varieties namely, NR 01/0004, CR 41-10, TMS 00/0203, and TMS 01/0040 (IITA 2011). On-farm pre-release trials involving farmers showed that the improved varieties out-performed local varieties with an average yield of 31 t/ha compared to 26 t/ha recorded by the local varieties (IITA 2011). Farmers greatly appreciate the new varieties for their excellent culinary qualities, high yield, and resistance to pests and diseases. TMS 00/0203 and TMS 01/0040 were bred by scientists at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria, while NR 01/0004 and CR 41–10 were bred at the National Root Crops Research Institute (NRCRI), Umudike, Nigeria, and the International Center for Tropical Agriculture (CIAT), Colombia, respectively.

Two further improved cassava varieties that were developed through collaborative effort between IITA and NRCRI were released (IITA 2013) in January 2013. Both varieties were originally recognized as IITA developed genotypes: IITA–TMS–I982132 and IITA–TMS–I011206; but with the official release, they are known as UMUCASS 42 and UMUCASS 43, respectively. Both varieties performed well in pre-varietal release trials conducted between 2008 and 2010 in different cassava growing regions of Nigeria, with high yield, high dry matter and good disease resistance. The roots of both varieties are yellow and contain moderate levels of pro-vitamin A activity. Potential maximum yield of both varieties is 49–53 t/ha, while local varieties typically yield <10 t/ha. These new varieties are also resistant to major pests and diseases that affect cassava including cassava mosaic disease, cassava bacterial blight, cassava anthracnose, cassava mealybug and cassava green mite. The varieties have the following distinct qualities: they produce high quality cassava flour, high in dry matter which is positively related to starch content and crucial for cassava value chain development; they display high leaf retention which is related to drought tolerance and is crucial for cassava production in the drier regions and in mitigating the impact of climate change; and they contain moderate levels of β-carotene for enhancing nutritional value.

Similarly, after a five-year multi-locational testing program spanning all the cassava growing areas, the Ghanaian government recommended three of the best IITA cassava varieties for adoption by farmers in that country. The varieties TMS 30572, TMS 4(2)1425, and TMS 50395 were given local names that mirror their characteristics and food qualities both in the farmers' fields and when processed (Babaleye 1996). In October 2013, the Cameroonian government released five new improved cassava varieties to help improve the food security in Cameroon. The varieties, which were developed through conventional breeding by the IITA and partners, are recognized as IITA genotypes as TMS 92/0326, TMS 96/1414, TMS 96/0023, TMS 92/0057, and TMS 92/0067. With an estimated yield of between 20 and 35 t/ha (Sankoh 2013), the improved varieties have improved nutritional qualities and are rich in carotenoids, iron and zinc. Partners that worked in the varietal development include the Programme National de Developpement des Racines et Tubercules (PNDRT), the Institute of Agricultural Research for Development (IRAD), the International Fund for Agricultural Development (IFAD), non-governmental organizations and local farmers. The varieties are expected to help close the yield gaps, improve yield and also put more money in farmers' pockets. Farmers who participated in the varietal release process 'loved' the varieties for their cooking qualities.

Appendix 2 Environmental impact of cassava production and processing

Most cassava is produced by smallholder farmers living in marginal and fragile environments, and particularly on erosion-prone, acid and infertile soils. This ability to produce on poor soils, where most other crops would fail, has given cassava a possibly undeserved reputation. However, there are serious environmental concerns about cassava production (FAO 2001). Cassava production can be detrimental to soil fertility through crop removal of nutrients. Due to the low value of cassava products, the application of manures and chemical fertilizers, which could easily address nutrient depletion, may not be economically justified or affordable for smallholders. However, at current yield levels, soil nutrient depletion by cassava is lower than depletion caused by other crops (FAO 2001).

Cassava production can result in serious erosion when the crop is grown on slopes or on light soils. Good agronomic practices (adequate fertilization, closer plant spacing, planting on contour ridges, intercropping, reduced tillage), used alone or in combination, reduce erosion by 50–90% and properly managed cassava production on slopes does not necessarily cause erosion (FAO 2001). It is considered unlikely that cassava production results in water pollution, as it is grown mainly by poor farmers who apply no or very low rates of fertilizers, pesticides and herbicides. However, this may change in the future (FAO 2001). Cassava production does not seem to have had broad effects on biodiversity, though some local situations merit further attention, such as deforestation in the northeast of Thailand or the competition with native cassava species in Latin America (FAO 2001).

Cassava processing produces large amounts of by-products and contributes significantly to environmental pollution (FAO 2001). A cassava starch production unit processing 100 t of tubers/day may produce 47 t of fresh by-products, which may cause environmental problems when left in the surroundings of processing plants or carelessly disposed of (Aro et al. 2010). In Nigeria, for example, cassava residues are mainly left to rot away or burnt off to create space for the accumulation of new generations of waste heaps, emitting carbon dioxide and producing a strong offensive smell (Adebayo 2008; Aro et al. 2010). Cassava peels (high levels of cyanogenic glucosides) and pomace (high levels of biodegradable organic matter) may cause surface water pollution, especially when stored under heavy rain or disposed of in surface waters (Cereda et al. 1996; Barana and Cereda 2000; Pandey et al. 2000).

The presence of a large processor or of a high concentration of small processors can cause the eutrophication of slow moving water systems, notably during the dry season (FAO 2001). On the other hand, cassava processing does not seem to affect groundwater supply, except perhaps in the immediate surroundings of processing units due to leachates filtering through the soil (FAO 2001). Starch extraction requires large volumes of water and may cause water depletion, but in most areas this problem is minimized by the adoption of processing technologies suited to the water resources available (FAO 2001). Generally, the long-term and broad-based impact of cassava processing on the environment can be corrected by proper waste treatment (FAO 2001) and the use of cassava by-products as feedstuffs or as an alternative substrate for biotechnological processes is a good way to alleviate environmental issues (Pandey et al. 2000).

Table A1. Nutritional composition of cassava (*M. esculenta*) by products used in livestock feeding programs

Fraction	Variety	Locale	Treatment	Age	DM	Crude protein	Digest protein	ADSCP or Sol CP	Crude fat or EE	Crude fiber	NDF	ADF	AD lignin	NFC	Starch (polar-imetry)	Total sugars	NFE	Ash	Energy (gross)	Reference
Unit (dry basis)					%	%		%	%	%	%	%	%	%	%	%	%	%	MJ/kg	
Leaf meal concentrate	*M. utilissima*	Nigeria	Pulped fresh, pressed, heat extracted, sun dried			34.56														Eggum, 1970
Leaf meal concentrate	MS6	Akure, Nigeria	Pulped fresh, pressed, heat extracted, sun dried			42.4			19.4	2.3							23.5	7.3	520	Fasuyi and Aletor 2005
Leaf meal concentrate	TMS 30555	Akure, Nigeria	Pulped fresh, pressed, heat extracted, sun dried			46.4			22.8	2.6							14.7	6.8	539.9	Fasuyi and Aletor 2005
Leaf meal concentrate	TMS 30572	Akure, Nigeria	Pulped fresh, pressed, heat extracted, sun dried			50			21.6	1.8							11.5	9.3	536.2	Fasuyi and Aletor 2005
Leaf meal concentrate	Ege Oda	Akure, Nigeria	Pulped fresh, pressed, heat extracted, sun dried			49.3			22.4	1.4							14.1	7.9	500.8	Fasuyi and Aletor 2005
Leaf meal concentrate	Pão da China (31)	Lavras, Brazil	Heat extracted, 80 C 15 min			54			17	0							26	2.2		Modesti et al. 2007
Leaf meal concentrate	Pão da China (33)	Lavras, Brazil	Acid extracted, pH 4			54			17.3	1.6							24	2.2		Modesti et al. 2007
Average						**47.2**			**20.1**	**1.6**							**19.0**	**6.0**		
Leaf meal concentrate residue	Pão da China	Lavras, Brazil	Heat extract residue		9.5	19.8			7	47.9							19.6	5.7		Modesti et al. 2007
Leaf meal concentrate residue	Pão da China	Lavras, Brazil	Acid extract residue		10.6	19.1			6.7	41							27.5	5.6		Modesti et al. 2007
Leaf meal						21						25						8.5		Ravindran 1993

Leaf meal	WT (wild type)	Puerto Rico	Stored frozen, dried, ground		92.2	31.24	40.00	7.05	20.39	19.85	8.35	39.59	6.29	Mutayoba et al. 2012
Leaf meal	p770	Puerto Rico	Stored frozen, dried, ground		92.4	30.84	22.00	7.65	22.12	21.53	9.06	42.94	6.82	Mutayoba et al. 2012
Leaf meal	p768	Puerto Rico	Stored frozen, dried, ground		91.4	23.30	18.00	6.13	28.77	28.45	9.85	37.20	7.77	Mutayoba et al. 2012
Leaf meal	Ouro do Vale	Lavras, Brazil	Shade dry, no petiole, 40 mesh	12 months	90.8	29.2			24.1					Wobeto et al. 2006
Leaf meal	Ouro do Vale	Lavras, Brazil	Shade dry, no petiole, 40 mesh	15 months	90.8	28.7			22.5					Wobeto et al. 2006
Leaf meal	Ouro do Vale	Lavras, Brazil	Shade dry, no petiole, 40 mesh	17 months	90.8	25.1			21.6					Wobeto et al. 2006
Leaf meal	Maracanã	Lavras, Brazil	Shade dry, no petiole, 40 mesh	12 months	90.8	33.3			24					Wobeto et al. 2006
Leaf meal	Maracanã	Lavras, Brazil	Shade dry, no petiole, 40 mesh	15 months	90.8	26.2			23					Wobeto et al. 2006
Leaf meal	Maracanã	Lavras, Brazil	Shade dry, no petiole, 40 mesh	17 months	90.8	24.7			22					Wobeto et al. 2006
Leaf meal	MANTIAC	Lavras, Brazil	Shade dry, no petiole, 40 mesh	12 months	90.8	32.7			24.8					Wobeto et al. 2006
Leaf meal	MANTIAC	Lavras, Brazil	Shade dry, no petiole, 40 mesh	15 months	90.8	26.5			26.9					Wobeto et al. 2006
Leaf meal	MANTIAC	Lavras, Brazil	Shade dry, no petiole, 40 mesh	17 months	90.8	24.1			25.7					Wobeto et al. 2006
Leaf meal	IAC 289-70	Lavras, Brazil	Shade dry, no petiole, 40 mesh	12 months	90.8	36.2			28					Wobeto et al. 2006

Leaf meal	IAC 289-71	Lavras, Brazil	Shade dry, no petiole, 40 mesh	15 months	90.8	24.9					29.6				Wobeto et al. 2006
Leaf meal	IAC 289-72	Lavras, Brazil	Shade dry, no petiole, 40 mesh	17 months	90.8	23.3					28.3				Wobeto et al. 2006
Leaf meal	Mocotó	Lavras, Brazil	Shade dry, no petiole, 40 mesh	12 months	90.8	35.9					23.6				Wobeto et al. 2006
Leaf meal	Mocotó	Lavras, Brazil	Shade dry, no petiole, 40 mesh	15 months	90.8	24.7					28.1				Wobeto et al. 2006
Leaf meal	Mocotó	Lavras, Brazil	Shade dry, no petiole, 40 mesh	17 months	90.8	27.2					24.5				Wobeto et al. 2006
Leaf meal	MS6	Abeokuta, Nigeria	Shade dried, milled 1 mm		90	23.5		7.3			59.6	29.3		1.6	Oni et al. 2010
Leaf meal	TMS 30555	Abeokuta, Nigeria	Shade dried, milled 1 mm		88.4	24		6			61.3	27.9		1.6	Oni et al. 2011
Leaf meal	TMS 30572	Abeokuta, Nigeria	Shade dried, milled 1 mm		90.1	20.8		7			61.3	25.4		6.5	Oni et al. 2012
Leaf meal	Idileruwa	Abeokuta, Nigeria	Shade dried, milled 1 mm		89.1	17.7		6.6			66.2	24.5		1.5	Oni et al. 2013
Leaf meal	61584 Ohupon (bitter)	Nigeria	Sun dried			35		5.96	11.76				42.04	5.2	Eggum, 1970
Leaf meal	GCH (bitter)	Nigeria	Sun dried			37.4		6.08	10.96				39.87	5.96	Eggum, 1970
Leaf meal	44086 Congo (Panja sweet)	Nigeria	Sun dried			32.85		5.74	11.38				44.79	5.34	Eggum, 1970
Leaf meal	Pão da China	Lavras, Brazil	Dried ambient temp 6 days, rinsed, ground		74.6	34	28.4	12	21.4				25	6.5	Modesti et al. 2007
Leaf meal	Short term	Phnom Penh, Cambodia	Sun dried 3 days; ground 5 mm	2 months	88.4	21.4			12.5		32	22.9		9.4	Borin et al. 2005
Leaf meal	Long term	Phnom Penh, Cambodia	Sun dried 3 days; ground 5 mm	2 months	88.9	22.9			13.6		35.6	26.4		7.4	Borin et al. 2005

Leaf		Umudike, Nigeria	Sun dried 3 days		93	25.1			5.5	7.9							51.9	6.1	1.8	Ukanwoko et al. 2009
Leaf	KM95 (bitter)	Vietnam	Sun dried		91.2	30.9		28.8												
Leaf	KM94 (bitter)	Vietnam	Sun dried		91.2	27.7		30.4												
Leaf	Sweet	Vietnam	Sun dried		92.1	31.3		31.9												
Leaf	White Rose (H226)	Tamil Nadu, India	Shade dry, ground 1 mm			19.2			10.6	20.6	48.4	31.6	9.2				39.4	9.3		Murugeswari et al. 2006
Leaf	Mulluvadi (MVD-1)	Tamil Nadu, India	Shade dry, ground 1 mm			21.9			9.7	14.7	42.7	27.6	6.6				46.6	8.1		Murugeswari et al. 2009
Leaf, dry		Thailand		3–4 months	90	25	18.3		5.9		29.6	24.1	4.7				44.2	10		Wanapat 2003
Hay		Thailand		3–4 months	86.3	25	22		6.2		44.3	30.3	5.8				48	12.5		Wanapat 2003
Leaf hay	White Rose (H226)	Tamil Nadu, India	Shade dry 2 days			20.7			9.8	19.9	47.7	30.5	9.3				42.5	8.8		Murugeswari et al. 2008
Leaf hay	Mulluvadi (MVD-1)	Tamil Nadu, India	Shade dry 2 days							14.7	43.6	27.6	7.6				47.6	7.9		Murugeswari et al. 2011
Literature average					**90.0**	**27.0**	**22.9**	**28.5**	**7.4**	**14.5**	**34.0**	**26.4**	**7.8**	**39.9**			**42.9**	**6.8**	**1.8**	
Foliage, dehydrated	**n = 3 to 27**	**Global database**			**89.6**	**25.5**			**7**	**17.1**	**42.2**	**31**			**1.7**	**4.9**		**8.4**	**19.7**	**Heuzé 2012**
Leaf, fresh		Thailand	Harvest 1 month and 2 months		16.4	28.5					42.7	25.9	10.4					7.7		Wanapat 2003
Leaf, fresh		Thailand	Harvest 2 months and 2 months		18.8	24.2					48.3	31	11.8					6.7		Wanapat 2003
Leaf, fresh		Thailand	Harvest 4 months and 1 month		18.9	28.7					49.2	32.1	12.6					7		Wanapat 2003
Leaf, fresh		Thailand	Harvest 4 months and 2 months		22.4	20.8					56	38	13.6					5.2		Wanapat 2003
Leaf, fresh	KM95 (bitter)	Vietnam	Fresh		26.4	33		28.8												

Leaf, fresh	KM94 (bitter)	Vietnam	Fresh		27.5	26.1	30.4									
Leaf, fresh	Sweet	Vietnam	Fresh		24.2	33.4	31.9									
Leaf, fresh		Vietnam	Fresh		26.2	23.3								15.4		Tram and Preston 2004
Literature average					**22.6**	**27.3**	**30.4**			**49.1**	**31.8**	**12.1**		**6.7**		
Foliage, fresh	**n = 4 to 54**	**Global database**			**22.5**	**24.9**		**6.8**	**17.7**	**42.3**	**27.2**	**9.4**		**7.4**	**19.9**	**Heuzé 2012**
Leaf, wilted		Vietnam	Wilted 8 hr in shade and overnight		60.5	23.1								12.2		Tram and Preston 2004
Leaf silage	Sweet	Tanga, Tanzania	Silage, pH 4.85		42.9	21.9	47.8			55.6	42.9					Kavana et al. 2005
Leaf silage		Cambodia	Harvest 2 months, pH 4		38.5	24.5				25.4						Chhay Ty et al. 2003
Leaf silage		Cambodia	Harvest 5 months, pH 3.9		34.2	23.6				23.5						Chhay Ty et al. 2003
Leaf silage	White Rose (H226)	Tamil Nadu, India	Wilted 3 hr, chop, pH 4.8			18.8		10.1	21.2	46.5	29.7	8.2	39.4	9.6		Murugeswari et al. 2007
Leaf silage	Mulluvadi (MVD-1)	Tamil Nadu, India	Wilted 3 hr, chop, pH 4.7			20.3		9.5	16.1	43.6	28.8	7.9	44.2	8.1		Murugeswari et al. 2010
Leaf silage	Short Term	Phnom Penh, Cambodia	Ensiled (wilted 1–2 h, chopped 3–6 mm)	2 months	49.5	20.8			14.4	34.9	24.1			10.6		Borin et al. 2005
Leaf silage	Long Term	Phnom Penh, Cambodia	Ensiled (wilted 1–2 h, chopped 3–6 mm)	2 months	53.5	20.7			14.7	35.3	23.5			5.7		Borin et al. 2005
Leaf silage		Vietnam	Silage, pH 3.5–4.0; 14 days		34.5	25.6		10.5	16.8							Du Thanh Hang 1998
Literature average					**42.2**	**22.0**	**47.8**	**10.0**	**16.6**	**37.8**	**29.8**	**8.1**	**41.8**	**8.5**		
Foliage, ensiled	**n = 2 to 8**	**Global database**			**24.4**	**23.8**		**8.3**	**17.9**	**42.5**	**30.3**	**8.4**		**7.9**	**20**	**Heuzé 2012**

Peel	Sweet	Akure, Nigeria	Innoculated fermented	93.6	21.5		2.1	11.7				51.1			7.2		Oboh 2006
Peel	Sweet	Akure, Nigeria	Naturally fermented	94.3	11.1		3.5	6.5				67.3			6		Oboh 2006
Peel	Sweet	Akure, Nigeria	Unfermented	94.9	8.2		3.1	12.5				64.6			6.4		Oboh 2006
Peel	Bitter																Tewe 1991
Peel	Sweet																Tewe 1991
Peel meal			Dried, ground	88.7	4.35		0.2	12						71	1		Nwokoro and Ekhosuehi, 2005
Peel		Ogbomoso, Nigeria	Dried	85.7	3.28		1.72	17.18	52	28.47				70.78	19.2	5.73	Asaolu et al. 2012
Peel		Umudike, Nigeria	Sun dried 3–5 days	87.6	4.9		2.1	16.6						71	8.5	1.82	Ukanwoko et al. 2009
Peel	WT (wild type)	Puerto Rico	Stored frozen, dried, ground	94.6	3.2	59.0	2.2		12.2	9.0	0.8	79.3			4.3		Mutayoba et al. 2012
Peel	p770	Puerto Rico	Stored frozen, dried, ground	90.5	14.9	91.0	3.8		20.7	14.8	2.4	55.9			6.9		Mutayoba et al. 2012
Peel	p768	Puerto Rico	Stored frozen, dried, ground	91.9	12.5	86.0	2.6		20.0	15.0	3.3	60.5			6.4		Mutayoba et al. 2012
Peel	p746	Puerto Rico	Stored frozen, dried, ground	92.9	8.0	80.0	2.2		15.6	12.6	2.7	69.9			5.9		Mutayoba et al. 2012
Peel		Nigeria	Dried	89.2	5.6		1.0	20.9	23.7	14.2				67.6	4.9		Asaolu et al. 2012
Literature average				**90.1**	**7.1**	**79.0**	**2.0**	**15.3**	**24.0**	**15.7**	**2.3**	**66.4**		**70.9**	**7.1**	**3.8**	
Peel, dehydrated	**n = 1 to 8**	**Global database**		**87.4**	**5.2**		**1.4**	**14**	**51.4**	**37.4**	**8.4**				**5.8**	**19.5**	**Heuzé 2012**
Peel, fresh	**n = 2 to 7**	**Global database**		**28.2**	**4.8**		**1.3**	**21**	**19.6**	**17.1**	**7.2**				**5.7**	**17.7**	**Heuzé 2012**
Tuber	WT (wild type)	Puerto Rico	Stored frozen, dried, ground	97.4	2.4	75.0	0.9		5.5	3.2	0.6	86.8			2.3		Mutayoba et al. 2012
Tuber	p770	Puerto Rico	Stored frozen, dried, ground	88.9	4.7	91.0	1.2		6.3	3.8	1.2	86.2			2.2		Mutayoba et al. 2012

Tuber	p768	Puerto Rico	Stored frozen, dried, ground	94.2	5.5		83.0	1.1		8.5	6.5	1.2	81.7				4.0		Mutayoba et al. 2012
Tuber	p746	Puerto Rico	Stored frozen, dried, ground	94.2	8.6		91.0	1.4		11.1	8.5	0.6	73.4				6.5		Mutayoba et al. 2012
Pulp, dehydrated		Thailand	Collected from 5 starch plants	88.5	2.4			0.4	14	40.6	27.7			50.2			5.8	16.1	Kossom et al. 2009
Pulp, dehydrated		Thailand	Dried	93.2	2.10	63.68		0.14	14.60					57.5			3.0		Khempaka et al. 2009
Pulp, dehydrated					1.55			0.12	27.75	36.7	9.8	3.9		69.9			1.7		Sriroth et al. 2000 in Khempaka et al. 2009
Tuber chip silage		Vietnam	Silage	42	2.25				2.5										Hang 1998
Composite pellet		Ibadan, Nigeria	Whole tuber, leaf and petiole	89.8	10.5			1.4		23.4						57.6	6.7		
Literature average				**92.7**	**3.9**	**63.7**	**85.0**	**0.7**	**18.8**	**18.1**	**9.9**	**1.5**	**82.0**	**59.2**			**3.6**	**16.1**	
Tubers, de-hydrated	**n = 50 to 3354**	**Global database**		**87.6**	**2.9**			**0.7**	**3.9**	**8.0**	**5.4**	**1.7**		**80.4**	**2.4**		**3.9**	**16.8**	
Tubers, Fresh	n = 11 to 12	Global database		37.8	2.6			0.8	3.7	7.8	5.3	1.6		80.8			2.8	17.1	
Tubers, Peeled, Fresh	n = 2			28.5	2.2			0.6	1	3.7	1.6	0					3.8	16.7	
Pomace, dehydrated	n = 1 to 12			89.2	2.2			0.6	16.7	36.7	19.3	3.6		52.3	3.3		4.3	16.2	
Pomace, fresh	n = 2			13.1	1.7			1.3	17.7								3.7	17.7	
Sievate, dehydrated	n = 18			86.8	1.1			0.7	2.4	29	2.1			72.5			1.2	17.2	

All values (except dry matter (DM) on a DM basis.

Table A2. Amino acid concentrations in tubers from Brazilian cassava (*M. esculenta*) hybrids

Fraction	Variety	Locale	Treatment	Crude protein (N × 3.24)	Crude protein STD calc (N × 6.25)	Asp	Thr	Ser	Glu	Gly	Ala	Cys	Val	Met	Iso	Leu	Tyr	Phe	Lys	His	Arg	Pro
						Amino acids expressed as % of crude protein (calculated as N × 3.24)																
Tuber	ICB 300-34	Brasilia, Brazil	Freeze-dried	5.78	11.15	5.2	0.8	0.7	58.5	0	0	21.1	2.4	0	0.3	0.3	0	0	0	0	10.7	0
Tuber	ICB 300-18	Brasilia, Brazil	Freeze-dried	5.71	11.01	4.9	2.4	2.7	43.7	2.6	14.2	0.9	2.5	1.4	1.3	1.9	0	3.1	1.7	3.2	10.5	3
Tuber	ICB 300-38	Brasilia, Brazil	Freeze-dried	5.64	10.88	3.5	2.2	2.9	30.3	2.8	9.8	3.3	0	0.9	1	1.5	0	1.4	10.2	5.3	21.1	3.9
Tuber	ICB 300-12	Brasilia, Brazil	Freeze-dried	5.33	10.28	7.5	3.9	4.5	21.6	0	8.2	20.2	3.4	0.4	1.8	4.5	0	3.7	0.9	0	19.2	0
Tuber	ICB 300 TE	Brasilia, Brazil	Freeze-dried	5.09	9.82	7.8	2.4	4.5	3.1	15.2	1.1	2.9	1.6	1.3	2.1	0	4.4	1.9	5	19.4	7.5	
Tuber	ICB 300-7	Brasilia, Brazil	Freeze-dried	4.35	8.39	5.2	2.2	3.4	22.2	2.9	14.11	0.9	2.4	1.1	1.2	1.8	0	2.9	2.2	4.5	28.5	4.5
Tuber	ICB 300-17	Brasilia, Brazil	Freeze-dried	3.88	7.48	2.8	2	2.6	23.3	2.7	11	2.1	0.3	0.7	1.1	1.6	0	1.5	8	4.6	33.3	2.6
Tuber	ICB 300	Brasilia, Brazil	Freeze-dried	3.5	6.75	3.2	1.5	2.5	34	1.6	7.8	3.5	3.1	3.3	1.9	2.5	0	2.9	1.6	5.7	23.8	1
Tuber	ICB 300-3	Brasilia, Brazil	Freeze-dried	3.44	6.64	3.7	2.7	4.8	45.9	1.9	6.9	0.6	2.6	0.9	1.3	1.3	0	1.9	1.7	2.8	17.7	3.3
Tuber	ICB 300-37	Brasilia, Brazil	Freeze-dried	3.42	6.60	10.6	1.1	2.2	26.5	2.7	1.7	8.7	2.4	4.5	0.6	0.7	0	2.4	1.6	0	34.4	0
Tuber	ICB 300-5	Brasilia, Brazil	Freeze-dried	3.06	5.90	3.7	2.2	3.2	28.4	2.1	6.8	5	4.7	4.7	2.4	3.2	0.9	3.3	1.9	3.8	23.1	0.6
Tuber	ICB 300 TE-2	Brasilia, Brazil	Freeze-dried	2.56	4.94	4	2.3	3.2	2.5	12	1	2.8	1.6	1.3	2	0	3.2	2	2.7	20.2	3.8	
Tuber	ICB 300 TE-12	Brasilia, Brazil	Freeze-dried	2.51	4.84	7.3	2.1	2.6	2.5	10.4	0	2.7	0.6	1.2	1.9	0	2.5	1.3	4.1	6.9	4.4	
Tuber	ICB 300-10	Brasilia, Brazil	Freeze-dried	2.5	4.82	5.5	3.4	2.7	33.3	3.1	14.9	0.8	2.5	1.6	1.6	1.9	0	3.1	1.9	3.2	15.2	5.1
Tuber	ICB 300 TE-15	Brasilia, Brazil	Freeze-dried	2.36	4.55	6.8	2.3	3.7	3	10.8	1.2	2.7	1.7	1.4	2.1	0	2.1	1.6	2.6	4.5	7.6	
Tuber	530 (local) cultivar	Brasilia, Brazil	Freeze-dried	2.3	4.44	4.1	1.6	2.6	51.9	2.3	8.5	1.1	2.4	1.5	0.9	1.3	0	1.9	1.8	3.9	12.2	2
Tuber	ICB 300 TE-10	Brasilia, Brazil	Freeze-dried	2.29	4.42	5.1	3	4.6	5.3	16.7	1.8	4.2	2.1	1.9	3	0	3.9	3.4	5.3	15.8	3	
Tuber	ICB 300-25	Brasilia, Brazil	Freeze-dried	2.16	4.17	3.9	2.2	3.6	42.7	2.7	7.5	0.5	2.1	1.2	1.2	1.6	0	2.3	2.2	3.7	18.6	4
Tuber	ICB 300 TE-16	Brasilia, Brazil	Freeze-dried	1.97	3.80	6.9	3.2	3.9	4	16.8	1.5	4.2	1.6	1.6	2.8	0	4.1	1.9	3	9.4	4.5	
Tuber	ICB 300 TE-8	Brasilia, Brazil	Freeze-dried	1.8	3.47	4.5	2.3	3	1.8	8.6	1.6	2.5	0.7	1.1	1.6	0	2.5	1.7	4	26.6	1.7	
Average				**3.48**	**6.72**	**5.31**	**2.29**	**3.20**	**24.23**	**5.90**	**5.98**	**4.54**	**2.04**	**1.60**	**1.61**	**1.21**	**1.18**	**2.21**	**3.12**	**7.18**	**15.04**	**2.31**

Data from Gomes and Nassar (2013).

Table A3. Mineral concentrations in various fractions of cassava (*M. esculenta*) cultivars used in livestock feeding programs

Fraction Unit (dry basis)	Variety	Locale	Treatment	Age	Ca g/100 g	P g/100 g	Na g/100 g	Mg g/100 g	K g/100 g	S g/100 g	Cu mg/kg	Fe mg/kg	Mn mg/kg	Zn mg/kg	Reference
Leaf meal concentrate	*M. utilissima*	Nigeria	Pulped fresh, pressed, heat extracted, sun dried		1.12	0.22	0.15	0.05							Eggum, 1970
Leaf meal concentrate	Pão da China (31)	Lavras, Brazil	Heat extracted, 80°C 15 min		0.4	0.2		0.1	0.2	0.6	9.8	188.5	60	91	Modesti et al. 2007
Leaf meal concentrate	Pão da China (33)	Lavras, Brazil	Acid extracted, pH 4		0.4	0.3		0.04	0.1	0.6	16.1	154.4	27	40	Modesti et al. 2007
Leaf meal concentrate residue	Pão da China	Lavras, Brazil	Heat extract residue		1.6	0.1		0.4	0.5	0.1	4.2	47.9	444	98	Modesti et al. 2007
Leaf meal concentrate residue	Pão da China	Lavras, Brazil	Acid extract residue		1.6	0.1		0.4	0.5	0.1	5.3	49.6	397	111	Modesti et al. 2007
Literature average					**1.02**	**0.18**	**0.15**	**0.20**	**0.33**	**0.35**	**8.85**	**110.1**	**232.0**	**85.0**	
Leaf meal					1.45	0.45									Ravindran 1993
Leaf meal	WT (wild type)	Puerto Rico	Stored frozen, dried, ground		0.99	0.33	0.02	0.32	1.34	0.42	7	86	217	57	Mutayoba et al. 2012
Leaf meal	p770	Puerto Rico	Stored frozen, dried, ground		0.76	0.36	0.02	0.27	1.7	0.36	7	73	133	51	Mutayoba et al. 2012
Leaf meal	p768	Puerto Rico	Stored frozen, dried, ground		1.2	0.33	0.01	0.32	1.63	0.24	4	94	77	50	Mutayoba et al. 2012
Leaf meal	Ouro do Vale	Lavras, Brazil	Shade dry, no petiole, 40 mesh	12 months	1.9	0.3		0.2	1.6	0.3	8.6	212.1	66.5	51.7	Wobeto et al. 2006
Leaf meal	Ouro do Vale	Lavras, Brazil	Shade dry, no petiole, 40 mesh	15 months	1.9	0.3		0.2	1.6	0.4	8.1	141.8	165.2	67.1	Wobeto et al. 2006
Leaf meal	Ouro do Vale	Lavras, Brazil	Shade dry, no petiole, 40 mesh	17 months	2.2	0.3		0.2	1.2	0.3	6.1	120.1	145.7	64.1	Wobeto et al. 2006

Leaf meal	Maracanã	Lavras, Brazil	Shade dry, no petiole, 40 mesh	12 months	1.2	0.3		0.2	1.6	0.4	12	202.9	102.3	42.8	Wobeto et al. 2006
Leaf meal	Maracanã	Lavras, Brazil	Shade dry, no petiole, 40 mesh	15 months	1.2	0.3		0.2	1.3	0.3	9.4	125.4	168.2	40	Wobeto et al. 2006
Leaf meal	Maracanã	Lavras, Brazil	Shade dry, no petiole, 40 mesh	17 months	1.2	0.3		0.2	1.1	0.4	29.1	126	192.9	45.5	Wobeto et al. 2006
Leaf meal	MANTIAC	Lavras, Brazil	Shade dry, no petiole, 40 mesh	12 months	1.6	0.3		0.2	1.5	0.4	8.5	216.4	122.2	43.6	Wobeto et al. 2006
Leaf meal	MANTIAC	Lavras, Brazil	Shade dry, no petiole, 40 mesh	15 months	1.6	0.3		0.2	1.4	0.3	7.8	135.4	138.1	35.8	Wobeto et al. 2006
Leaf meal	MANTIAC	Lavras, Brazil	Shade dry, no petiole, 40 mesh	17 months	1.6	0.3		0.2	1.2	0.3	6	139.1	115	37.6	Wobeto et al. 2006
Leaf meal	IAC 289-70	Lavras, Brazil	Shade dry, no petiole, 40 mesh	12 months	1.6	0.3		0.3	1.5	0.4	10.1	224.5	126.3	50.6	Wobeto et al. 2006
Leaf meal	IAC 289-71	Lavras, Brazil	Shade dry, no petiole, 40 mesh	15 months	1.7	0.3		0.3	1.4	0.3	4.1	203.5	141.4	54.2	Wobeto et al. 2006
Leaf meal	IAC 289-72	Lavras, Brazil	Shade dry, no petiole, 40 mesh	17 months	1.8	0.2		0.4	1.6	0.3	7.6	152.2	128.2	51.6	Wobeto et al. 2006
Leaf meal	Mocotó	Lavras, Brazil	Shade dry, no petiole, 40 mesh	12 months	1	0.3		0.3	1.6	0.4	10.3	225.6	158	52.4	Wobeto et al. 2006
Leaf meal	Mocotó	Lavras, Brazil	Shade dry, no petiole, 40 mesh	15 months	1.2	0.3		0.3	1.5	0.3	8.1	132.8	190.1	63.2	Wobeto et al. 2006
Leaf meal	Mocotó	Lavras, Brazil	Shade dry, no petiole, 40 mesh	17 months	1.1	0.3		0.3	1.3	0.4	7.3	148.6	163.5	64.1	Wobeto et al. 2006
Leaf meal	61584 Ohupon (bitter)	Nigeria	Sun dried		0.62	0.3	0.1	0.28							Eggum, 1970

Leaf meal	GCH (bitter)	Nigeria	Sun dried		0.68	0.31	0.1	0.31						Eggum, 1970
Leaf meal	44086 Congo (Panja sweet)	Nigeria	Sun dried		0.75	0.3	0.14	0.29						Eggum, 1970
Leaf meal	Pão da China	Lavras, Brazil	Dried ambient temp 6 days, rinsed, ground		1.1	0.3		0.3	1.6	0.3	10.7	98.4	188	93	Modesti et al. 2007
Hay		Thailand		3–4 months	2.4	0.3									Wanapat 2003
Leaf		Thailand	Dried	3–4 months	1.5	0.4									Wanapat 2003
Leaf	White Rose (H226)	Tamil Nadu, India	Shade dry, ground 1 mm		2.3	0.3		0.8			29.5			29	Murugeswari et al. 2006
Leaf silage	White Rose (H226)	Tamil Nadu, India	Wilted 3 hr, chop, pH 4.8		2.3	0.3		0.7			30.2			29.6	Murugeswari et al. 2007
Leaf hay	White Rose (H226)	Tamil Nadu, India	Shade dry 2 days		2.5	0.3		0.8			31.3			30.1	Murugeswari et al. 2008
Leaf	Mulluvadi (MVD-1)	Tamil Nadu, India	Shade dry, ground 1 mm		2.4	0.3		0.7			28.9			20.3	Murugeswari et al. 2009
Leaf silage	Mulluvadi (MVD-1)	Tamil Nadu, India	Wilted 3 hr, chop, pH 4.7		2.5	0.3		0.8			30.1			29.4	Murugeswari et al. 2010
Leaf hay	Mulluvadi (MVD-1)	Tamil Nadu, India	Shade dry 2 days		2.6	0.4		0.9			31.3			36.4	Murugeswari et al. 2011
Leaf	20 lines	Cali, Colombia	Dried, ground		1.2	0.3	0.001	0.7	1	0.3	7.3	94.4	67.9	51.6	Chavez et al. 2000
Literature average	**n = 30**				**1.57**	**0.31**	**0.06**	**0.39**	**1.43**	**0.34**	**13.9**	**147.6**	**140.3**	**47.8**	
Foliage, dehydrated	n = 1 to 5	Global database			2.09	0.32		0.75			23.0	500.0	51.0	30.0	Heuzé 2012
Foliage, ensiled	n = 2	Global database			2.51	0.33		0.86			31.0			33.0	Heuzé 2012
Foliage, fresh	n = 2 to 33	Global database			1.19	0.37	0.06	0.73	1.25		29.0			25.0	Heuzé 2012
Foliage, wilted	n = 1	Global database			1.40	0.30									Heuzé 2012
Database average					**1.80**	**0.33**	**0.06**	**0.78**	**1.25**		**27.7**	**500.0**	**51.0**	**29.3**	

Peel	Sweet	Akure, Nigeria	Innoculated fermented	0.03		0.04		0.05					0.01	Oboh 2006
Peel	Sweet	Akure, Nigeria	Naturally fermented	0.03		0.04		0.06					0.01	Oboh 2006
Peel	Sweet	Akure, Nigeria	Unfermented	0.03		0.04		0.05					0.01	Oboh 2006
Peel meal			Dried, ground	1.33	0.44									Nwokoro and Ekhosuehi, 2005
Peel	WT (wild type)	Puerto Rico	Stored frozen, dried, ground	0.69	0.11	0.01	0.08	1.25	0.09	<1.0	52	12	20	Mutayoba et al. 2012
Peel	p770	Puerto Rico	Stored frozen, dried, ground	1.15	0.15	0.03	0.2	1.52	0.33	6	66	97	40	Mutayoba et al. 2012
Peel	p768	Puerto Rico	Stored frozen, dried, ground	1.25	0.14	0.02	0.17	1.3	0.29	3	66	63	35	Mutayoba et al. 2012
Peel	p746	Puerto Rico	Stored frozen, dried, ground	0.85	0.12	0.02	0.14	1.46	0.18	2	44	43	40	Mutayoba et al. 2012
Literature average				**0.67**	**0.19**	**0.03**	**0.15**	**0.81**	**0.22**	**3.7**	**57.0**	**53.8**	**19.3**	
Peels, dry	n = 3	Global database		0.45	0.08		0.11	0.71						Heuzé 2012
Peels, fresh	n = 1 to 2	Global database		0.17	0.21	0.03	0.06	0.64		0	15	0		Heuzé 2012
Database average				**0.31**	**0.15**	**0.03**	**0.09**	**0.68**		**0.00**	**15.00**	**0.00**		
Tuber	20 lines	Cali, Colombia	Dried, ground	0.06	0.1	0.007	0.1	0.9	0.03	2.2	9.6	1.2	6.4	Chavez et al. 2000
Tuber		Thailand	Collected from 5 starch plants	0.8	0.02									Kossoom et al. 2009
Tuber		Thailand	Dried	0.1	0.1									Khempaka et al. 2009
Tuber	WT (wild type)	Puerto Rico	Stored frozen, dried, ground	0.06	0.13	0.02	0.07	1.13	0.02	3	14	12	6	Mutayoba et al. 2012
Tuber	p770	Puerto Rico	Stored frozen, dried, ground	0.06	0.13	0.04	0.07	0.87	0.04	3	9	10	6	Mutayoba et al. 2012
Tuber	p768	Puerto Rico	Stored frozen, dried, ground	0.14	0.18	0.06	0.15	1.73	0.03	4	10	23	8	Mutayoba et al. 2012

Tuber	p746	Puerto Rico	Stored frozen, dried, ground	0.19	0.19	0.07	0.15	3.04	0.03	5	12	25	10	Mutayoba et al. 2012
Literature average				**0.20**	**0.12**	**0.04**	**0.11**	**1.53**	**0.03**	**3.4**	**10.9**	**14.2**	**7.3**	
Tubers, dehydrated	n = 3 to 125	Global database		0.17	0.11	0.03	0.09	0.99		5	24	23	33	Heuzé 2012
Tubers, fresh	n = 7 to 8	Global database		0.16	0.12		0.11	0.77						Heuzé 2012
Tubers, peeled, fresh	n = 1	Global database		0.10	0.04									Heuzé 2012
Sievate, dehydrated	n = 17–18	Global database		0.14	0.02	0.04	0.07	0.1						
Database average (tubers)				**0.14**	**0.07**	**0.03**	**0.09**	**0.62**		**5.0**	**24.0**	**23.0**	**33.0**	
Pomace, dehydrated	n = 1 to 7	Global database		0.74	0.04		0.12			0	559		102	Heuzé 2012
Pomace, fresh	n = 1 to 2	Global database		0.56	0.14	0.01	0.01	0.01		11	6			Heuzé 2012
Database average (pomace)				**0.65**	**0.09**	**0.01**	**0.065**	**0.01**		**5.5**	**282.5**		**102**	

Data from Gomes and Nassar (2013).

Table A4. Vitamin concentrations in various fractions of cassava (*M. esculenta*) cultivars used in livestock feeding programs

Fraction	Variety	Locale	Treatment	Age	Vitamin C	ß-carotene	Total carotene	Polyphenols	Reference
Unit of measure					mg/100 g	mg/100 g	mg/100 g	mg/g	
Leaf meal	WT (wild type)	Puerto Rico	Stored frozen, dried, ground			23.4	77.4		Mutayoba et al. 2012
Leaf meal	p770	Puerto Rico	Stored frozen, dried, ground			27.6	88.2		Mutayoba et al. 2012
Leaf meal	p768	Puerto Rico	Stored frozen, dried, ground			7	32.5		Mutayoba et al. 2012
Leaf meal	Mocotó	Lavras, Brazil	Dried 30°C, ground, no petioles	10 months	281.5	50.2		29.5	Simão et al. 2013
Leaf meal	Mocotó	Lavras, Brazil		12 months	294.8	70.3		52.1	Simão et al. 2013
Leaf meal	Mocotó	Lavras, Brazil		14 months	521.3	65.9		55.1	Simão et al. 2013
Leaf meal	Ufla	Lavras, Brazil	Dried 30°C, ground, no petioles	10 months	149.3	53.1		29.1	Simão et al. 2013
Leaf meal	Ufla	Lavras, Brazil		12 months	249.7	70.1		54.5	Simão et al. 2013
Leaf meal	Ufla	Lavras, Brazil		14 months	474.1	65.6		50.1	Simão et al. 2013
Leaf meal	Pão da China	Lavras, Brazil	Dried 30°C, ground, no petioles	10 months	244.7	65.9		29.2	Simão et al. 2013
Leaf meal	Pão da China	Lavras, Brazil		12 months	277.0	72.7		55.6	Simão et al. 2013
Leaf meal	Pão da China	Lavras, Brazil		14 months	568.6	61.6		56.2	Simão et al. 2013
Leaf meal	Ouro do Vale	Lavras, Brazil	Dried 30°C, ground, no petioles	10 months	171.4	51.8		16.5	Simão et al. 2013
Leaf meal	Ouro do Vale	Lavras, Brazil		12 months	310.9	68.8		31.7	Simão et al. 2013
Leaf meal	Ouro do Vale	Lavras, Brazil		14 months	463.7	51.4		36.3	Simão et al. 2013
Leaf meal	Mocotó			12 months	55.7	126.6		44.1	Wobeto et al. 2006

Leaf meal	Ouro do Vale			12 months	64.1	124.4	61.5	Wobeto et al. 2006
Leaf meal	Balana		Oven-dried 30°C			84.8		Corrêa 2004
Leaf meal	Balana		Shade-dried			64.9		Corrêa 2004
Leaf meal	Ouro do Vale	Lavras, Brazil	Shade dry, no petiole, 40 mesh	12 months	64.1	124.2	61.5	Wobeto et al. 2006
Leaf meal	Ouro do Vale	Lavras, Brazil	Shade dry, no petiole, 40 mesh	15 months	50.3	54.9	52.3	Wobeto et al. 2006
Leaf meal	Ouro do Vale	Lavras, Brazil	Shade dry, no petiole, 40 mesh	17 months	175.4	91.8	92.3	Wobeto et al. 2006
Leaf meal	Maracanã	Lavras, Brazil	Shade dry, no petiole, 40 mesh	12 months	61.3	137.4	43.4	Wobeto et al. 2006
Leaf meal	Maracanã	Lavras, Brazil	Shade dry, no petiole, 40 mesh	15 months	100.9	70.9	75.3	Wobeto et al. 2006
Leaf meal	Maracanã	Lavras, Brazil	Shade dry, no petiole, 40 mesh	17 months	181.9	92.5	106.4	Wobeto et al. 2006
Leaf meal	MANTIAC	Lavras, Brazil	Shade dry, no petiole, 40 mesh	12 months	67.3	113.8	48.6	Wobeto et al. 2006
Leaf meal	MANTIAC	Lavras, Brazil	Shade dry, no petiole, 40 mesh	15 months	51.6	50.4	60.5	Wobeto et al. 2006
Leaf meal	MANTIAC	Lavras, Brazil	Shade dry, no petiole, 40 mesh	17 months	140	58.5	95.8	Wobeto et al. 2006
Leaf meal	IAC 289-70	Lavras, Brazil	Shade dry, no petiole, 40 mesh	12 months	43.6	131.1	47.3	Wobeto et al. 2006
Leaf meal	IAC 289-71	Lavras, Brazil	Shade dry, no petiole, 40 mesh	15 months	48.5	60.2	59.7	Wobeto et al. 2006
Leaf meal	IAC 289-72	Lavras, Brazil	Shade dry, no petiole, 40 mesh	17 months	95	82.8	71.2	Wobeto et al. 2006
Leaf meal	Mocotó	Lavras, Brazil	Shade dry, no petiole, 40 mesh	12 months	55.7	126.6	44.1	Wobeto et al. 2006
Leaf meal	Mocotó	Lavras, Brazil	Shade dry, no petiole, 40 mesh	15 months	75.1	58.9	78.9	Wobeto et al. 2006
Leaf meal	Mocotó	Lavras, Brazil	Shade dry, no petiole, 40 mesh	17 months	141.7	66.6	79.9	Wobeto et al. 2006
Leaf	500 lines	Cali, Colombia	Dried, ground		120	48.3		Chavez et al. 2000
Leaf					60 to 370*			Montagnac et al. 2009

Peel	WT (wild type)	Puerto Rico	Stored frozen, dried, ground		94.6	0.01	0.01		Mutayoba et al. 2012
Peel	p770	Puerto Rico	Stored frozen, dried, ground		90.5	0.001	0.01		Mutayoba et al. 2012
Peel	p768	Puerto Rico	Stored frozen, dried, ground		91.9	0.5	0.5		Mutayoba et al. 2012
Peel	p746	Puerto Rico	Stored frozen, dried, ground		92.9	0.4	0.5		Mutayoba et al. 2012
Tuber	500 lines	Cali, Colombia	Dried, ground		9.5	0.23			Chavez et al. 2000
Tuber	01/1371 High BC	Ibadan, Nigeria	Fresh	12 months?		4.1			Thakkar et al. 2009
Tuber	01/1412 High BC	Ibadan, Nigeria	Fresh	12 months?		3.2			Thakkar et al. 2009
Tuber	01/1663 High BC	Ibadan, Nigeria	Fresh	12 months?		2.8			Thakkar et al. 2009
Tuber	WT (wild type)	Puerto Rico	Stored frozen, dried, ground		97.4	0.003	0.004	661	Mutayoba et al. 2012
Tuber	p770	Puerto Rico	Stored frozen, dried, ground		88.9	0.070	0.078		Mutayoba et al. 2012
Tuber	p768	Puerto Rico	Stored frozen, dried, ground		94.2	0.037	0.043		Mutayoba et al. 2012
Tuber	p746	Puerto Rico	Stored frozen, dried, ground		94.2	0.090	0.101		Mutayoba et al. 2012
Tuber					~15 to 50*				Montagnac et al. 2009

*Presumed to be reported on a dry basis.

Table A5. Secondary metabolite concentrations in various cassava (*M. esculenta*) cultivars/fractions

Fraction	Yield (% of plant)	Variety	Locale	Treatment	Age	Cyanide	Condensed Tannins (eq catechin)	Tannins (eq tannic acid)	Nitrate	Oxalate	Phytate	Reference
Unit (dry basis)						mg/kg	%	g/kg	mg/100 g	g/100 g	mg/100 g	
Leaf meal		p770	Puerto Rico	Stored frozen, dried, ground		1325						Mutayoba et al. 2012
Leaf meal		p768	Puerto Rico	Stored frozen, dried, ground		227						Mutayoba et al. 2012
Leaf meal		Ouro do Vale	Lavras, Brazil	Shade dry, no petiole, 40 mesh	12 months	11.3			74.6	2.5		Wobeto et al. 2007
Leaf meal		Ouro do Vale	Lavras, Brazil	Shade dry, no petiole, 40 mesh	15 months	20.9				2.2		Wobeto et al. 2007
Leaf meal		Ouro do Vale	Lavras, Brazil	Shade dry, no petiole, 40 mesh	17 months	29.2				2.9		Wobeto et al. 2007
Leaf meal		Maracanã	Lavras, Brazil	Shade dry, no petiole, 40 mesh	12 months	19.3			74.3	1.5		Wobeto et al. 2007
Leaf meal		Maracanã	Lavras, Brazil	Shade dry, no petiole, 40 mesh	15 months	18				1.6		Wobeto et al. 2007
Leaf meal		Maracanã	Lavras, Brazil	Shade dry, no petiole, 40 mesh	17 months	35				1.4		Wobeto et al. 2007
Leaf meal		MANTIAC	Lavras, Brazil	Shade dry, no petiole, 40 mesh	12 months	10.8			88.7	1.9		Wobeto et al. 2007
Leaf meal		MANTIAC	Lavras, Brazil	Shade dry, no petiole, 40 mesh	15 months	16				2		Wobeto et al. 2007
Leaf meal		MANTIAC	Lavras, Brazil	Shade dry, no petiole, 40 mesh	17 months	34.5				2		Wobeto et al. 2007
Leaf meal		IAC 289-70	Lavras, Brazil	Shade dry, no petiole, 40 mesh	12 months	13.8			43.1	1.9		Wobeto et al. 2007
Leaf meal		IAC 289-70	Lavras, Brazil	Shade dry, no petiole, 40 mesh	15 months	12.5				2.5		Wobeto et al. 2007
Leaf meal		IAC 289-70	Lavras, Brazil	Shade dry, no petiole, 40 mesh	17 months	12.4				2.5		Wobeto et al. 2007
Leaf meal		Mocotó	Lavras, Brazil	Shade dry, no petiole, 40 mesh	12 months	12.5			43.2	1.4		Wobeto et al. 2007
Leaf meal		Mocotó	Lavras, Brazil	Shade dry, no petiole, 40 mesh	15 months	20				1.8		Wobeto et al. 2007

Leaf meal		Mocotó	Lavras, Brazil	Shade dry, no petiole, 40 mesh	17 months	31.6		1.4	Wobeto et al. 2007
Leaf meal		MS6	Abeokuta, Nigeria	Shade dried, milled 1 mm		83.7	1		Oni et al. 2010
Leaf meal		TMS 30555	Abeokuta, Nigeria	Shade dried, milled 1 mm		58.5	1.4		Oni et al. 2011
Leaf meal		TMS 30572	Abeokuta, Nigeria	Shade dried, milled 1 mm		78.6	2.2		Oni et al. 2012
Leaf meal		Idileruwa	Abeokuta, Nigeria	Shade dried, milled 1 mm		86.7	3.8		Oni et al. 2013
Hay			Thailand			38	3.9		Wanapat 2003
Leaf			Thailand	Dried	3–4 months	46	4.3		Wanapat 2003
Leaf		Sweet	Tanga, Tanzania	Fresh	3–4 months	289			Kavana et al. 2005
Leaf			Thailand	Harvest 1 month and 2 months	1 month and 2 months		5		Wanapat 2003
Leaf			Thailand	Harvest 2 months and 2 months	2 months and 2 months		5.2		Wanapat 2003
Leaf			Thailand	Harvest 4 months and 1 month	4 months and 1 month		2.9		Wanapat 2003
Leaf			Thailand	Harvest 4 months and 2 months	4 months and 2 months		5.5		Wanapat 2003
Leaf meal	23 T/ha/yr; 3.7 T protein	Short term	Phnom Penh, Cambodia	Sun dried 3 days; ground 5 mm	2 months	203/545			Borin et al. 2005
Leaf	24 T/ha/yr; 3.7 T protein	Short term	Phnom Penh, Cambodia	Ensiled (wilted 1-2 h, chopped 3-6 mm)	2 months	122/545			Borin et al. 2005
Leaf meal	25 T/ha/yr; 3.7 T protein	Long term	Phnom Penh, Cambodia	Sun dried 3 days; ground 5 mm	2 months	273/408			Borin et al. 2005
Leaf	26 T/ha/yr; 3.7 T protein	Long term	Phnom Penh, Cambodia	Ensiled (wilted 1-2 h, chopped 3-6 mm)	2 months	94/408			Borin et al. 2005

Leaf			Vietnam	Fresh		269					Tram and Preston 2004	
Leaf			Vietnam	Wilted		42					Tram and Preston 2004	
Leaf			Vietnam	Fresh		177					Hang 1998	
Leaf silage			Vietnam	Silage, pH 3.5-4.0; 14 days		60.9					Hang 1998	
Leaf		White Rose (H226)	Tamil Nadu, India	Shade dry, ground 1 mm		1934					Murugeswari et al. 2006	HCN drop to 193 in 24 hr
Leaf silage		White Rose (H226)	Tamil Nadu, India	Wilted 3 hr, chop		107					Murugeswari et al. 2007	
Leaf hay		White Rose (H226)	Tamil Nadu, India	Shade dry 2 days		51.8					Murugeswari et al. 2008	
Leaf		Mulluvadi (MVD-1)	Tamil Nadu, India	Shade dry, ground 1 mm		1143					Murugeswari et al. 2009	
Leaf silage		Mulluvadi (MVD-1)	Tamil Nadu, India	Wilted 3 hr, chop		72.4					Murugeswari et al. 2010	
Leaf hay		Mulluvadi (MVD-1)	Tamil Nadu, India	Shade dry 2 days		87.1					Murugeswari et al. 2011	
Leaf silage		Sweet	Tanga, Tanzania	Silage, pH 4.85		20.1					Kavana et al. 2005	
Leaf silage			Cambodia	Harvest 2 months, pH 4		200					Chhay Ty et al. 2003	
Leaf silage			Cambodia	Harvest 5 months, pH 3.9		97.2					Chhay Ty et al. 2003	
Leaf + tuber chips		Sweet	Tanga, Tanzania	Fresh mixture		178					Kavana et al. 2005	
Leaf, fresh						2650–7200					Apata and Babalola 2012	
Database average												
Foliage, dehydrated		n = 1 to 3	Global database				2.02	0.1			Heuzé 2012	
Foliage, fresh		n = 4 to 11	Global database				2.63	65.9			Heuzé 2012	
Peel	11-15%	Sweet	Akure, Nigeria	Innoculated fermented	3 days pulp pure culture, 7 days peel	6.2				789.7	Oboh 2006	

Peel		Sweet	Akure, Nigeria	Naturally fermented	3 days pulp no added, 7 days peel fermentation	23.3				705.1	Oboh 2006
Peel		Sweet	Akure, Nigeria	Unfermented		44.6				1043.6	Oboh 2006
Peel			Nigeria			32.9	3.9		33	823.8	Aro et al. 2010
Peel		Bitter	Nigeria			650					Tewe 1991
Peel		Sweet	Nigeria			200					Tewe 1991
Peel		Nase 2	Kampala, Uganda	Freshly peeled	9 months	703					Tweyongyere and Katongole 2002
Peel		Nase 3	Kampala, Uganda	Freshly peeled	9 months	653					Tweyongyere and Katongole 2002
Peel		Nase 10	Kampala, Uganda	Freshly peeled	9 months	556					Tweyongyere and Katongole 2002
Peel		Nase 11	Kampala, Uganda	Freshly peeled	9 months	384					Tweyongyere and Katongole 2002
Peel		Nase 12	Kampala, Uganda	Freshly peeled	9 months	253					Tweyongyere and Katongole 2002
Peel		PDB	Kampala, Uganda	Freshly peeled	9 months	870					Tweyongyere and Katongole 2002
Peel	Bitter	Tongolo	Kampala, Uganda	Freshly peeled	9 months	971					Tweyongyere and Katongole 2002
Peel	Bitter	Ogwak (local)	Kampala, Uganda	Freshly peeled	9 months	1081					Tweyongyere and Katongole 2002
Peel		MH/96 1319	Kampala, Uganda	Freshly peeled	9 months	466					Tweyongyere and Katongole 2002
Peel		97/NA	Kampala, Uganda	Freshly peeled	9 months	256					Tweyongyere and Katongole 2002

Peel	MH/96 1425	Kampala, Uganda	Freshly peeled	9 months	543			Tweyongyere and Katongole 2002
Peel	95/SE 00087	Kampala, Uganda	Freshly peeled	9 months	628			Tweyongyere and Katongole 2002
Peel	AH 96 0264	Kampala, Uganda	Freshly peeled	9 months	290			Tweyongyere and Katongole 2002
Peel	97/NA 0024	Kampala, Uganda	Freshly peeled	9 months	463			Tweyongyere and Katongole 2002
Peel	Mixed n = 12	Kampala, Uganda	Freshly peeled	9 months	843			Tweyongyere and Katongole 2002
Peel	Mixed n = 11	Kampala, Uganda	Freshly peeled	9 months	795			Tweyongyere and Katongole 2002
Peel	Mixed n = 10	Kampala, Uganda	Freshly peeled	9 months	964			Tweyongyere and Katongole 2002
Peel	Mixed n = 10	Kampala, Uganda	Freshly peeled	9 months	822			Tweyongyere and Katongole 2002
Peel, fresh					1300-2250			Apata and Babalola 2012
Peel, fresh	Bitter	NECRI, Nigeria	Freshly peeled		70.2		0.67	Akpabio et al. 2012
Peel, fresh	Bitter	NECRI, Nigeria	Freshly peeled		45.8		0.68	Akpabio et al. 2012
Peel, dried	Sweet	NECRI, Nigeria	Freshly peeled, dried		288.4		0.22	Akpabio et al. 2012
Peel, dried	Sweet	NECRI, Nigeria	Freshly peeled, dried		304.4		0.16	Akpabio et al. 2012
Database average								
Peels, fresh	n = 1 to 2	Global database				0.55	29.4	Heuzé 2012
Pomace, fresh	n = 1	Global database					25.3	Heuzé 2012

Tuber chips	Sweet	Tanga, Tanzania	Fresh	71.9		Kavana et al. 2005
Tuber chip silage	Sweet	Tanga, Tanzania	Silage	17.2		Kavana et al. 2005
Tuber chip silage		Vietnam	Silage	95.9		Hang 1998
Tuber	Bitter			310		Tewe 1991
Tuber	Sweet			38		Tewe 1991
Tuber		Thailand		4.2		Kosoom et al. 2009
Tuber	WT (wild type)	Puerto Rico		96	0.06	Mutayoba et al. 2012
Tuber	p770	Puerto Rico		110		Mutayoba et al. 2012
Tuber	p768	Puerto Rico		127		Mutayoba et al. 2012
Tuber	p746	Puerto Rico		141		Mutayoba et al. 2012
Tuber	ICB 300-34	Brasilia, Brazil	Freeze-dried	98.5		Gomes and Nassar 2013
Tuber	ICB 300-18	Brasilia, Brazil	Freeze-dried	132.1		Gomes and Nassar 2014
Tuber	ICB 300-38	Brasilia, Brazil	Freeze-dried	99.9		Gomes and Nassar 2015
Tuber	ICB 300-12	Brasilia, Brazil	Freeze-dried	56.3		Gomes and Nassar 2016
Tuber	ICB 300 TE	Brasilia, Brazil	Freeze-dried	130.6		Gomes and Nassar 2017
Tuber	ICB 300-7	Brasilia, Brazil	Freeze-dried	54.9		Gomes and Nassar 2018
Tuber	ICB 300-17	Brasilia, Brazil	Freeze-dried	93.3		Gomes and Nassar 2019
Tuber	ICB 300	Brasilia, Brazil	Freeze-dried	83.2		Gomes and Nassar 2020
Tuber	ICB 300-3	Brasilia, Brazil	Freeze-dried	110.3		Gomes and Nassar 2021
Tuber	ICB 300-37	Brasilia, Brazil	Freeze-dried	172.6		Gomes and Nassar 2022

Tuber		ICB 300-5	Brasilia, Brazil	Freeze-dried	78.2		Gomes and Nassar 2023
Tuber		ICB 300 TE-2	Brasilia, Brazil	Freeze-dried	36.4		Gomes and Nassar 2024
Tuber		ICB 300 TE-12	Brasilia, Brazil	Freeze-dried	80.7		Gomes and Nassar 2025
Tuber		ICB 300-10	Brasilia, Brazil	Freeze-dried	73		Gomes and Nassar 2026
Tuber		ICB 300 TE-15	Brasilia, Brazil	Freeze-dried	66.6		Gomes and Nassar 2027
Tuber	Local	530 cultivar	Brasilia, Brazil	Freeze-dried	50.6		Gomes and Nassar 2028
Tuber		ICB 300 TE-10	Brasilia, Brazil	Freeze-dried	19.7		Gomes and Nassar 2029
Tuber		ICB 300-25	Brasilia, Brazil	Freeze-dried	41.6		Gomes and Nassar 2030
Tuber		ICB 300 TE-16	Brasilia, Brazil	Freeze-dried	33.4		Gomes and Nassar 2031
Tuber		ICB 300 TE-8	Brasilia, Brazil	Freeze-dried	31.5		Gomes and Nassar 2032
Tuber, fresh					233-1150	62400	Apata and Babalola 2012
Tuber, dry					14-65		Apata and Babalola 2012

All values on a dry matter basis.

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