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Recent developments in goat nutrition and application: A review☆

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Abstract

This paper analyses the progress in recent research in goat nutrition since the last International Conference on Goats (Tours, 2000). This review reveals clear progress in the quality of papers, now similar to those on cattle or sheep, particularly on nutritional aspects in tropical areas. Topics dealt with in goat nutrition are feeding behaviour, particularly on pastures or rangelands, feed digestibility, tree leaf or by-product utilization, effects of nutritional factors on growth, milk and hair production, while nutritional adaptation to harsh environments, underfeeding, factors influencing energy consumption, quality of goat products (milk, cheese, meat) and reproduction performance along with the connection between nutrition and pathology require more attention. Goat nutrition in a tropical environment follows the same physiological mechanisms as under temperate conditions, but genotypes can present specificities enabling a better adaptation to feeding conditions. Complete and precise information on the nutritive value of tropical forage, rangeland vegetation in accordance with the season, and new feed or by-products is still missing. Researchers in goat nutrition frequently use different methods, making it difficult to compare results from several research teams. Agreement on the methodology in goat nutrition is easier when the research teams are organized in networks at the national or international level. To be successful with technological transfer in goat nutrition, the message for the end users must be clear and well adapted. At the present time, we are short of review papers that provide an analysis of all results already published to establish quantitative relationships between variables, which can clarify the messages for the field. Methods of meta-analysis can be used to analyse the quantitative results from experimental data banks and to establish response laws and define limits of application. Finally, if we implement a research project on goat nutrition dedicated to application in the field, not only the research works but also the actions of technological transfer must be financed.

Keywords: Goat nutrition; Intake; Nutrition application; Feed utilization; Goat product quality; Research efficiency

1. Introduction

Nutrition plays an essential and special role in the systems of goat farming for the following main reasons. First, it is the production factor that goat farmers or keepers can act on the most easily and rapidly (amounts

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of feeds, composition of diets, on-pasture goat management). It has the most marked effect on production costs (from 50 to 85% of the total cost for milk production under European conditions (Ouin, 1995), and accordingly on farmer incomes. Furthermore, the management of feeding in goat flocks depends on vegetal mass production and rangeland, pasture and crop by-product management. Feeding directly impacts the other components of systems of goat production, such as pathological conditions and the reproductive performance of flocks. Moreover, a nutritional program for goats must always be established by taking into account the genetic characteristics of the breed or genotype used (potential of production, ability for adaptation, etc.)

Until around 1970, research on goat nutrition was limited and late in comparison with the knowledge already obtained in cattle and sheep. As the economic interest in goat farming was diminishing and goats were being accused of deforestation and desertification, little research was carried out to solve goat farmers' practical questions. On the one hand, scientific research of excellent quality used goats as experimental animal model on subjects concerning, particularly, physiology of behaviour, metabolism, digestion and secretion of milk in ruminants (amongst the most famous references: Linzell, 1960; Anderson and Larsson, 1961; Armstrong and Blaxter, 1965). On the other hand, there were a lot of books and booklets on goat farming where information was difficult to verify, and sometimes some preconceived ideas on goats were regenerated by successive authors. Before 1970, French (1970) observed in his reference book: 'Observations on the Goat' that "... the literature on the goat abounds in the most unfounded ideas concerning its feeding habits". He was one of the first authors to try to synthesize knowledge on goat nutrition to facilitate objective and useful application of information in the field.

After the political events around 1968, which were the first criticism of productivism and the affluent society, the image of goat farming improved. People rediscovered goats as ecological animals and the socio-economical role of goats in many tropical countries (Morand-Fehr and Boyazoglu, 1999).

At the outset, developed countries were the leaders in research on goat nutrition as 45% of the research on goats was carried out by these countries which had only 5% of the world's goat herds (Morand-Fehr, 1996). But for the last 20 years, research on goat nutrition has been developed to obtain results that can be applied in the field, particularly in developing countries. Several chapters dedicated to nutrition included in books on goat farming (Gall, 1981; Devendra and Mc Leroy, 1982; Coplan, 1985; Galbraith, 1992), invited reports in the Proceedings of Conferences or Symposia (ITOVIC-INRA, 1981; ICG, 1982, 1987, 1992, 1996, 2000) or scientific books on goat nutrition (Morand-Fehr, 1991; AFRC, 1998; Dronchner et al., 2003) have pooled and generated scientific and objective knowledge on goat nutrition and its application possibilities.

However, even if progress on this topic has been rapid, research on goat nutrition remains more limited than in cattle and sheep, and very poor in certain aspects.

Under the current conditions, it would be interesting to review the most recent progress on goat nutrition, to analyse the possibilities of transferring these results into various practical conditions as well as to suggest ways of improving the quality of research on goat nutrition and to use its results efficiently in the field. Indeed, the observation from Devendra and Mc Leroy (1982) that "little attention has been paid to the goat feeding in the past so that relatively low inputs to improve feeding could produce relatively high gains in productivity" remains true, even if progress has recently been achieved.

The aim of this paper is to objectively analyse the progress and advances of recent research works dating back to the last International Conference (ICG, 2000), particularly as concerns developing countries where the possibility of applying research results in the field is essential. We have decided to comment only on those papers that complete the research noted in preceding papers, or have brought about new advances in goat nutrition even if our choice risks to be a little arbitrary.

2. Present situation of goat nutrition

2.1. Feeding behaviour

The level of intake and the characteristics of digestion depend closely on the feeding behaviour in goats reared in the goat house, on pastures, on rangelands or under very harsh conditions. The feeding behaviour at trough has already been described thoroughly by Morand-Fehr et al. (1991a) and Morand-Fehr (2003a), particularly the feeding pattern, main and secondary meals, factors linked to animals and feeds influencing feed choices and preferences and individual variability. The physiological stage does not influence the preferences but the risks of feed refusal are optimal around parturition. Innate and acquired preferences during unproductive growth periods are essential for explaining behavioural responses in gestating or lactating goats. Previous daily diets or nutritional experiences can influence them. Generally goats seek diversity in their ingesta, probably to maintain the rumen environment within a certain physiological and microbiological range. But they also seek to limit the variability of ingested nutrient proportions inside a short period or over a year.

Narjisse (1991), Baumont et al. (2000), Landau et al. (2000) and Provenza et al. (2003) have presented the different aspects of goat feeding behaviour on pastures or rangelands. Several aspects, such as training, main and secondary meals, feeding pattern and preferences have been closely observed at trough. It is clear that goats are not obligatory browsers or fibrous material eaters. They are, however, capable of changing very quickly from herbaceous stratum to shrub or tree strata or the inverse. The importance of the characteristics of available vegetation, particularly its prehensibility, and of animal management on rangelands is clearly stressed by Meuret (1993, 1997). A lot of outstanding papers from the Provenza team present extensive studies on the alternatives that enable individual small ruminants to meet their nutritional needs better and to cope better with toxins. Past experience plays a crucial role in ruminant propensity to learn to eat different foods, particularly in goats that can memorize feeding events very easily.

This research is very rich in scientific knowledge and applications for animal management. For example, Provenza et al. (2003) showed the interest of getting experienced goats on rangeland in comparison to naïve animals. Morand-Fehr et al. (1991a) had already shown how, under intensive conditions, goat farmers could use goat-feeding behaviour to change distributed forage of bad quality to ingested forage of good quality by accepting a high rate of refused forage.

The most recent papers published since 2000 validate and complete previous knowledge. Solanki (2000) confirms the feeding pattern in rangelands already observed in the goat house. Flint and Murray (2001) indicate that the improvement of the feedlot environment can reduce stress and aggressiveness at trough and improve goat performance. Very selective behaviour is an essential component of goat behaviour because it enables goats to stay in difficult areas as well as to cope better with toxic plants (Duncan and Young, 2002). The training of young goats by does in pastures is very efficient (Knubel, 2001). Fedele et al. (2002) indicate that goats can choose their ingesta in free-choice feeding systems according to their energy and protein needs. Water needs take priority over nutritional needs (Shaheen, 2001). When water and mineral needs are covered, goats can select tree leaves or forage which are richer in nitrogen and lower in fibre (Fisher et al., 1999; Raghavendra et al., 2002). First, as other animals, goats eat to meet their needs and then for hedonic reasons which can disturb the ration balance, such as when goats consume too much fruit during the wild fruit season in rangelands (Meuret and Guérin, 2001). The experienced goats strongly modify their preferences and the vegetal stratum chosen according to the season (Dziba et al., 2003a,b). These changes are also modulated by plant prehensibility, particularly plant height (Dziba et al., 2003b). On the other hand, Rosa et al. (2002) showed that the specific flavours of forage plants play an essential role in choices made by goats. Still, various goat breeds or genotypes present different behavioural responses (Odo et al., 2001; Dziba et al., 2003b), probably according to their feeding and past behavioural experiences, rather than due to exclusively genetic factors. Hence, a large number of recent observations have shown that the features of feeding behaviour in goats identified by reviewers in recent years can be observed within various environments, under different types of animal management and in animals following a variety of diets.

2.2. Level of intake

The published estimates of the voluntary feed intake in goats differ owing to the frequent refusals and strong selection of ingesta. Still, every publication presents the dietary recommendations or needs in goats, summarizing the knowledge in this field (NRC, 1981; Morand-Fehr and Sauvant, 1989; AFRC, 1998; Dronchner et al., 2003). Other review papers referring to normal conditions of livestock farming (Morand-Fehr, 1981; Skjevdal, 1982; Sauvant et al., 1991) contribute to the specific knowledge on goat intake. They try to present equations or systems to predict the level of goat intake under various physiological conditions. We must point out that these methods of prediction can be applied under controlled conditions only and generally in temperate countries. The INRA Fill Unit System has been validated for goats (Dulphy et al., 1989). Still, the system should be applied with caution by adapting both the fill values of forage and the ingestive capacities of the goat breed or population used (AFRC, 1998). Nevertheless, this approach is very valuable for establishing a feeding program and for calculating diets. The next step in predicting intake is to model it (Baumont et al., 2000) by taking into account the characteristics of goat feeding behaviour.

Research on the regulation of intake is continuing in goats. Sunagawa et al. (2002a,b) showed that the saliva flow and induced decrease in blood plasma volume are factors regulating feed intake in goats. Every factor decreasing the fermentation activities in rumen as a deficit of fermentable N in diets (Kijora et al., 2002) reduces goat feed intake. On the contrary, an extra N supply through supplemented feeds, such as fodder shrubs, particularly leguminous species, increases the level of intake (Papachristou, 2000).

As the standards of ruminant intake have been measured in sheep, many papers compare the level of intake and digestibility of the same forage in sheep and goats. Fernandes et al. (2002), Intong and Robles (2001), Lamba and Rajora (2002) and Lokesh and Murdia (2002) confirm that the intake of forage DM of medium or bad quality rich in fibre tends to be higher in goats than in sheep. The different intakes in sheep and goats could be explained principally by the modification of digestive factors (transit, urea N recycling, etc.) when animals are given feed supplies ad lib. (mentioned after).

2.3. Digestion

Morand-Fehr (1981), Tisserand et al. (1991) and Lindberg and Gonda (1996) have pooled all the available information on the characteristics of digestion in goats. The digestive tract of goats is very similar to that of other ruminants. No difference has been observed in the mean retention time of feed particles in the whole digestive tract of sheep and goats eating the same quantity of good quality forage, but the retention time of goats receiving poor quality forage is longer. Digestion in goats and sheep is similar with moderate to high quality forage, but goats best digest forage rich in cell wall and poor in nitrogen. There are indications of more efficient nitrogen digestive utilization in goats fed diets low in protein.

Even if a lot of papers have been published on the digestibility of feeds in sheep and goats, it is a little surprising to observe the limited number of papers on the digestive features in goats when goats are well known to digest feeds rich in fibre and poor in nitrogen, better than the other ruminants. Since 2000, several papers have confirmed the importance of the balance between starch and nitrogen supplies in optimising the fermentation activities and microflora growth in the rumen (Das, 2002) under both tropical and temperate climatic conditions. Goats are extremely sensitive to diets that are very poor in fibre and rich in concentrate feeds, particularly around the time of parturition. The rumen pH decreases when the concentrate proportion in diets exceeds 60% DM (Goncalves et al., 2001a,b), or when diets are composed of feeds or forage characterized by small particle size (Rapetti et al., 2001). If the lowering of rumen pH lasts several hours, symptoms of acidosis can appear as diarrhoea and a fall in intake. In this case, cellulolytic activity, protozoal counts and fibre digestion are clearly reduced (Jani et al., 2001).

As goats frequently browse leaves or other parts of trees rich in tannins, a lot of authors have studied the effects of tannins on the nitrogen utilization in their rumen. Makkar (2003) describes the effects of tannins on ruminants from beneficial to toxicity and death. Even if it has sometimes been reported that goats are not very sensitive to tannins (Lee and Lee, 2002), the proteolytic ruminal bacteria cannot digest protein that is complexed with condensed tannins (McSweeney et al., 1999; Pintus, 2000). But the addition of polyethylene glycol (PEG) to goat diets inhibits the negative effects on nitrogen digestion in the rumen by binding the condensed tannins (Landau et al., 2002, 2003) and improves the digestibility of tree leaves which are rich in condensed tannins (Nguyen Thi, 2001; Nguyen Thi et al., 2002; Villalba et al., 2002; Raghavendra et al., 2003). It is a pity that no paper deals with the operating conditions or economical aspects of PEG utilization in the field, since this method could be valuable under arid conditions.

2.4. Utilization of various feeds by goats

2.4.1. Tree or plant leaves

In tropical countries, particularly in humid ones, goats frequently feed on leaves in addition to grazing or consuming grass. At present, we have data on a large number of vegetal leaves that can be included in goat diets. Generally, studies present a chemical analysis and results on levels of intake and in vivo digestibility (Azim et al., 2002; Bais et al., 2002; Brij and Murdia, 2002; Bamikole et al., 2003) sometimes with complementary mineral analyses, since some of these fodders can be very unbalanced in minerals (Urbani and Tewe, 2001; Elseed et al., 2002; Rajendiran and Kardivel, 2002a). Special attention is paid to toxins or anti-nutritionals, such as tannins, which can strongly limit fodder utilization (Urbani and Tewe, 2001; Elseed et al., 2002; Rajendiran and Kardivel, 2002b). The main progress has been in the quantity of information on the ingestibility, digestibility, and nutritive value of these fodders. Results on milk or growth performance are often given since digestibility values cannot always be interpreted in performance results (Brij and Murdia, 2002; Maharem and Eman, 2002; Nguyen Thi et al., 2002; Rajendiran and Kardivel, 2002b; Bamikole et al., 2003). It is also important to know how to include them in goat rations with another forage (Bamikole et al., 2003) or a concentrate mixture (Brij and Murdia, 2002; Nguyen Thi et al., 2002). It is still rare for authors to give information on the economic interests of the fodder used.

The most common leaves present in goat diets are probably *Leucaena leucocephala* and *Gliricidia sepium*, and a little less frequently *Artocarpus integrifolia*, Manihot and *Sesbania grandiflora*. These have been given to goats for a long time and can be used as pellets or meal to replace other concentrate feeds (Dutta et al., 2002; Patra et al., 2002) as excellent protein sources (Srinivasulu et al., 1998; Patra et al., 2002). Supplying these leaves in supplementation of forage of medium quality, such as *Penisetum purpureum*, results in a clear improvement of performance (Ogundola and Tobioka, 2001; Mpairwe et al., 2003). The same remains true even with forage of better quality, such as *Panicum maximum* or Sudan grass (Viengsavanh and Ledin, 2002; Kanani et al., 2003). Some plant leaves, such as Leucaena, can contain toxics, such as mimosine, but Kumar and Ashwani (1998) show that after 7–8 weeks, goats can degrade mimosine and are very well adapted to increasing their rate of productivity by feeding on Leucaena.

All these recent results confirm the importance of tree leaves to goat diets in the Tropics and their interest to improving milk and meat performances. But in order to persuade farmers, substantial efforts must be made to present very complete results answering all of their needs.

2.4.2. Pastures and rangelands

Since 2000, many papers have reported the genetic progress in adapting fodder crops to various agro-climatic conditions in temperate or tropical areas by improving ingestibility or digestibility of already well-known species or by creating new varieties. Concerning their utilization in goat nutrition, for some years, we have read papers advising farmers to manage goats grazing cultivated pastures in temperate conditions (Pommaret and Le Frileux, 2001) and in tropical conditions (Fai and Fomunyam, 2000; Alexandre et al., 2001). These papers are particularly interesting showing that there was a lack of information based on scientific results about the utilization of pastures by goats. Moreover, more and more papers are being published to indicate the best supplementation for optimal digestive utilization of forage plants and optimal performance (Areghore, 2001; Goncalves et al., 2001b; Bamikole et al., 2003). In most cases, the authors suggest an optimal proportion of other cultivated or native plants, which reduces diet costs in comparison to the utilization of concentrate feeds.

Nastis (1996) and Ramirez (1996) reviewed the characteristics of the utilization of rangelands and browsing by goats under extensive conditions. Ngwa et al. (2000) published an interesting paper on the behaviour of sheep and goats on Sahelian rangelands, which proposes management programs ensuring the survival of the tree species browsed by small ruminants. Another paper (Luginbuhl et al., 2000) indicated that methods such as controlled grazing by goats could improve native mountain pastures and that grazing goats with cattle was especially beneficial for the control of multiflora, bushes and other woody species. This observation contrasts with the common idea that goat grazing is adverse to an improvement of vegetation on pastures.

It seems that in tropical situations, better use is made of pastures by suckling goats in a cut-and-carry system rather than grazing the pastures, as with dairy goats in intensive systems.

Finally, Obied et al. (2003) emphasize that even if goats are known to have great skill at avoiding the ingestion of vegetation containing toxins or anti-nutritionals in pastures, naïve goats staying usually kept in the goat-house may not share the same abilities.

Recent progress has appeared in the management of pastures dedicated to goats and in the management of goat flocks on rangelands in various environments. The problem of rangeland utilization by goats in arid environments can now be dealt with objectively.

2.4.3. Crop residues and agro-industrial by-products

For the last 30 years, the nutritive value of crop residues and agro-industrial by-products has been one of the main research fields in ruminant nutrition, particularly in tropical countries. Since 2000, a lot of research works have contributed to improving our knowledge on the utilization of these foods for goats. First, several papers demonstrate that certain crop residues can replace concentrate feeds in goat diets without reducing performance and generally with better economic results (Meffeja et al., 2000; Morales et al., 2000; Malau-Aduli et al., 2003). Cassava by-products (Meffeja et al., 2000; Kim et al., 2002; Mouro et al., 2002) and citrus pulp (Bueno et al., 2002) seem to be utilized successfully by goats in place of maize grain. Cotton by-products (seed-cake or waste, Belewu and Ademilola, 2002) and maize stubble and stovers (Morales et al., 2000; Meffeja et al., 2000) also give good results in goats. Poultry manure was also tested on growing goats and the daily body gain did not reduce when a mixture of tapioca + manure was included up to 30% of the diet (Kim et al., 2002). Animut et al. (2002) enhanced the interest of the supplementation of wheat straw with broiler litter in growing goats.

The aim of another group of papers is to improve the nutritive value of these by-products by treating them. The well-known treatment of soya by formaldehyde under tropical conditions has rigorously similar positive effects on goat milk performance as under temperate conditions (Chowdhury et al., 2002). Other less well-known treatments, such as sunflower meal with added fibrolytic enzyme (Titi, 2003) and cotton waste treated with fungus (Belewu and Ademilola, 2002), have been successfully tried in goats. All these papers extend the scope of the various foods, which can be included in goat diets while generally reducing dietary costs.

2.5. Nutritional factors linked to animals, metabolism and efficiency of nutrient utilization for goat production

A larger number of papers are dedicated to the evaluation of the nutritive value of feeds than to the utilization of digested nutrients in goats for milk, meat or hair production and the variation of this metabolic utilization. Some specific physiological characteristics in small ruminants and particularly in goats, such as high prolificacy, short duration of gestation, mating seasonality, composition of milk and live weight gain, and the capacity of adapting to various agro-climatic conditions can modify dietary utilization. Landau et al. (1996) try to describe maternal lipolysis at the end of pregnancy, the efficiency of nutrient utilization for ovulation, pregnancy and milk synthesis. They observed that manipulation of ruminal starch degradability could improve glucose production and utilization while affecting litter weight and milk production positively. An excess of energy during the first stages of pregnancy could be deleterious. Since the publication of this paper, our knowledge has largely advanced owing to the work of the Garza Institute for goat research (Sahlu et al.), of INRA teams (Schmidely et al.) and of other institutes. Chilliard et al. are working on the role of leptin in goats. All these papers cannot be quoted here.

It appears that in goats, the basic metabolic features are very similar to those in sheep, and frequently, cattle, but the capacity of physiological adaptation to various agro-climatic conditions can modify them extensively in goats.

We shall now turn our attention more to these aspects that must be taken into account to define feeding programs and diets for goats.

2.5.1. Body reserves and body conditions

Goats can mobilize their body reserves according to the nutritional status, physiological stage and availability of adipose tissues. The storage and mobilization of lipid reserves are the main means by which goats adapt to variations in dietary supply. Body condition, which reflects body reserves, mainly lipid reserves, is a useful parameter in assessing nutritional status under various conditions. Before ICG (2000), Morand-Fehr et al. (1992) had already analysed variations in body reserves in goats during a cycle of reproduction and during the growth period, methods of assessing them, the relationships between body conditions and goat performance and various uses of body condition scores (BCS) for managing goat feeding under intensive and extensive conditions. A BCS method based on body palpations is difficult to work out in goats because of a lack of subcutaneous adipose tissue in this species. The last proposed method (Hervieu and Morand-Fehr, 1999) is based on two palpations on lumbar vertebrae and sternum in a 5-point scale, the only regions where subcutaneous adipose tissue is somewhat developed in goats. Hervieu and Morand-Fehr (1999) explain how to apply this method in the field by describing each quarter point of the scale anatomically and by defining score objectives for each sensible physiological stage, such as mating, parturition, top of lactation curve and drying, or for each vegetation growth period, such as the beginning and end of dry or humid periods. Hence, this method could be used to establish a feeding program when the quantities and nutritive value of ingested feeds are unknown.

This BCS method can be used in all the cases of pasture or rangeland grazing where goat intake cannot be controlled to establish the nutritional status of the flock and program a strategy of supplementation so as to improve production or fertility performance or reduce the pathological risks in the flock (Morand-Fehr, 2003b).

2.5.2. *Nutritional mechanisms of adaptation to various agro-climatic conditions*

Goats are well known for their adaptability to various agro-climatic conditions (low availability of vegetation in arid areas, feeds rich in fibre and low in nitrogen, lack of water, heat stress). Unfortunately, few recent papers deal with these important subjects for goat husbandry in tropical countries.

For 20–25 years, it has been a common knowledge that digestion in sheep, goats and cattle is similar with moderate to high quality forage, but goats are better able than sheep to ingest and digest forage rich in cell wall and poor in nitrogen, i.e. of low nutritive value (Morand-Fehr, 1981; Devendra and Mc Leroy, 1982). Silanikove et al. (1980) and Silanikove (2000) showed that Bedouin goats recycle 87% of the urea N entry rate, i.e. twice N intake, when they eat wheat straw containing only 3% protein. Tisserand et al. (1991) analysed all the possible mechanisms which could explain the good digestion of poor forage in goats and concluded that goats tend to retain nutrients longer in the digestive tract, have a higher concentration of cellulolytic bacteria in the rumen and are more efficient in recycling blood urea. Other works confirm these observations although Chilliard et al. (1998) conclude that ruminants are incapable of compensating for levels of intake below maintenance level by increasing urea recycling and digestive efficiency. It would be interesting to know the animal or feed factors that could favour these adaptation mechanisms. Doreau et al. (2000) summarize the effects of under-feeding on digestion in ruminants, which is not always a negative relationship. It has been suggested that a reduction in bacterial growth and microbial degradation potential could explain some reductions in digestibility resulting from a decrease of intake. Still, no goat specificity can be pointed out in this topic owing to very few studies on under-nutrition in goats.

Silanikove (2000) summarizes 20 years of research work by the Israeli team (Shkolnik et al.) on the physiological mechanisms of adaptation in goats to scarcity of food and water in harsh environments, particularly in rumen metabolism and nutrient utilization in tissues. Silanikove (1996) enhanced clearly the different digestive and metabolic mechanisms in breeds un-adapted (Saanen) and adapted (Bedouin) to tropical conditions. Morand-Fehr and Doreau (2001) describe the evolution of intake and digestion in ruminants exposed to heat stress. Under harsh conditions, goats generally consume less water but more feed dry matter than sheep. Goats adapted to heat stress resist the negative impact of heat better than unadapted goat breeds (usually exotic breeds) by adapting their intake so as to reduce their heat production due to rumen fermentation by grazing at night and by increasing the number of short meals. Ferreira et al. (2002) also showed that goats need less water to synthesize 1 kg of weight gain than sheep, but they point out that a diet rich in energy (i.e. in concentrate) requires a lower water intake than a diet low in energy. This information supports the idea that increasing the energy density of diets is an efficient way to combat heat stress. On the other hand, goats well adapted to semi-arid zones do not reduce their feed intake when they are short of water for less than 48 h (Misra and Khub, 2002). In Sudanese desert goats, a water deficit reduces their forage intake and increases their digestibility in most cases, but has no effect on N balance (Muna and Ammar, 2001). The effect of a lack of water is more deleterious on low than on high quality forage.

2.6. Nutrition goat production and product quality

Numerous reviews presenting the nutritional characteristics of dairy goats and the strategy of feeding them during a cycle of reproduction or the influence of nutritional factors on the quality of goat milk (Hadjipanayiotou, 1987; Morand-Fehr and Sauvant, 1987; Hadjipanayitou and Morand-Fehr, 1991; Morand-Fehr et al., 1991a,b) as well as books presenting nutritional recommendations (Morand-Fehr, 1991; AFRC, 1998; Dronchner et al., 2003) supply rich information on this subject. This information is, however, principally devoted to intensive and temperate conditions and clearly less to tropical or less intensive conditions. Over the last 4 years, the main papers from the USA, Spain and Italy on nutrition of dairy goats under intensive conditions have studied the effects of energy (lipid and fibre supplies) and nitrogen sources on milk yield and composition with unfortunately little on the technological characteristics of goat milk for cheese making. The papers published recently on the subjects under tropical conditions have already been quoted in previous paragraphs on digestion and the utilization of foods.

The main subject studied over recent years is the effect of feeding on the composition and dietetic quality of goat milk (trans and conjugated fatty acids, cholesterol, etc.). Several reviews have been published on this subject (Schmidely and Sauvant, 2001; Chilliard et al., 2002, 2003). We will limit our contribution to this subject by indicating that a lot of papers report the effects of various fat sources on milk production and composition (Brown-Crowder et al., 2001; Sanz Sampelayo et al., 2002a,b; Rapetti et al., 2001, 2002; Rouel et al., 2002; Schmidely et al., 2002; Schmidely et al., 2004) and the effects of various feeds on milk flavours (Rouel et al., 2002; Gaborit et al., 2002). The cheese flavours and the quality criteria, such as unctuousness of cheese paste, tend to be reduced when the milk fat percentage is low or when the milk protein is higher than the fat percentage. We can observe these cheese quality defects when the goats' diets are lacking in fat or fibre. Balancing fat or forage supplies can increase the fat percentage and reduce these defects. It is interesting to observe that in contrast to the dairy cows (Morand-Fehr et al., 2000a,b), in goats, a fat supply in correct proportions (fat source not too rich in unsaturated fatty acids, fat limited to less than 5% DM in diets) generally does not reduce the milk protein percentage or the cheese yield index.

It is a pity that, except for Landau et al. (2000), information on the effects of various nutritional factors on the reproductive performance in goats is very limited, particularly under tropical conditions. Our information is limited to quantitative aspects: when goats receive a dietary supplementation, their reproductive performance is improved (Badawy et al., 2001; Madibela et al., 2002). Moniruzzaman et al. (2002b) showed that under the conditions found in Bangladesh reproductive performance is better with stall-fed goats than with goats in tethering or grazing feeding systems, probably because the food supplies are higher in stall. It is also interesting to note that research has started off on the effect of feeding on the reproductive performance in young females mated between 7 and 9 months under intensive conditions (Bocquier et al., 2000). A set of observations tends to indicate that the nutritional status of female goats must be of a good level to assure better success with artificial ovulation or super ovulation treatments than with natural mating.

Scientific and applied knowledge on the influence of nutritional factors on mohair and cashmere production by hair goats (Morand-Fehr and Galbraith, 1993; Reis and Salhlu, 1994; Qi and Lu, 1996; Galbraith et al., 2000) was reviewed. Over recent years, research has focused on the physiology of hair nutrition, particularly on the effects of various hormones (Puchala et al., 2001, 2002) and on hair nitrogen nutrition (Ivey et al., 2000; Puchala et al., 2002). With the nutritional recommendations for hair goats (NRC, 1981; AFRC, 1998; Dronchner et al., 2003), the knowledge about hair goat nutrition is largely sufficient to elaborate well-adapted diets and feeding programs.

The nutrition of growing goats has not been the subject of reviews pooling all the scientific knowledge since Morand-Fehr et al. (1982), unlike the other fields of goat nutrition. Accordingly, it is more difficult to evaluate the level of scientific knowledge in this field.

Several papers published recently confirm what Morand-Fehr et al. had already indicated in 1982 for milk feeding periods but under various rearing conditions: first growth is higher with ad lib. intake of milk than with limited quantities of milk (Goetsch et al., 2000; Genandoy et al., 2002; Su et al., 2002c). The feeding method, whether it is ad lib., feeder, lamb bar or computer controlled distribution, has no direct effect on growth performance, which depends closely on the ingested milk (or energy) quantity (Maier-Ruprecht et al., 2003). Still, the method that limits the quantities of milk ingested most is naturally the least costly. Secondly, supplemental concentrate makes up for a limited access to milk, particularly from 3 weeks after birth, but a diet with limited milk + concentrate gives better economical results than ad lib. intake of milk (Genandoy et al., 2002; Su et al., 2002c). Thirdly, provision of a concentrate before weaning improves weight gain after weaning because it prepares the goat well for weaning and the shock at weaning is thus more limited (Goetsch et al., 2002). Fourthly, as before weaning, growth performance after weaning depends mainly on the energy ingested (or food intake) and not on the feeding method (restricted or unrestricted grazing, intensive stall feeding, tethering) (Aydin and Arik, 1999; Moniruzzaman et al., 2002a). A concentrate feed well balanced in energy and protein is more efficient than barley grain for growing goats but the economic results are better with barley (Goonewardene et al., 2002a). The physical forms of diets: hay chopped to 2.5 or 5 cm lengths and whole or rolled barley have very little effect on growth performance and carcass traits in young goats (Goonewardene et al., 2002b). Corn-sorghum distiller's grain silage is as efficient as concentrate in diets for growing goats while giving better economic results (Su and Yan, 2001). More and more often, authors complete their studies on growth by giving results on carcasses, such as done by Moniruzzaman et al. (2002a) and Su et al. (2002b).

Bas and Morand-Fehr (2000) presented the effects of nutritional factors on fatty acid composition of lamb fat deposits thanks to a meta-analysis of all published references. We can suppose that a large part of the results on lambs can be applied to young goats. Grass-based diets increase $C_{18:0}$ and $C_{18:3}$ in muscles and adipose tissue. Inclusion of maize in the diet results in an increase in linoleic acid contents in fat deposits. Under tropical conditions, some agricultural by-products, such as tofu cake, can increase the percentage of unsaturated fatty acids in young goat muscles (Hirayama et al., 2002).

In summary, the main advance on the nutrition of young goats is that the best economic results are obtained with limited quantities of milk or concentrate, or by replacing concentrate with by-products, while growth or carcass results are better with milk or concentrate ad lib.

2.7. Needs, balanced diets and feeding program for 1 year

As already mentioned, numerous references present the dietary requirements or recommendations for growing, gestating or lactating goats (NRC, 1981; Skjevdal, 1982; Haenlein, 1987, 1992; Lu et al., 1987; Brun-Bellut et al., 1987, 1991; Morand-Fehr and Sauvant, 1989; Ademosun et al., 1992; Sauvant and Morand-Fehr, 1991; Hadjipanayiotou et al., 1991; Kessler, 1991; AFRC, 1998). Over the past few years, this list has grown with two German publications (Pfeffer, 2001; Dronchner et al., 2003) and one on the protein requirements of Angora goats (Luo et al., 2003). Furthermore, information on this topic is relatively rich even if we are still short on requirement values observed in goats for gestation and late growth of gestating young does. There is also only limited information about some macro- and oligo-elements and vitamins. Moreover, these requirements or recommendations concern goats reared under semi-intensive or intensive conditions. For this reason, a work from India (Saraswat and Sengar, 2000) is of interest as it reviews all the nutrient requirements of goats living under tropical conditions. The authors emphasize that in this environment, water and mineral requirements are higher and the energy and nitrogen requirements vary greatly depending on the season.

Finally, we have to mention interesting progress on two specific kinds of requirements: locomotion energy requirements, particularly on pastures or rangelands (Lachica et al., 1999; Lachica and Aguilera, 2003), and macro- and oligo-elements recommendations (Meschy, 2002). The growth requirements for P and Ca have been re-evaluated, becoming slightly lower than in calves but higher than in lambs.

2.8. Feeding systems, calculation of diets and feeding programs

To calculate a balanced ration covering goat requirements, we need a feed evaluation system which estimates the energy, nitrogen and mineral value of feeds indicated in feed tables, and a system of recommended allowances or requirements of goats for growth, gestation, lactation and maintenance using the same units in energy, protein and minerals as in feed evaluation systems. Various feeding systems have been published for goats (NRC, 1981; Morand-Fehr and Sauvant, 1987; AFRC, 1998; Dronchner et al., 2003) and can give satisfying results only if they are applied with both accuracy and discrimination. Generally, diets are calculated using these feeding systems under temperate conditions where goat feeding can be standardized and feed intake controlled in both quantity and quality. This procedure was applied successfully under tropical conditions with goats in stalls or paddocks (Bhadauria et al., 2002; Raghavendra et al., 2002; Garg et al., 2002; Su et al., 2002a). These methods make it possible to propose feeding strategies and efficient advice to goat farmers, for example, by periodically calculating rations to complement grazing in Spain (Haba et al., 2001). Moreover, rations that are well balanced in energy, protein and minerals result in reduced N and P excretion (Paengkoum et al., 2002). Such excretion is an ever-increasing problem due to its effect on environment maintenance.

Diet presentation and distribution methods must also be studied. Su et al. (2002a) obtained better results in dairy goats with a total mixed ration than with forage concentrate separately. Feed blocks as alternative supplements, a long-known technique (Sansoucy, 1995), has been developing for several years in the sheep and goat sectors owing to substantial scientific studies showing that they can cover a large part of all the nitrogen and mineral requirements. Moreover, the methods used in solving the practical problems (block technology, formulation, manufacturing process, etc.) are easy for goat farmers to implement (Ben Salem and Nefzaoui, 2003). Feed blocks may be used to promote the use of regional agro-industrial by-products or be an efficient carrier of tannin-neutralising agents, such as PEG and anthelmintic medicines.

What is more, feed blocks make feed transport and storage easier (Samanta et al., 2003). Forsberg et al. (2002) emphasize that the palatability of feeds must be kept high, particularly when they are rich in minerals or urea, by using wheat bran as fibre source. Finally, El-Hag et al. (2002) show that the diet with multi-nutrient blocks can reduce feeding costs in goats.

It is a pity that the strategy for supplying concentrate throughout lactation or a cycle of reproduction has not been studied more as a lot of questions on this topic preoccupy goat farmers. Macedo et al. (2002) observe that in Saanen goats, a supplementation strategy with a 30% energy requirement throughout lactation is more efficient than with 60% at the beginning and 15% at the end, because a fall in milk production occurs when concentrate supplies decrease from 60 to 15%.

It is not surprising that the number of papers on this topic is limited because their experimental design is complex and difficult to implement. But all these papers are very interesting and can feed the reflection of goat nutrition experts.

3. Some comments on the present knowledge and research work on goat nutrition

3.1. Background knowledge

This review has revealed the progress made over the past 15 years. This has gone from relatively limited knowledge on the nutritional characteristics of goats, e.g. their frequent refusals and thorough feed choices in the behaviour field, to how each nutritional characteristic expresses itself in various environments, in different animal management systems and under varying feeding conditions. To avoid setting up experiments or research programs on subjects about which publications have already been made, every researcher should review the preceding work thoroughly. The grey literature on goat nutrition is sometimes more interesting than papers published in scientific journals. Topics dealt with in goat nutrition are feeding behaviour, particularly on pastures or rangelands, feed digestibility, tree leaf or by-product utilization, effects of nutritional factors on growth, milk and hair production, while nutritional adaptation to harsh environments, underfeeding, factors influencing energy consumption, quality of goat products (milk, cheese, meat, etc.) and reproduction performance along with the connection between nutrition and pathology require more attention.

3.2. Genotype specificity

A general deduction is that goat nutrition in a tropical environment follows the same physiological mechanisms as under temperate conditions, but genotypes can present specificities enabling a better adaptation to feeding conditions. For example, Dutta et al. (1998) observed no difference in nitrogen utilization in three Indian breeds well adapted to these agro-climatic conditions, while Silanikove et al. (1980) observed large differences in digestibility of very poor forage and urea recycling in Bedouin and Saanen goats.

3.3. Economic importance

Many papers indicate that the best economical results are not obtained with the diet that gives the best milk or growth performance (Su et al., 2002b; Goonewardene et al., 2002a; Brij and Murdia, 2002). No matter how well the animals may perform, goat farmers may reject the recommendations if they are not both practical and economical.

3.4. Interpreting experimental results

The interpretation of the results of nutritional experiments sometimes raises problems. In order to produce a set of valid data and to avoid misinterpretations of results and hence confusion in applying these, researchers should (1) review the literature to be acquainted with the progress in the field; (2) note the evolution of methodology and use the most appropriate and up to date methodology; (3) present experimental diets on the basis of the energy and protein values of these diets, taking into account the estimated energy and protein requirements of goats, according to their physiological status; (4) be sure not to include supplements or medication in the diets that may have inexplicable effects; (5) if a supplement is being tested, be sure to test it so that all its consequences can be verified; (6) be sure not to limit or invalidate the experiment by having too few goats in the experiment, animals that differ in their physiological status (growing, adult, pregnant, lactating, sex, diseased, such as parasite infested, etc.) and genotype; (7) be sure of the timeframe for the experiment to avoid momentary responses that are not sustained over changing physiological conditions, such the whole lactation period; (8) fit the genotype to the environment and if the experiment includes genotypes being compared, be sure to have the correct controls.

Farmers are interested in results being practical (applicable without major reorganisation of their infrastructure) and the results must have a positive economic outcome. Farmers' production capacity is also better off if the variability in responses to nutritional improvements between animals within the herd is reduced. Furthermore, farmers are more likely to accept and apply results if they were part of the planning of the experiment and the anticipated outcome, such as carcass quality or milk yield and composition.

3.5. Factors limiting the application of scientific results in the field

Progress in research has resulted in the nutritive value, ingestibility, digestibility of the new feed tested on goats, the effect on performance and the optimal proportion in diets being presented together, as in the McMillan et al. (2002) paper, making it possible for a goat farmer to decide whether or not to use a specific feed with full knowledge of objective data. Still, results on feed palatability, which determines the level of acceptability for goats (Morand-Fehr, 2003a), remain lacking. Required are accurate tables on tropical feeds like those on feeds of temperate areas (Sauvant et al., 2002) are still lacking. The nutrient requirements for goats well adapted to arid areas must be produced because such animals digest bad quality forage better and save protein through efficient urea recycling.

When feed intake cannot be controlled, as on rangelands, the ingested energy and protein cannot be estimated, hence the difficulty in establishing feeding programs and strategies. Under tropical conditions, the serious constraints imposed by the environment and livestock conditions explain why in certain cases, technological transfer is still difficult in goat nutrition in spite of progress. However, knowledge about goat body conditions can partly make up for the impossibility of calculating what goats ingest in rangelands or pastures, and so make it possible to establish a feeding program in this kind of environment.

4. Some suggestions to improve efficiency in applying knowledge on goat nutrition in the field

It is probable that the financial support for goat research, particularly on goat nutrition, will not increase in the future. The alternative is to seek better research efficiency.

In developed countries, the application of research results generally raises few difficulties owing to standardized feeding methods and basic organization. It is also relatively easy to know how to apply new results obtained on sheep or cows to goats owing to past experience and to the similarities in the production systems of the three ruminant species.

We have to support and develop basic research on ruminant behaviour, digestion and mechanisms explaining the influence of nutrients on neurohormonal balance or on immunity replies, etc., using goats as the experimental model. At the same time, “spin-off” from this research, which is interesting for the field, must be accumulated.

Still, the main question to solve is how to improve the efficiency of research on goat nutrition and technological transfer in tropical areas where 95% of the world’s goats live and goat farming is frequently linked to the poorest areas.

The choice of research topics useful for goat farming is essential and it is essential to include goat farmers and executive officers of goat development in the planning phase, and where necessary also the end users of products (consumers) to match experimental programs with user demand.

Much can be achieved with research teams and networks at the national or international level (Morand-Fehr, 2000a,b; Devendra, 2000a,b; Lebbie, 2000). In Europe, the European FAO-CIHEAM network enables quicker progress in these topics by establishing standard methods for the definition of goat carcasses or evaluation of body conditions, or by using meta-analysis to analyse experimental results from several research teams working with various experimental conditions (Meschy et al., 2001).

Successful technological transfer includes informing the end users of all the consequences and pathological risks (increased the risk of acidosis with high energy diets).

These proposals require better organization of research on goat nutrition by avoiding researcher isolation, by founding networks and by improving the spread of research knowledge. Moreover, everyone involved in goat development and in goat research, particularly in goat nutrition, must be in constant contact and meet regularly.

5. Conclusions

This update of scientific knowledge and recent progress in goat nutrition has brought into focus the substantial progress achieved over the last few years, particularly for research involving tropical aspects, feeding behaviour, nutritional utilization of rangelands, pastures, tree leaves, and by-products. Nutritive adaptation of goats in arid areas under nutrition and the effect of nutritional factors on reproduction and product quality, are not yet sufficiently studied.

Efforts have been undertaken to facilitate the application of scientific research in the field. The application of feed blocks, the method of body condition evaluation, of the substitution of concentrate by tropical plants or by-products have already given significant results in the field because goat farmers are particularly motivated by these three subjects. The efficiency of research and the technological transfer on goat nutrition can be further improved by facilitating contact between goat development and research, and by implementing research networks which can define the priority in research subjects, establish standard methods and analyse the overall results published to make their application in the field easier under a variety of conditions. This technological transfer must not accept one model of goat feeding, the intensive one which is the easiest to study and to manage. On the contrary, it must protect the biodiversity of various goat-feeding systems and maintain the sustainability of intensive or extensive systems of goat feeding, of pastures and rangelands used by goats.

The points raised in this paper cannot be taken for granted, but must be said regularly because though specialists of goat development and applied research may agree on them, they do not always applied them in the field.

Even if goat farming has very different characteristics in temperate and tropical areas, collaboration between north and south research units in the sector of goat nutrition seems easy to implement owing to complementary objectives. This kind of collaboration must be supported by FAO and other international organizations, such as IGA, since the improvement of goat feeding is an efficient way to rapidly obtain better technical and economical results.

In conclusion, as Devendra (2000b) already mentioned in, the use of research results and improved technologies are rapidly responsive approaches to overcome existing constraints. The focus on improved nutrition is especially critical, since it is the major constraint throughout large portions of the world.

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