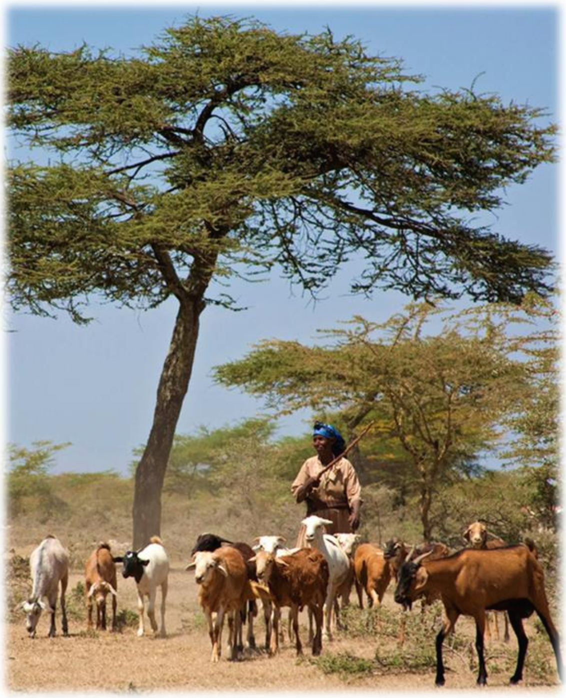


Sustainable intensification of integrated livestock production systems in the Sahel, West Africa

A literature analysis to identify suitable browse species as supplementary livestock feed in Burkina Faso, Mali and Senegal

University of Kassel

Faculty of Organic Agriculture

Thesis submitted for the Degree of Bachelor of Science in Organic Agriculture

Submitted by
Hannah Grund-Magomu
Born on 28.09.1991 in Düsseldorf

Matriculation Number
33364250

Reviewers
1st Dr. habl. Regina Rößler
2nd Prof. Dr. Eva Schlecht

Department
Animal Husbandry in the Tropics and Subtropics

Submission
June 2021

Acknowledgments

Completing this thesis and my Bachelor studies was made possible through the generous and patient support of my family and friends. I warmly thank my husband, Apollo Magomu, and my children, “Liby” Liberty, Alinda and Thomas, who have always given me inspiration and motivation to complete my studies and this thesis with success. Furthermore, I wish to thank my mother, Regina Vickery-Grund, for simultaneously providing invaluable support and professional proofreading, and my friends, Anne, Lea, Teresa and Jule, for helping me to digest and reflect my work. To the first and second reviewer, Dr. Regina Rößler and Prof. Dr. Eva Schlecht, I extend my gratitude for inviting me to research on the manifold Sahel region, and for guiding me and trusting in my ability to ‘bachelor’ this interesting study. To write my thesis with the aim of providing relevant insights for the SustainSahel project has been exciting and motivating. It is within my ambition that the results will be – to some extent – beneficial to livestock keepers and their animals, and to promoting sustainability in the unique Sahel region.

TABLE OF CONTENTS

I Figures

II Tables

III Abbreviations

ADF	*acid detergent fiber*
ADL	*acid detergent lignin*
ANF	*anti-nutritional factors*
BF	*Burkina Faso*
BW	*body weight*
BWG	*body weight gain*
CH4	*methane*
CILSS	*Comité Permanent Inter-états de Lutte contre la Sécheresse dans le Sahel*
CO2	*carbon dioxide*
CP	*crude protein*
DM	*dry matter*
DMDeg	*dry matter degradability*
DMI	*dry matter intake*
FCR	*food conversion ratio*
FiBL	*Institut de recherche de l'agriculture biologique*
GP	gas production
GP24	*gas production after 24 hours of incubation*
ME	*metabolic energy*
MPT	*multi-purpose trees and shrubs*
ND	*nitrogen degradability*
NDF	*neutral detergent fiber*
OM	*organic matter*
OMDeg	*organic matter degradability*
OSS	*Sahara and Sahel Observatory*
PA	*proanthocyanidins*
SE	*standard error of mean*
SEM	*standard error of weighted mean*
UNDESA	*United Nations Department of Economic and Social Affairs*

1 Introduction

Immense pressure is placed on food production systems in the Sahel region. Major influencing factors are climate change and population growth. Strategies of dealing with the growing demands of the population have not been sufficient, especially under constant unstable environmental, political and economic conditions (CILSS 2016, p. 30). “Re-greening” (CILSS 2016, p. 70), in the form of agroforestry, has been adopted by farmers in Burkina Faso and other West African countries for economic and ecological reasons. The inclusion of perennials on cropland along with sustainable management and improvement of grazing areas have great potential to improve the degraded lands of the region (CILSS 2016). “*SustainSahel - Synergistic use and protection of natural resources for rural livelihoods through systematic integration of crops, shrubs and livestock in the Sahel*” (FiBL 2021b) is a EU funded research and innovation project that takes a holistic approach to improving agri-production systems in the Sahelian region of Burkina Faso, Mali and Senegal. The aim is to enhance productivity to benefit the people while including climate relevant factors such as soil fertility and biodiversity. (FiBL 2021a). The overall aim of this thesis is to analyze available literature to identify browse trees and shrubs of semi-arid and arid regions that have the potential to enhance livestock productivity in these regions through a comparative literature analysis.

1.1 Problem definition

Study site

The three West African countries Burkina Faso (BF), Mali and Senegal are all in the sub-tropics, and to some extent, partly in the Sahel: the northern areas of BF and Senegal, and the central area of Mali. The Sahel is often described as a belt that spreads across West, Central and East Africa and is on average 350km wide (CILSS 2016, p. 7). Its natural border to the north is the Sahara Desert, to the south it is the equatorial region (OSS 2019). The climate of this region is described as arid or semi-arid with a distinct wet and dry season. It is characterized by an average annual precipitation of 200 to 600 mm and a mean temperature of 33°C to 36°C. The difference of temperatures is greater between day and night (10°C to 15 °C difference) than the interannual variation (6°C to 10°C) (OSS 2019, p. 8). The precipitation in West Africa is determined by certain air masses from the Atlantic Ocean and the Sahara Desert leading to the unique belt-like pattern of different climate regions. Figures 1 and 2 show these regions which are distinguished by increases from north to south in of both the amount of rainfall and length of the rainy season.

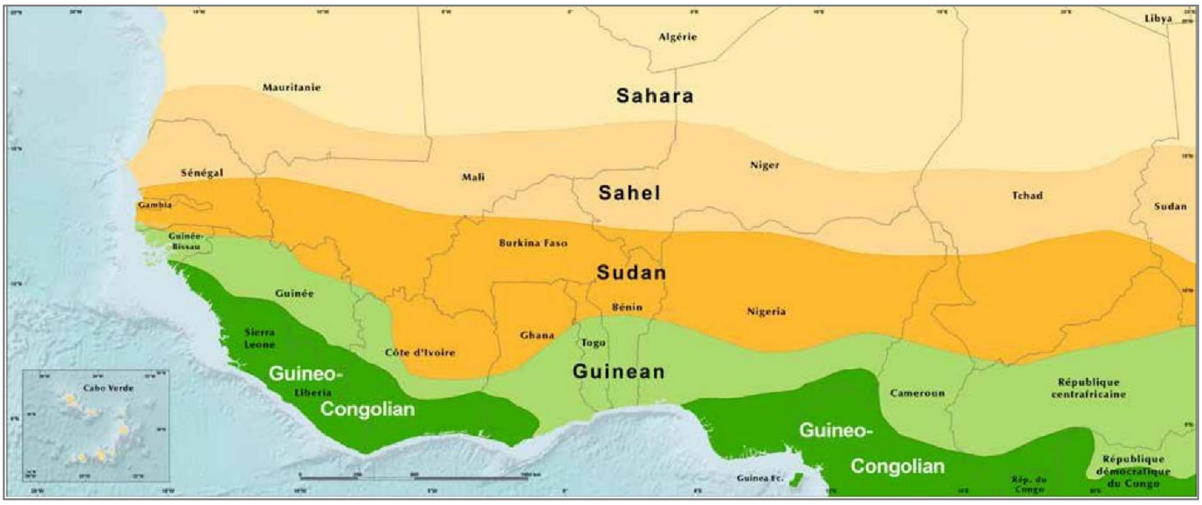


Figure 1 The bioclimatic regions of West Africa from north to south: Sahara, Sahel, Sudan, Guinean, Guineo-Congolian region

(Source: CILSS 2016, p.8)

The greater constraint in the Sahel zone is not the low average precipitation, but the variations in onset and distribution throughout a year and over decades making the environment harsh and vulnerable at the same time. On one hand, most of the rainfall occurs once a year in a three-month rainy season. The sandy soils in the region cannot store the water masses sufficiently and high losses through run-off and soil erosion are typical. On the other hand, years of adequate rainfall are often followed by years of heavy drought, which makes forecasting nearly impossible (CILSS 2016, p. 34).

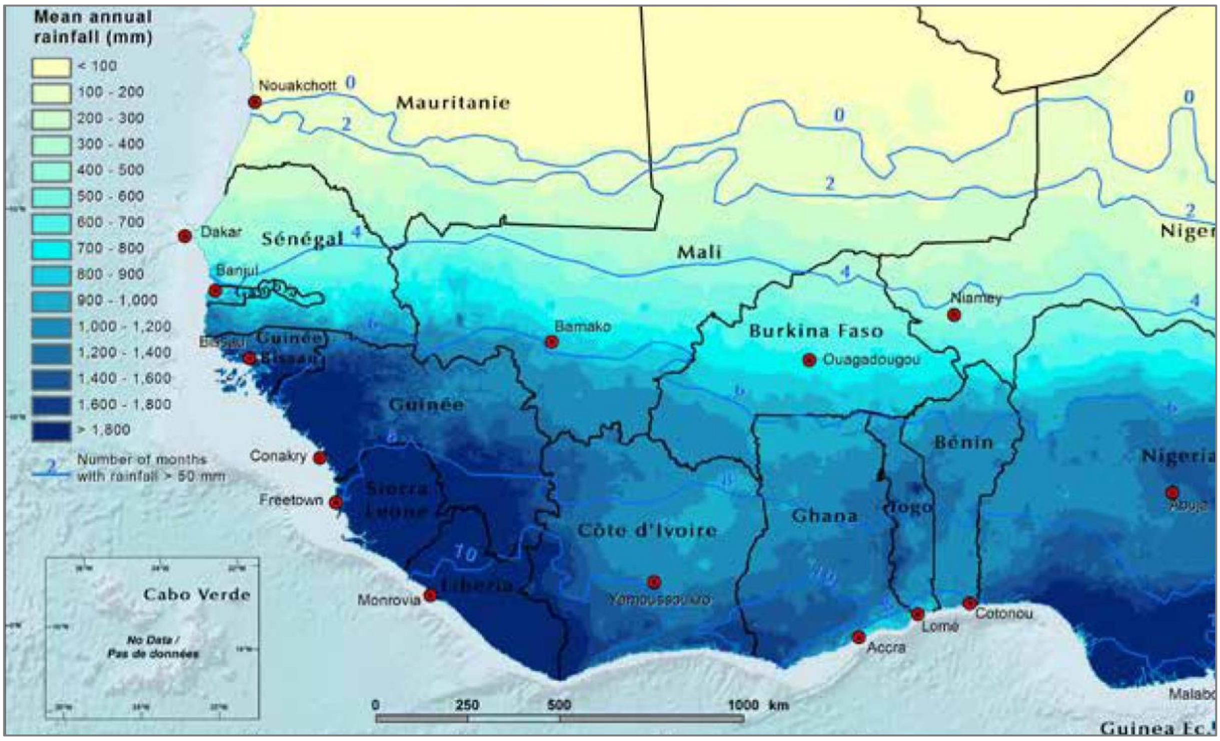


Figure 2 Mean annual rainfall 1981–2014, with number of months of 50 mm or more of rainfall

(Source: Funk et el. 2015, in: CILSS 2016, p. 34)

The natural vegetation in the Sahelian area of BF, Mali and Senegal is mainly shrub and/or tree steppe or savannah. It is the result of the long presence of humans and animals. Spiny trees, especially the genus *Acacia*, and the predominantly annual grasses of the genera *Aristida* and *Cenchrus* are distinguishing features. As the aridity gradually increases from south to north, the natural vegetation decreases (OSS 2019, p. 16). Within one place the difference in vegetation and land productivity can be strongly influenced by the seasonal changes of the wet and dry seasons. In the Sahel region, a tree savannah can look vital and productive in the wet season but appears most unfavorable in the dry season (Figure 3).

Figure 3 Dry versus wet season ground photographs of a tree savanna area in north-central Senegal (Source: CILSS 2016, p. 29)

Vulnerability of the Sahel region is also contributed to by poor soil quality and soils susceptible to erosion due to low organic matter incorporation. Most of the Sahel countries are prone to land degradation and desertification, and have been affected by this for some decades (OSS 2019, p. 33).

Food production systems and land-use changes

Natural resources are the main source of livelihood and/or income for the (rural) people of the Sahel region. The region is rich in diversity and, if managed well, has the potential to cater for a large population. Three food production systems dominate the region: a) transhumance, b) mixed agriculture and animal keeping, and c) irrigated agriculture with animal breeding (OSS 2019, p.19). During dry seasons, grazing and foraging animals of semi-arid regions are not sufficiently supplied with nutrients, with low protein content being a major concern (Bosma and Bicaba 1997; Mafindi et al. 2018; Sanon et al. 2008a). Alternative feed sources and supplements for the intensification of the livestock sector is of utmost importance.

In trying to adapt to climate disasters of the last decades, many people in these countries have either expanded crop lands or returned to (agro-)pastoralism. In both cases, the traditional extensive production systems have not been altered sufficiently and this limits their potential. Furthermore, pastoralism is also negatively affected by climate changes and thus needs improving for future adaptiveness (OSS 2019). In the Sahel region, livestock fattening is a traditional production focus (Sanon et al. 2008a). The keeping of small ruminants, such as sheep and goats, is more affordable to rural people in developing countries, and the produce is important in their diets. (Yusuf et al. 2018).

Land-use in West Africa has been affected by two major drivers of change over the last three decades: human activity and climate change. With human activity, the growing population is part of the problem. The global population continues to grow, and projections estimate that the populations of BF, Mali and Senegal will double by 2050 with an annual growth rate of approximately 2.9% (UNDESA 2019, p. 14). Consequently, there is a growing demand for food (OSS 2019). The increase in population, alongside a lack of job creation in other sectors, has led to over-exploitation of natural resources and land usage. So far, agricultural intensification mainly involves cropland expansion, which changes forests and grazelands into cropping areas and thus eliminates the natural vegetation (CILSS 2016, p. 42). Deforestation due to changes in land-use management has impacted in several ways: land degradation, soil erosion, loss of carbon stock, loss of biodiversity and loss of browse areas for pastoralists (OSS 2019, p. 34).

Sustainable intensification of livestock production in the Sahel of West Africa has two equally paramount demands which must be intertwined: improving the level of animal performance, and protection and enhancement of the natural environment. There is potential to increase food production (quality and quantity) and its sustainability by integrating trees and shrubs (FiBL 2021a). Browse species, in particular multi-purpose trees and shrubs (MPT), can be adequate low-cost alternatives or supplements to low-value feed (Bamikole and Ikhatua 2010; Hailemariam et al. 2016; Melesse et al. 2019; Ouédraogo-Koné et al. 2009; Yusuf et al. 2018). There is great need to identify the suitability and applicability of individual MPTs for livestock production in the Sahel zone.

1.2 Research objective

Despite the potential of MPTs, the present state of research regarding supplementation with browse feed in ruminant production in the Sahel region is limited. The question arises whether **the available literature on MPTs as livestock feed in the tropics can be used to identify suitable MPTs for sustainable intensification of livestock production in the Sahel region.** This is the subject of this thesis. The specific aims are to provide an overview of the available literature on this topic and to identify possible relevant browse species by evaluating their potential suitability as feed in ruminant production in the Sahel. The species will be compared according to (a) nutritional value, and (b) impacts on animal performance. If suitable browse species are identified, the analysis will be completed with recommendations for further feeding experiments, more specifically for those in the ongoing SustainSahel project.

1.3 Structure of the thesis

Following the introduction, a theoretical framework is presented to give background information on animal nutrition and how suitable feed can be identified. Methods of acquiring the reviewed literature and the selection criteria for suitable browse species will be outlined in chapter three. In chapter four, an overview of the literature sources and their data is presented. Results regarding the browse species are presented in this manner: (a) chemical composition, (b) nutritional value obtained through experiments (degradability and gas production characteristics) and (c) nutritional value and animal performance obtained in feeding trials (digestibility, feed intake and body weight changes). The results are discussed in chapter five according to the defined criteria. Finally, in the conclusion, the question will be answered if suitable MPTs for sustainable intensification of livestock production in the Sahel region could be identified using the available literature on MPTs as livestock feed in the tropics, and which of these can be recommended for the SustainSahel project.

2 Theoretical framework

2.1 Sustainable intensification

Only looking at intensification cannot be the answer to fulfilling the needs of a growing population (OSS 2019, p. 19). When considering sustainability, both productivity and natural resources need to be part of the strategy. Protecting forests and savannah is crucial to biodiversity and climate change mitigation. But protecting these areas would seem to contradict with the need to produce more food for growing populations (and development). However, increasing production without continual land extension is the most advisable solution for sustainable intensification in this area. The current trend for more sustainable food production in this region is to integrate agriculture and pastoralism into one system. “Re-greening” (CILSS 2016, p. 70), in the form of agroforestry, has been adopted by farmers in BF and other West African countries for economic and ecological reasons. The inclusion of perennials on cropland, along with sustainable management and improvement of grazing areas, have great potential to enhance biodiversity, improve the degraded lands of the region and increase productivity at the same (CILSS 2016). Only species which are adapted to the local climate can be suitable for sustainable intensification (Melesse et al. 2019). Introduced species have more constraints than indigenous species, which are known to be more adaptive to the local environment (Larbi et al. 1996b). Neglect of the socio-economic perspectives in the last decades has put programs of enhancing productivity in the West African Sahel region on an unsustainable path. The SustainSahel project includes human and environmental factors, and aims at the improvement of both (FiBL 2021a).

2.2 Multi-purpose trees and shrubs

Apart from their value for humans as, for example, fuel wood, timber, medicinal purpose and forage production, MPTs have various positive effects on climate relevant aspects, namely the potential to increase soil fertility, enhance biodiversity and reduce methane (CH4) emissions caused by small ruminants (Melesse et al. 2019). They are woody species, often leguminous browse, in a category of high fiber-high protein feeds (Jayasuriya 2002). The common acacias are also among MPTs and have great potential regarding sustainable intensification because they are adapted to the climate and contain high protein levels (Abdulrazak et al. 2000). But it is important to note that MPTs contain high amounts of anti-nutritional factors (ANF) which influence the digestibility of the forage negatively. ANFs are secondary plant substances that protect the plant against herbivores (van Soest 1994, p.196) and are associated with CP content in plants (Stangl 2014a, p.26). High CP-forage, such as MPTs, is known to have high ANF content (Reed 1995, p. 1516). ANFs include toxic substances which inhibit digestion and, therefore, utilization of MPTs (Wilkins 2000, p. 7). Tannins, which are a part of ANFs, have been reported to have various effects on animal performance. Condensed tannins impair protein digestion, while the effects of soluble tannins and the extent of their toxicity are not yet fully comprehended (van Soest 1994, pp.203-204). In addition, tannins analyzed through different methods are incomparable because the respective methods have different objectives, and results are interfered with through different sampling handling (ibid.). Here it should be noted that although the frequent synonymous use of proanthocyanidins (PA) and condensed tannins is not strictly correct (Reed 1995), its common use will be maintained in this thesis.

2.3 Livestock Production

Ruminant nutrition fulfils a double role of simultaneously providing for the animal itself, and the microbes in the rumen. In turn, the microbial activity in the rumen determines the digestibility of feed and is essential for protein utilization (Jayasuriya 2002). Ruminants can digest fibrous forages well and they can utilize feed which is less favorable in its constituents for other livestock (Schwarz 2014, p. 358). Feed is usually evaluated by the energy it can provide to the animals as metabolic energy (ME). The energy requirements of the animals depend on the performance of the animal (maintenance, production) (Stangl 2014b, 139f.). In cases where ME is unknown, the nutritional value needs to be obtained in feeding trials (where effects of feed on animal performance are measured) or through analytical experiments. Different feedstuff has different chemical composition. Positive interaction between different feedstuff can improve the utilization of a ration. Supplementation can provide for additional values in basal diets and improve production. A valuable supplement allows for maximum utilization of feed without conflicting with human demands. (Jayasuriya 2002). "*Supplements should also be easily available, cheap and require minimum labour for storing and feeding. At the same time, they should improve animal productivity, be compatible with on-farm feeding practices and offer minimum chances of poisoning or ill health to the animal*" (ibid., p.14)

2.3.1 Body weight changes, feed intake and digestibility

An important value for livestock fattening is the body weight gain (BWG), which is mainly influenced by feed intake and digestibility of feed. There are two aspects defining intake: firstly, the quantity of feed that is taken in by the animal and secondly, the quality of what the system of the animal ingests through the feed (digestibility) (van Soest 1994, p. 337). Browsing animals such as goats are more selective than cattle and sheep when it comes to feed. In feeding experiments where the voluntary preference of feeds is in question, choice should be allowed for. If the BWG of a particular feed is of interest, feed should be chopped and mixed well to reduce possible selection by preference (van Soest 1994, p. 338). 3-4% dry matter intake (DMI) relative to the body weight (BW) of the animals is the recommended intake for ruminants (Mafindi et al. 2018; Partey et al. 2018). The feed conversion ratio (FCR) measures the amount of feed consumed (g/day) to gain weight (g/day). Low FCR means less DMI is needed per kg weight gain (Sanon et al. 2008a; Yusuf et al. 2018). One must bear in mind that because of varying digestibility, higher DMI does not necessarily lead to more weight gain (Sanon et al. 2008a). BWG, feed intake and digestibility are interactions between animals (species, breed, size etc.) and the feed offered (quantity, quality, fiber content, palatability etc.). To truly know the value of a particular feed, feeding trials can be conducted. But these are time-consuming and expensive (Beever and Mould 2000), and a uniform environment for the trial animals must be provided to obtain valid values (Rymer 2000). Nevertheless, feedstuff needs to be evaluated for its potential intake and digestibility to make planning possible for producers.

2.3.2 Degradability

In order to predict DMI and digestibility, a faster and less expensive way is to estimate degradability. This can be done through *in vitro* and *in situ* experiments (Ørskov 2000, p. 186). *In vitro* gas production (GP) measures the volume of gas produced when incubating a feed sample in rumen fluid. Gas is a by-product of rumen digestion caused by microbial activity; carbon dioxide (CO2) and CH4 are the main gases produced (Beever and Mould 2000, p. 29). The extent of GP indicates microbial activity and, hence, digestibility (Williams 2000, p. 195). Digestibility can be estimated either by interpreting the volumes produced or calculated from the GP characteristics. At the same time, the presence of ANFs which inhibit microbial activity can be identified (Larbi et al. 1996b). As the analysis is not standardized, comparing results is difficult. Among other aspects, duration of incubation, animal species used as inoculum donors as well as feeds offered to the inoculum donors are all unique to each study (Williams 2000, p. 195). *In situ* degradability, which is also known as *in sacco* degradability or nylon bag technique, evaluates the disappearance of both soluble and fermentable contents from a feed sample fistulated in the rumen (Ørskov 2000, 186ff.).. Nitrogen degradability (ND) is useful in identifying any need for supplementation. Dry matter degradability (DMDeg) reflects the cell-wall degradability of forages. Organic matter degradability (OMDeg) values can be sometimes useful. Degradability values are only comparable to a certain extent for similar reasons as the GP values. Degradability values can accurately predict DMI, but the actual consumption can be different from the prediction (ibid.).

2.3.3 Chemical composition

The Weende feed analysis provides information on the chemical composition of biomass. It can give valuable information for estimating the nutritional value of feed but does not give detailed information on which feed rations can be calculated (Stangl 2014a, 20ff.). A modification of the Weende analysis by van Soest allows for the differentiation between fiber fractions. This helps to identify the more digestible and less digestible fiber fractions. The fractions in the Weende/van Soest analysis are dry matter (DM), organic matter (OM), CP, crude fat, neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL) and crude ash (ibid.). CP is a major source of nitrogen in animal feed and is crucial for sufficient microbial activity and synthesis of amino acids in ruminants. Cellulose and hemicellulose, represented by the NDF and ADF fractions, are digestible for ruminants because of the ruminal microbes. The ADF:NDF ratio indicates the amount of cellulose and lignin, whereby a low ratio is preferable (Abdulrazak et al. 2000). ADL has a negative impact on digestibility and, furthermore, it is negatively correlated to PAs which influence intake negatively (see Chapter 2.2). High CP levels can help to overcome the negative impact of lignin on digestibility (van Soest 1994, pp. 191–192). Medium levels of digestible fiber and low values of ADL are desirable. It is impossible to make accurate predictions on digestibility and feed intake of forage knowing only the chemical composition, but if no other data is available, then CP, NDF, ADF and ADL fractions can be useful to classify feedstuff. In combination with *in vitro* and/or *in situ* analyses, they provide relevant information for classifying the nutritional value of browse species (El Hassan et al. 2000).

3 Material and Methods

3.1 Literature search and selection

To find articles regarding browse species relevant for livestock production in the Sahelian region of BF, Mali and Senegal, a desktop research was conducted by a team of researchers within the Task/Deliverable 6.1 of the SustainSahel project between 6th November and 11th December 2020. The search was done in French and English and limited to publications from 1995 to 2020 (SustainSahel 2021). All categories for the literature selection process are presented in Table 1. The search was done through electronic catalogues and databases, search engines and scientific journals. Search entries were a combination of three, sometimes four, key terms. An example search term was “trees, livestock feed, Sahel”. Articles were then selected according to relevance (ibid.). The used information sources and classification categories for relevant literature to the project are in Appendix I. From the potentially relevant literature, 27 articles in English containing information on browse as feed in dry sub-humid areas and/or animal health care were provided to analyze in this thesis.

Table 1 Relevance criteria for the literature selection

Step	Process	Criteria
1	Desktop Research by SustainSahel	1.) "*trees*" or "*shrubs*" + 2.) "*livestock feed*" or "*forage*" or "*woody fodder*" + 3.) "*Sahel*" or "*West Africa*" or "*Burkina Faso*" or "*Mali*" or "*Senegal*" or "*dry subhumids*" optional: 4.) "*nutritional value*" or "*gastrointestinal nematodes*" or "*local knowledge*" or "*seasonality*" or "*phenology*" or "*pruning*"
2	Selection by thesis reviewers	1.) trees/shrubs as feed and/or animal health care but outside the focus area **or** additional information on relevant tree species 2.) English language
3	Selection by thesis author	1.) experimental studies 2.) ruminants

(Source: own Table, Steps 1 and 2 based on SustainSahel 2021)

The abstracts of these 27 articles provided the first overview of the literature for this thesis. The first author, year, title, journal, keywords, region, browse species, animals, obtained values, study type and conclusions were tabulated using Microsoft Excel. A focus was then set on experimental studies which refer to ruminants. Five articles did not fulfil all these additional criterions and were excluded. After reviewing the full articles, including tables and figures, details on tree/shrub species name (full scientific name, synonyms), family, country, region (Sahara, and/or Sahel, and/or Sudano-Sahel, other), parts used, livestock species, season (dry and/or wet), composition, energy content, digestibility and degradability of nutrients, anti-nutritional factors, DMI, opportunities and constraints, were again tabulated using Microsoft Excel according to the procedure used in SustainSahel (SustainSahel 2021). The pool of selected literature was evaluated for its relevance to the Sahel. The two main parameters were frequency of country and method of study. Then the literature was separated into either experimental analyses or feeding trials to analyze the content for its relevance to livestock keeping.

3.2 Data selection and analysis

Selection process to verify that species reviewed in this thesis could be adapted to the climate of the Sahel region was realized from April 5th to 9th 2021 using two scientific plant databases (CABI 2021; Fern 2014). The species had to fulfil the following two criterions: their habitat is within regions with 1.) annual precipitation of not more than 600 mm, and 2.) dry seasons of 8 to 9 months (see Chapter 1.1). From the 70 species presented in the relevant articles, 24 species from eleven articles were excluded. In cases of species presented in studies for humid regions but without further information online, plants were also disregarded. These were *Dactyledania barterii* (Welw.) and *Senna nodosa* (Larbi et al. 1998). In this process, one article was excluded because one of the two species did not fulfil the climate criteria and the browse was analyzed as mixture. Some descriptions of sampled materials (parts used) were not clearly distinguishable. Results regarding leaves and leaves mixed with petioles, or small stems, twigs, or branches are included. One article in which the studies were based on other sampling material was also excluded.

Variations in use of scientific names among studies were eliminated by using the online database 'The Plant List' (Royal Botanic Gardens, Kew and Missouri Botanical Garden 2021). Corrections were made for *Acacia nilotica* (L.) Delile (presented as *Acacia nilotica var. adansonii* (Guill. & Perr.) Kuntze by Zabré et al. 2018), *Acacia tortilis subsp. raddiana* (Savi) Brenan (presented as *Acacia raddiana* (Savi) by Zabré et al. 2018), *Agelaea pentagyna* (Lam.) Baill. (presented as *Agelaea obliqua* by Aschfalk et al. 2000) *Cytisus proliferus* L.f. (presented as *Chamaecytisus palmensis* by El Hassan et al. 2000 and Melesse et al. 2019), *Ficus sycomorus* L. (presented as *Ficus gnaphalocarpa* (Miq.) Steud. ex Miq. by Partey et al. 2018) and *Pouteria alnifolia* (Baker) Roberty (presented as *Malacantha alnifolia* by Aschfalk et al. 2000). The two acacias *Acacia tortilis* and *A. tortilis subsp. raddiana* were treated as two different species. All species with their full scientific names and respective references are listed in Appendix II.

Regarding the chemical composition, the most frequently mentioned parameters – CP, NDF, ADF and ADL – were compared. The fermentation characteristics of total GP, GP after 24 hours of incubation (GP24) and CH4 were compared. Asymptotic GP, potential GP and GP96 were all treated as 'total volume of gas produced'. Furthermore, potential and effective DM degradability a well as true and *in vitro* DM digestibility were treated as 'DM degradability' (DMDeg). Effective OM degradability, degraded OM, true OM digestibility and *in vitro* OM digestibility were all treated as 'OM degradability' (OMDeg). Digestibility, DMI and BWG were compared to the respective control diets. Abdulrazak et al. (2000) presented potential and effective DMDeg which showed high variation. In their study, the effective DMDeg was based on an estimated outflow rate (0.05/h). These values were excluded from the comparison. The evaluation of the browse was done according to the criteria in Table 2.

Table 2 Evaluation criteria for the examined values

Examined values	**Criteria**
Composition	high CP above 100 g/kg DM (Jayasuriya 2002) moderate NDF below 600 g/kg DM (Bamikole and Ikhatua 2010) low ADL , or low ADF:NDF ratio exclusion of toxic ANFs
Gas Production	moderate to high GP above 25 ml/200mg DM (Steingass and Arbelot 1994) low CH4 production below 15L CH4/kg DM (Schlecht May 2021)
Degradability	moderate or high degradability above 60% (Schlecht May 2021)
Digestibility	similar or improved digestibility compared to control diet
Animal Performance	similar or improved feed intake compared to control diet positive BWG, similar or improved ccompared to control diet

(Source: own Table)

Results of the same species within one study were averaged. This was also done for the two varieties of *Sesbania sesban* (var 10 865 and var 15 036, El Hassan et al. 2010). Results in the study of Sanon et al. (2008a) regarding chemical composition of plants at different heights and of the 'biomass' (possibly pods were analyzed) were excluded. In cases of more than one value for the same species between studies, the mean and the standard error of mean (SE) were calculated. For the descriptive statistics, the weighted mean and standard error of weighted mean (SEM) were calculated. For the evaluation of correlations, the coefficient of determination, R^2, was calculated. By using a ranking method based on Steingass and Arbelot (1994), correlations became visibly obvious. The FCR was calculated for studies where it was not presented, and both the daily gains and the daily intake were given.

4 Results

In total, 21 literature sources (20 scientific articles and 1 CGIAR info note) published between 1997 and 2019 were found and analyzed. Four studies were published before 2000 (Bosma and Bicaba 1997; Larbi et al. 1996a; b; 1998), nine studies between 2000 and 2010 (Abdulrazak et al. 2000; Aschfalk et al. 2000; Bamikole and Ikhatua 2010; Calabrò et al. 2007; El Hassen et al. 2000; Ouédraogo-Koné et al. 2008; 2009; Sanon et al. 2008a; b) and seven after 2010 (Hailemariam et al. 2016; Pal et al. 2015; Mafindi et al. 2018; Melesse et al. 2019; Partey et al. 2018; Yusuf et al. 2018; Zabré et al. 2018). The studies were from Benin (1), BF (6), Ethiopia (3), Ghana (1), India (1), Kenya (1), Niger (1), Nigeria (5) and South Africa (1). Seven studies, namely Bosma and Bicaba (1997), Calabrò et al. (2007), Ouédraogo-Koné (2008; 2009), Sanon et al. (2008a; b) and Zabré et al. (2018), pertained directly to the Sahel region. In total, 46 browse species adapted to dry sub humid climate were found. The following twelve species were studied in the Sahel/Sudano zone: *Acacia nilotica*, *Acacia tortilis subsp. raddiana*, *Acacia senegal, Afzelia africana*, *Combretum aculeatum, Gliricidia sepium, Guiera senegalensis*, *Leucaena leucocephala*, *Maerua crassifolia*, *Pergularia tomentosa*, *Pterocarpus erinaceus* and *Pterocarpus lucens*. Table 3 presents all species of the review, including the countries and regions they were studied in with respective references. Some species were studied in more than one country and/or region. The most cited species was *L. leucocephala* with six references. Other species with three or more references were *A. africana* (3), *Albizia lebbeck* (4), *A. nilotica* (4), *A. senegal* (3), *Azadirachta indica* (3), *Moringa oleifera* (4) and *Pterocarpus erinaceus* (3). Nine of the articles covered ten acacia species. Except Hailemariam et al. (2016), all reviewed studies presented the CP content and other chemical compositions of browse to identify nutritional values. Furthermore, the studies could be grouped into experimental studies with *in situ* and *in vitro* analyses (n = 9) or with feeding trials (n = 12).

Table 3 List of browse species and countries of study with respective references.

Browse Species	Countries	References
Acacia abysinica	Ethiopia	Melesse et al. 2019[1]
Acacia angustissima	Ethiopia, Nigeria	El Hassan et al. 2000[4]; Larbi et al. 1998[5]
Acacia brevispica	Kenya	Abdulrazak et al. 2000[2]
Acacia mellifera	Kenya	Abdulrazak et al. 2000[2]
Acacia nilotica [a]	Kenya, Ethiopia, India, BF	Abdulrazak et al. 2000[2]; Melesse et al. 2019[1]; Pal et al. 2015[3]; Zabré et al. 2018[1]
Acacia nubica	Kenya	Abdulrazak et al. 2000[2]
Acacia senegal [a]	Ethiopia, India, BF	Hailemariam et al. 2016[1]; Pal et al. 2015[3]; Sanon et al. 2008[1]
Acacia seyal	Kenya	Abdulrazak et al. 2000[2]
Acacia tortilis	Kenya, India	Abdulrazak et al. 2000[2]; Pal et al. 2015[3]
Acacia tortilis subsp. raddiana [a]	BF	Zabré et al. 2018[1]
Afzelia africana [b]	BF, Ghana	Ouédraogo-Koné et al. 2008[2]; 2009[2]; Partey et al. 2018[6]
Agelaea pentagyna	Benin	Aschfalk et al. 2000[1]
Ailanthus excelsa	India	Pal et al. 2015[1]
Albizia lebbeck	Nigeria, India	Larbi et al. 1996a[4];b[5];1998[5]; Pal et al. 2015[1]
Albizia procera	Nigeria	Larbi et al. 1996a[4]
Azadirachta indica	Ethiopia, India	Hailemariam et al. 2016[1]; Melesse et al. 2019[1]; Pal et al. 2015[3]
Bridelia ferruginea	Benin	Aschfalk et al. 2000[1]
Cajanus cajan	Ethiopia	Melesse et al. 2019[1]
Combretum aculeatum [b]	BF, Niger	Bosma and Bicaba 1997[1]; Calabrò et al. 2007[1]
Cytisus proliferus	Ethiopia	El Hassan et al. 2000[4]; Melesse et al. 2019[1]
Ficus religiosa	India	Pal et al. 2015[1]
Ficus sycomorus	Ghana	Partey et al. 2018[6]
Ficus thonningii	Nigeria	Bamikole and Ikhatua 2010[1]
Gliricidia sepium [b]	Niger, Nigeria	Calabrò et al. 2007[1]; Larbi et al. 1998[5]
Guiera senegalensis [a]	BF	Sanon et al. 2008b[1]
Leucaena diversifolia	Nigeria	Larbi et al. 1998[5]
Leucaena leucocephala [b]	Benin, BF, Nigeria, Ethiopia, Nigeria, India	Aschfalk et al. 2000[1]; Bosma & Bicaba 1997[1]; El Hassan et al. 2000[4]; Melesse et al. 2019[1]; Larbi et al. 1998[5]; Pal et al. 2015[3]
Maerua crassifolia [b]	Niger	Calabrò et al. 2007[1]
Mallotus oppositifolius	Benin	Aschfalk et al. 2000[1]
Mangifera indica	Benin, India	Aschfalk et al. 2000[1]; Pal et al. 2015[1]
Moringa oleifera	Nigeria, Ethiopia, India, South Africa	Mafindi et al. 2018[4]; Melesse et al. 2019[1]; Pal et al. 2015[1]; Yusuf et al. 2018[4]
Moringa stenopetala	Ethiopia	Melesse et al. 2019[1]
Morus alba	India	Pal et al. 2015[1]
Newbouldia laevis	Nigeria	Larbi et al. 1998[5]
Parkia biglobosa	Nigeria	Larbi et al. 1998[5]
Pergularia tomentosa [b]	Niger	Calabrò et al. 2007[1]
Pericopsis laxiflora	Ghana	Partey et al. 2018[6]
Pouteria alnifolia	Benin	Aschfalk et al. 2000[1]
Prosopis cineraria	India	Pal et al. 2015[1]
Prosopis juliflora	Ethiopia	Melesse et al. 2019[1]
Pterocarpus erinaceus [b]	BF	Ouédraogo-Koné et al. 2008[2]; 2009[2]; Partey et al. 20186
Pterocarpus lucens [a]	BF	Sanon et al. 2008a[1]; b[1]
Senna siamea	Nigeria	Larbi et al. 1998[5]
Senna spectabilis	Nigeria	Larbi et al. 1998[5]
Sesbania sesban	Ethiopia	El Hassan et al. 2000[4]; Melesse et al. 2019[1]
Tamarindus indica	India	Pal et al. 2015[1]

Note: Superscript letters indicate Sahel (a) or Sudano-Sahel (b) region. Superscript numbers indicate different descriptions of sampling material: 1: leaves, 2: leaves and petioles, 3: leaves and small branches, 4: leaves and small twigs, 5: leaves and small stems, 6: no specification. (Source: own Table)

4.1 Chemical Composition

CP values were analyzed to identify the species potential as CP supplements. For better clarity, the browse species were grouped into four categories: acacias, high CP (above 220 g/kg DM), medium CP (between 150 and 220 g/kg DM) and low CP (below 150 g/kg DM). Table 4 shows CP, NDF, ADF and ADL values for browse species of the CP groups. The ranges of CP, NDF, ADF as well as ADL are presented in Figure 4. The weighted mean CP for the browse species except the acacias was 185 g/kg DM (SEM = 7). The highest CP value was found for *M. stenopetala* (296 g/kg DM). The lowest CP values were found for *Bridelia ferruginea* and *Pergularia tomentosa* (each 99 g/kg DM). All other browse species had CP above 100 g/kg DM. High CP values above 220 g/kg DM were found for *M. oleifera* (281 g/kg DM, n = 4, SE = 15), *Prosopis juliflora* (261 g/kg DM), *S. sesban* (236 g/kg DM, n = 8, SE = 8), *Leucaena diversifolia* (232 g/kg DM), *A. lebbeck* (231 g/kg DM, n = 4, SE = 17) and *L. leucocephala* (223 g/kg DM, n = 6, SE = 18).

For some species, there were wide ranges found for CP values between studies. In the high CP group, the CP values of *A. lebbeck* ranged from 184 to 257 g/kg DM (Pal et al. 2015 and Larbi et al. 1998, respectively). Those found for *L. leucocephala* ranged from 174 to 270 g/kg DM (Pal et al. 2015 and Aschfalk et al. 2000, respectively). Five of the examined studies presented CP levels above 230 g/kg DM. For *M. oleifera*, CP ranged from 256 to 315 g/kg DM (Melesse et al. 2019 and Yusuf et al. 2018, respectively). In the medium CP group, *A. africana*, *A. indica* and *G. sepium* were presented with different CP values among the studies. CP for *A. africana* ranged from 137 to 226 g/kg DM (Partey et al. 2018 and Ouédraogo-Koné et al. 2009, respectively), for *A. indica* from 149 to 222 g/kg DM (Aschfalk et al. 2000 and Pal et al. 2015, respectively) and for *G. sepium* from 150 to 254 g/kg DM (Calabrò et al. 2007 and Larbi et al. 1998, respectively). In the low CP group, wide differences of CP values were found for *C. aculeatum* and *P. erinaceus*. CP of *C. aculeatum* ranged from 95 to 161 g/kg DM (Calabrò et al. 2007 and Bosma and Bicaba 1997, respectively) and for *P. erinaceus* from 105 to 197 g/kg DM (Partey et al. 2018 and Ouédraogo-Koné et al. 2009, respectively).

The values of the fiber fraction were studied to identify species with favorable fiber content with regard to digestibility. NDF and ADF values were found for the same 29 species. The lowest fiber values were found for species with medium and high CP content. *S. sesban*, *Maerua crassifolia* and *Morus alba* had NDF below 300 g/kg DM (206, 231 and 285 g/kg DM, respectively) and ADF below 180 g/kg DM (139, 170 and 159 g/kg DM, respectively). Highest NDF values above 600 g/kg DM were found for species of low and medium CP: *Newbouldia laevis, Albizia procera, F. sycomorus* and *Pericopsis laxiflora* (627, 648, 669 and 676 g/kg DM, respectively). These were also the species with the highest ADF values, all above 400 g/kg DM (457, 565, 506 and 576 g/kg DM, respectively). The weighted mean NDF was 426 g/kg DM (SEM = 19). The weighted mean ADF was 306 g/kg DM (SEM = 16). In the high CP group, all NDF values were below these mean values and the weighted mean NDF and ADF of this group were also lower (339 and 220 g/kg DM, respectively). In the low CP group, the weighted mean NDF was 475 g/kg DM and ADF 343 g/kg DM. Figure 5 shows the strong positive correlation between NDF and ADF with $R^2 = 0,90$.

ADL values were found for 27 species. The lowest ADL values below 50 g/kg DM were found for *M. crassifolia* (35 g/kg DM), *M. oleifera* (37 g/kg DM, n = 2, SE = 9), *Moringa stenopetala* (37 g/kg DM) and *C. aculeatum* (49 g/kg DM, n = 2, SE = 11). All highest ADL values were found in the medium and low CP groups. The highest, found in the medium group, was found for *A. procera* (324 g/kg DM), followed by *G. senegalensis* (234 g/kg DM), from the low CP group. All other browse species had ADL values below 200 g/kg DM. The weighted mean ADL was 103 g/kg DM (SEM = 9). The weighted mean ADL of the low CP group was 115 g/kg DM. In the high CP group, it was 63 g/kg DM. Wide ranges between individual values were found for *L. leucocephala* (high CP group), *A. africana* (medium CP group) and *P. erinaceus* (low CP group). The found ADL values for *L. leucocephala* ranged from 33 to 140 g/kg DM (Bosma and Bicaba 1997 and Pal et al. 2015, respectively), for *A. africana* from 129 to 163 g/kg DM and for *P. erinaceus* from 86 to 152 g/kg DM (Partey et al. 2018 and Ouédraogo-Koné et al. 2008 respectively).

Values of the fiber fractions NDF, ADF and ADL were not found for *Agelaea pentagyna*, *B. ferruginea*, *Mallotus oppositifolius* and *Pouteria alnifolia*, which were all analyzed in the same study (Aschfalk et al. 2000). The authors presented crude fiber values of 374, 283, 188 and 256 g/kg DM respectively. They also analyzed *L. leucocephala* and *M. indica* and presented crude fiber values of 204 and 287 g/kg DM, respectively. For *L. diversifolia*, *N. laevis*, *P. biglobosa*, *Senna spectabilis* and *S. siamea,* which were all analyzed in the same study (Larbi et al. 1998), no ADL values were found. To estimate their lignin content and compare them to the other species in this thesis, their ADF:NDF ratios were calculated. They were 82%, 73%, 74%, 77% and 67%, respectively. *G. sepium* and *A. lebbeck*, for which ADL values were found in other studies, were also analyzed by Larbi et al. (1998). *G sepium* had ADL above the weighted mean and its ADF:NDF ratio was 79% while *A. lebbeck* had ADL below the weighted mean and its ADF:NDF ratio was 60%.

Table 4 Chemical composition of browse leaves grouped into low, medium and high CP.

	Browse Species	CP	NDF	ADF	ADL
low CP	*Agelaea pentagyna*	131	n.a.	n.a.	n.a.
	Ailanthus excelsa	146	369	219	65
	Bridelia ferruginea	99	n.a.	n.a.	n.a.
	Combretum aculeatum	128 (33)[2]	309 (24)[2]	246 (29)[2]	49 (11)[2]
	Ficus religiosa	125	402	291	73
	Ficus sycomorus	116	669	506	146
	Guiera senegalensis	105	590	401	234
	Mangifera indica	102 (5)[2]	364	211	118
	Pergularia tomentosa	99	418	371	73
	Pericopsis laxiflora	102	676	576	103
	Pouteria alnifolia	133	n.a.	n.a.	n.a.
	Prosopis cineraria	134	431	282	135
	Pterocarpus erinaceus	145 (27)[3]	551 (35)[3]	374 (13)[3]	119 (33)[2]
	Pterocarpus lucens	148 (1)[2]	489 (9)[2]	355 (4)[2]	180
	Tamarindus indica	119	431	308	147
medium CP	*Afzelia africana*	181 (26)[3]	593 (27)[3]	390 (5)[3]	146 (17)[2]
	Albizia procera	188	648	565	324
	Azadirachta indica	186 (37)[2]	324	234	121 (2)[2]
	Cajanus cajan	200	n.a.	n.a.	125
	Cytisus proliferus	209 (1)[2]	388	217	72 (4)[2]
	Ficus thonningii	205	558	402	114
	Gliricidia sepium	202 (52)[2]	404 (23)[2]	320 (15)[2]	171
	Maerua crassifolia	193	231	170	35
	Mallotus oppositifolius	161	n.a.	n.a.	n.a.
	Morus alba	184	285	159	52
	Newbouldia laevis	171	627	457	n.a.
	Parkia biglobosa	163	539	398	n.a.
	Senna siamea	173	444	285	n.a.
	Senna spectabilis	212	414	319	n.a.
high CP	*Albizia lebbeck*	231 (17)[4]	388 (30)[4]	232 (62)[4]	77 (16)[2]
	Leucaena diversifolia	232	414	338	n.a.
	Leucaena leucocephala	223 (18)[6]	319 (42)[4]	213 (34)[4]	80 (24)[4]
	Moringa oleifera	281 (15)[4]	311 (45)[2]	189 (65)[2]	37 (9)[2]
	Moringa stenopetala	296	n.a.	n.a.	37
	Prosopis juliflora	261	n.a.	n.a.	119
	Sesbania sesban	236 (8)[2]	206	139	54 (11)[2]
	Weighted mean	185 (7)	435 (19)	306 (16)	103 (9)

Note: low: CP < 150, medium: 150 – 220; high: CP> 220. All values in g/kg DM. Single values taken from the original sources, mean values calculated (n>1 presented in superscript numbers, SE in parentheses). See Appendix II for corresponding references. ADF: acid detergent fiber, ADL: acid detergent lignin, CP: crude protein, DM: dry matter; n.a.: not available; NDF: neutral detergent fiber; SE: standard error of mean. (Source: own Table)

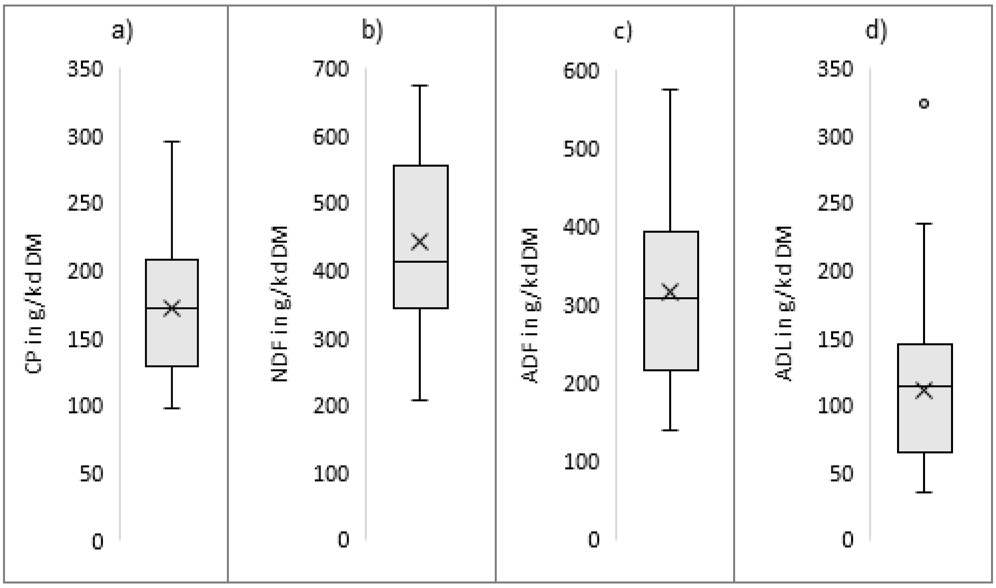


Figure 4 Boxplots of a) CP, b) NDF, c) ADF and d) ADL values of browse leaves

Note: All values in g/kg DM. ADF: acid detergent fiber; ADL: acid detergent lignin, CP: crude protein; DM: dry matter. (Source: own Diagram, values as in Table 4)

Acacia spp.

The chemical composition of the acacias is presented in Table 5. With the exception of NDF and ADF for *A. abysinica*, all chemical composition values were found for all acacias. *A. tortilis subsp. raddiana* had the lowest CP (120g/kg DM) and *A. abysinica* (277 g/kg DM) the highest. The weighted mean CP of the acacias was 186 g/kg DM (SEM = 12). Besides *A. abysinica,* CP above 200 g/kg DM was also found for *A. nubica* (213 g/kg DM), *A. brevispica* (213 g/kg DM) and *A. angustissima* (265 g/kg DM, n = 2, SE = 10).

NDF and ADF values were found for nine acacias. NDF and ADF were lowest for *A. nubica* (154 and 114 g/kg DM, respectively) and highest for *A. angustissima* (459, n = 2, SE = 67, and 362 g/kg DM, n= 2, SE = 97, respectively). The weighted mean NDF was 326 g/kg DM (SEM = 23), but seven out of nine species lie below that. Similarly, six out of nine species lie below the weighted mean value found for ADF (216 g/kg DM, SEM = 17). The lowest ADL values were found for *A. nubica* (51 g/kg DM), *A. senegal* (62 g/kg DM, n = 2, SEM = 9), *A. tortilis subsp. raddiana* (71 g/kg DM) and *A. mellifera* (77 g/kg DM). Highest ADL was 176 g/kg DM for *A. abysinica*. The weighted mean ADL was 102 g/kg DM (SEM = 9).

Table 5 Chemical composition of acacia leaves

	Browse Species	CP	NDF	ADF	ADL
Acacias	*A. abysinica*	277	n.a.	n.a.	176
	A. angustissima	265 (7)[2]	459 (67)[2]	317 (97)[2]	82
	A. brevispica	213	308	210	114
	A. mellifera	194	269	192	77
	A. nilotica	165 (3)[4]	389 (54)[3]	256 (33)[3]	127 (38)[4]
	A. nubica	213	154	114	51
	A. senegal	156 (15)[2]	316 (6)[2]	175 (7)[2]	62 (9)[2]
	A. seyal	134	230	168	121
	A. tortilis	163 (10)[2]	309 (13)[2]	233 (18)[2]	106 (5)[2]
	A. tortilis subsp. Raddiana	120	272	118	71
	Weighted Mean	186 (12)	326 (23)	216 (17)	102 (9)

Note: All values in g/kg DM. Single values taken from the original sources, mean values calculated (n>1 presented in superscript numbers, SE in parentheses). See Appendix II for corresponding references. ADF: acid detergent fiber; ADL: acid detergent lignin; CP: crude protein; n.a.: not available; NDF: neutral detergent fiber; SE: standard error of mean. (Source: own Table)

The data concerning the fiber fraction of *A. angustissima* and *A. nilotica* varied widely. Larbi et al. (1998) tested leaves and small stems and found 553 g/kg DM NDF and 454 g/kg DM ADF, while El Hassan et al. (2000) used leaves and small twigs and found 364 g/kg DM NDF and 179 g/kg DM ADF. Only one value for ADL was found (82 g/kg DM, El Hassan et al. 2000). Yet, the CP values of the respective references are similarly high (274 and 255 g/kg DM, respectively). In the case of El Hassan et al. (2000), the ADF:NDF ratio and ADL content was more favorable. For A. nilotica, CP ranged from 159 (Zabré et al. 2018 and Pal et al. 2015) to 172 g/kg DM (Abdulrazak et al. 2000), NDF ranged from 312 to 520 g/kg DM, ADF from 214 to 338 g/kg DM (Abdulrazak et al. 2000 and Zabré et al. 2018, respectively) and ADL from 43 to 250 g/kg DM (Melesse et al. 2019 and Zabré et al. 2018, respectively).

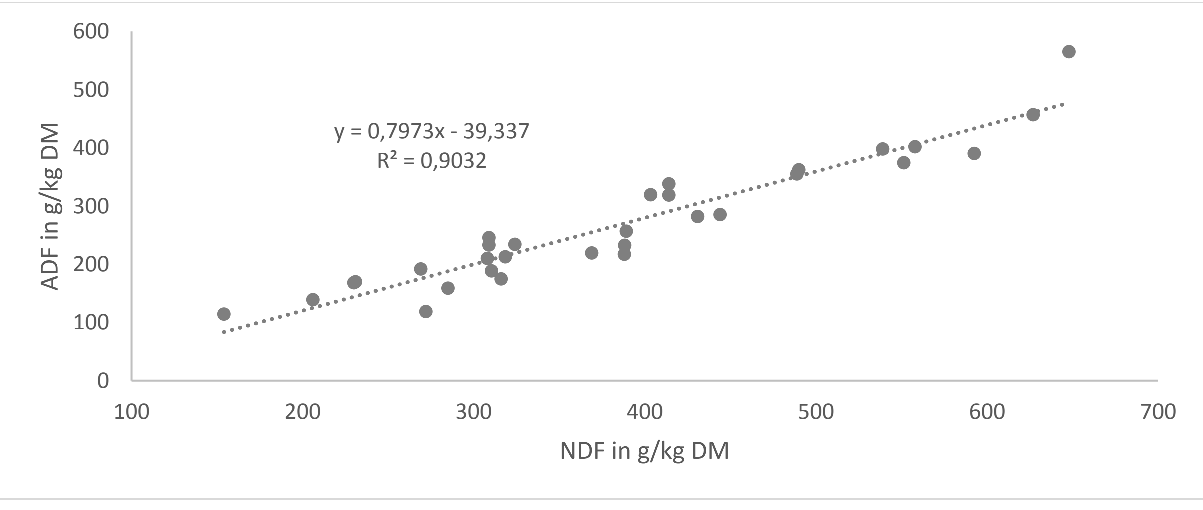


Figure 5 Relation between NDF and ADF in browse species

Note: All values in in g/kg DM. ADF: acid detergent fiber; DM: dry matter; NDF: neutral detergent fiber. (Source: own Diagram, values as in Tables 4 and 5)

Because of the assumption that MPTs are high in CP and fiber, correlations between fiber and CP were calculated but none were found. In Table 6, species are ranked according to their CP and ADL content. It can be seen that high CP (above the weighted mean) coincides with low ADL (below the weighted mean), even though the correlation could not be proven statistically (R^2 = 0,08).

Table 6 Classification of browse samples according to ADL and CP content

	CP above	CP below
ADL below	*Acacia angustissima* *Acacia mellifera* *Acacia nubica* *Albizia lebbeck* *Cytius proliferus* *Leucaena leucocephala* *Mallotus crassifolia* *Moringa oleifera* *Moringa stenopetala* *Sesbania sesban*	*Acacia senegal* *Acacia tortilis subsp. raddiana* *Ailanthus excelsa* *Combretum aculeatum* *Ficus religiosa* *Morus alba* *Pergularia tomentosa*
ADL above	*Acacia abysinica* *Acacia brevis* *Prosopis juliflora*	*Acacia nilotica* *Acacia seyal* *Acacia tortilis* *Afzelia africana* *Albizia procera* *Azadirachta indica* *Cajanus cajan* *Ficus sycomorus* *Ficus thonningii* *Gliricidia sepium* *Guiera senegalensis* *Mangifera indica* *Pericopsis laxiflora* *Prosopis ceneraria* *Pterocarpus lucens* *Tamarindus indica*

Note: Entries in alphabetical order. 'above': above weighted mean; 'below': below weighted mean. ADL: acid detergent lignin; CP: crude protein. (Source: own Table based on Steingass and Arbelot 1994).

4.2 *In situ* and *in vitro* experiments

Nine studies obtained GP values through *in vitro* experiments (Abdulrazak et al. 2000; Calabrò et al. 2007; El Hassan et al. 2000; Larbi et al. 1996a; b;1998; Melesse et al. 2019; Pal et al. 2015; Zabré et al. 2018). Five of these calculated degradability using the GP values (Calabrò et al. 2007; El Hassan et al. 2000; Melesse et al. 2019; Pal et al. 2015; Zabré et al. 2018). Five obtained degradability values through *in situ* experiments (Abdulrazak et al. 2000; El Hassan et al. 2000; Larbi et al. 1996a; b;1998). El Hassan et al. (2000) did both. The animal species used in the *in situ* and *in vitro* trials were buffalo, cattle and sheep. The animals and breeds of the different the *in situ* and *in vitro* studies are presented in Appendix III. In total, 35 species (including ten acacias) were analyzed for degradability (72% of all species) and 34 species (including nine acacias) for GP (74% of the species). Excluding the acacias, DMDeg was presented for 19 species in five studies (El Hassan et al. 2000; Larbi et al. 1996a; b; 1998; Pal et al. 2015) and OMDeg for 19 species were also found in five studies (Calabrò et al. 2007; El Hassan et al. 2000; Melesse et al. 2019; Pal et al. 2015; Zabré et al. 2018). ND was analyzed *in situ* for eleven species in four studies (El Hassan et al. 2000; Larbi et al. 1996; b; 1998). Except El Hassan et al. (2000), all studies obtained OMDeg *in vitro*. For the acacias, DMDeg was obtained for eight species in four studies (Abdulrazak et al. 2000; El Hassan et al. 2000; Larbi et al. 1998; Pal et al. 2015), OMDeg for all species and ND for one species (El Hassan at al. 2000). Without the acacias, GP24 was presented in two articles for 15 species (Melesse et al. 2019; Pal et al. 2015) and CH4 was measured for the same 15 species in the high, medium and low CP group. For the acacias, GP24 was presented in four articles for eight acacias (Abdulrazak et al. 2000; Melesse et al. 2019; Pal et al. 2015; Zabré et al. 2018). CH4 for five acacias was obtained in one study (Abdulrazak et al. 2000). Two of the three studies which obtained CH4 values were from outside Africa (Melesse et al. 2019; Pal et al. 2015). Calabrò et al. (2007) and Zabré et al. (2018) studied GP and degradability characteristics of six species in the Sahel region. The studies from Larbi et al. (1998), Pal et al. (2015) and Melesse et al. (2019) covered 25 species (54% of the species). Nine of the species which were not covered by *in situ* or *in vitro* experiments had CP below average. Five species (apart from the acacias) that were analyzed in more than one study were from the medium and high CP groups and showed different results for each parameter with SE from 0 to 8 and 4 to 11 for degradability and GP, respectively.

4.2.1 Degradability

The degradability of DM, OM and nitrogen are of interest to estimate the utilization of forages. The values are presented in Table 7 (grouped according to CP) and Table 8 (acacias). The DMDeg among the browse species was relatively similar, which can be seen from the low SEM (SEM = 1). All DMDeg values were above 60%. Highest degradability was found for *M. oleifera* (83%), followed by *A. excelsa*, *M. alba* (each 82%) and *S. spectabilis* (80%). The lowest DMDeg was found for *A. procera* (61%) and *L. leucocephala* (63%, n=2, SE = 4). The weighted mean DMDeg was 72%. DMDeg for *A. lebbeck* and *L. leucocephala* was analyzed in more than one study. The former ranged from 70% (*in vitro* DMDeg) to 80% (potential DMDeg) (Pal et al. 2015 and by Larbi et al. 1996b, respectively) and the latter from 53% (*in vitro* DMDeg) to 70% (potential DMDeg) (Pal et al. 2015 and Larbi et al. 1998, respectively). Three of four values of *L. leucocephala* were above 60%. For *C. proliferus* and *S. sesban*, *in vitro* and *in situ* DMDeg were presented (El Hassan et al. 2000). For the former, it ranged from 68% (*in vitro* DMDeg) to 73% (*in situ* DMDeg) and for the latter, the results for *in vitro* and *in situ* DMDeg were identical (73% both).

Table 7 In situ and in vitro degradability of browse leaves

	Species	DMDeg	OMDeg	ND
low CP	*Ailanthus excelsa*	82 [c]	83 [e]	n.a.
	Combretum aculeatum	n.a.	63 [e]	n.a.
	Ficus religiosa	76 [c]	76 [e]	n.a.
	Mangifera indica	69 [c]	71 [e]	n.a.
	Pergularia tomentosa	n.a.	68 [e]	n.a.
	Prosopis cineraria	65 [c]	66 [e]	n.a.
	Tamarindus indica	72 [c]	72 [e]	n.a.
medium CP	*Albizia procera*	61 [a]	n.a.	68
	Azadirachta indica	77 [c]	69 [e] (8)[2]	n.a.
	Cajanus cajan	n.a.	49 [e]	n.a.
	Cytisus proliferus	70 [bc] (2)[2]	71 [de] (1)[2]	68
	Gliricidia sepium	74 [a]	57 [e]	84
	Maerua crassifolia	n.a.	83 [e]	n.a.
	Morus alba	82 [c]	79 [e]	n.a.
	Newbouldia laevis	66 [a]	n.a.	71
	Parkia biglobosa	73 [a]	n.a.	65
	Senna siamea	79 [a]	n.a.	92
	Senna spectabilis	80 [a]	n.a.	94
high CP	*Albizia lebbeck*	73 [ac] (2)[2]	70 [e]	90 (3) [3]
	Leucaena diversifolia	74 [a]	n.a.	76
	Leucaena leucocephala	63 [abc] (4)[4]	62 [de] (4)[3]	52
	Moringa oleifera	83 [c]	80 [e] (3)[2]	n.a.
	Moringa stenopetala	n.a.	83 [e]	n.a.
	Prosopis juliflora	n.a.	44 [e]	n.a.
	Sesbania sesban	73 [bc] (0)[2]	71 [de] (3)[2]	67
	Weighted Mean	72 (1)	69 (2)	77 (4)

Note: All values in %. Single values taken from the original sources, mean values calculated (n>1 presented in superscript numbers, SE in parentheses). See Appendix II for corresponding references. Superscript letters indicate different parameters: a: potential DMDeg; b: effective DMDeg; c: in vitro DMDeg; d: effective OMDeg; e: in vitro OMDeg. DMDeg: dry matter degradability; OMDeg: organic matter degradability; n.a. not available; ND: nitrogen degradability; SE: standard error of mean. (Source: own Table)

The OMDeg showed higher variation between species than DMDeg. The weighted mean OMDeg was 69% (SEM = 2). The lowest OMDeg values were found for *P. juliflora* (44%) and *C. cajan* (49%, ibid.). The highest values were found for *A. excelsa*, *M. crassifolia*, *M. stenopetala* (each 83%) and *M. oleifera* (80%, n = 2, SE = 3). *M. oleifera* showed high OMDeg in both references (76% and 82%, Melesse et al. 2019 and Pal et al. 2015, respectively). Besides *M. oleifera*, OMDeg for was presented in two or more studies for *A. indica*, *L. leucocephala, C. proliferus* and *S. sesban*. The former two varied widely. Their ranges (with respective studies) were as follows: *A. indica* from 61% to 77% (Melesse et al. 2019; Pal et al. 2015) and *L. leucocephala* from 56% to 70% (Pal et al. 2015; Melesse et al. 2019). Lowest ND was found for *L. leucocephala* (48%) and highest for *S. spectabilis* (94%), *S. siamea* (92%) and *A. lebbeck* (90%, n = 3, SE = 3). High ND above 80% was also found for

G. sepium (84%). Except for *L. leucocephala*, all found ND values were above 60%. The weighted mean ND was 77% (SEM = 4).

Acacia spp.

The lowest DMDeg was found for *A. angustissima* (52%, n = 3, SE = 4). The highest values were found for *A. senegal* (82%, Pal et al. 2015) and *A. nubica* (88%, Abdulrazak et al. 2000). The mean DMDeg was 69% (SEM = 3). More than one DMDeg value was found for *A. angustissima*, *A. nilotica* and *A. tortilis*. For *A. angustissima*, it ranged from 44% to 59% (Larbi et al. 1998 and El Hassan et al. 2000, respectively). For *A. nilotica* the range was 64% to 74% (Abdulrazak et al. 2000 and Pal et al. 2015, respectively) and for *A. tortilis*, from 74% to 80% (Pal et al. 2015 and Abdulrazak et al. 2000, respectively). The degradability of OM ranged from 51% (*A. nilotica*) to 81% (*A. senegal* and *A. tortilis subsp. raddiana*). The weighted mean OMDeg was 62% (SEM = 3). Differing values were again found for *A. nilotica* and *A. tortilis*. For *A. nilotica* OMDeg ranged from 48% to 75% (Abdulrazak et al. 2000 and Pal et al. 2015, respectively) and for *A. tortilis* it ranged from 52% to 75% (Pal et al. 2015 and Zabré et al. 2018, respectively). ND was only found for *A. angustissima* and it was 45% (n = 2, SE = 4).
Abdulrazak et al. (2000) presented DMDeg measurements after 16, 24, 48, 72 and 96 hours. The results show that 94% of *A. nubica*'s DM was degraded after 16 hours. For *A. brevispica* and *A. mellifera* roughly 90% or more DM was degraded after 48 hours (89% and 97%, respectively). The other species (*A. nilotica*, *A. seyal* and *A. tortilis*) needed longer for the same amount of DM degradation.

Table 8 In situ and in vitro degradability of acacia leaves

Species		DMDeg	OMDeg
Acacias	*A. abysinica*	n.a.	65 [e]
	A. angustissima	52 [abc] (4)[3]	52 [d]
	A. brevispica	72 [a]	48 [e]
	A. mellifera	77 [a]	49 [e]
	A. nilotica	69 [ac] (5)[2]	59 [e] (6) [4]
	A. nubica	88 [a]	64 [e]
	A. senegal	82 [c]	81 [e]
	A. seyal	66 [a]	n.a.
	A. tortilis	77 [ac] (2)[2]	63 [e] (11)[2]
	A. tortilis subsp. raddiana	n.a.	81 [e]
	Weighted Mean	69 (3)	62 (3)

Note: All values in %. Single values taken from the original sources, mean values calculated (n>1 presented in superscript numbers, SE in parentheses). See Appendix II for corresponding references. Superscript letters indicate different degradability parameters: a: potential DMDeg; b: effective DMDeg; c: in vitro DMDeg; d: effective OMDeg; e: in vitro OMDeg. DMDeg: dry matter degradability; OMDeg: organic matter degradability; n.a.: not available; ND: nitrogen degradability; SE: standard error of mean. (Source: own Table)

Tables 9 and 10 show little correlation between CP and ADL with OMDeg which was also the statistical finding (R^2= 0,01 and R^2=0,29, respectively). Nevertheless, most species are in the categories ‘above mean OMDeg/above mean CP’ and ‘above mean OMDeg/below mean ADL’.

Table 9 Classification of browse samples according to CP content and OMDeg

	OMDeg above	OMDeg below
CP above	*Acacia abysinica* *Acacia nubica* *Acacia senegal* *Albizia lebbeck* *Azadirachta indica* *Cytisus proliferus* *Maerua crassifolia* *Moringa oleifera* *Moringa stenopetala* *Sesbania sesban*	*Acacia angustissima* *Acacia brevispica* *Acacia mellifera* *Albizia procera* *Cajanus cajan* *Gliricidia sepium* *Leucaena leucocephala* *Prosopis juliflora*
CP below	*Acacia tortilis subsp. raddiana* *Acacia tortilis* *Ailanthus excelsa* *Ficus religiosa* *Mangifera indica* *Morus alba* *Tamarindus indica*	*Acacia nilotica* *Combretum aculeatum* *Pergularia tomentosa* *Prosopis cineraria*

Note: Entries in alphabetical order. ‘above’: above weighted mean; ‘below’: below weighted mean, CP: crude protein; OMDeg: organic matter degradability. (Source: own Table based on Steingass and Arbelot 1994)

Table 10 Classification of browse samples according to ADL content and OMDeg

	OMDeg above	OMDeg below
ADL below	*Acacia nubica* *Acacia senegal* *Acacia tortilis subsp. Raddiana* *Ailanthus excelsa* *Albizia lebbeck* *Cytius proliferus* *Ficus religiosa* *Maerua crassifolia* *Moringa oleifera* *Moringa stenopetala* *Morus alba* *Sesbania sesban*	*Acacia angustissima* *Acacia mellifera* *Combretum aculeatum* *Leucaena leucocephala* *Pergularia tomentosa*
ADL above	*Acacia abysinica* *Acacia tortilis* *Azadirachta indica* *Mangifera indica* *Tamarindus indica*	*Acacia brevispica* *Acacia nilotica* *Cajanus cajan* *Gliricidia sepium* *Prosopis cineraria* *Prosopis juliflora*

Note: Entries in alphabetical order. 'above': above weighted mean; 'below': below weighted mean. ADL: acid detergent lignin; OMDeg: organic matter degradability. (Source: own Table based on Steingass and Arbelot 1994)

4.2.2 Gas Production

Table 11 shows that highest and lowest GP were found in the high CP group. Total GP was lowest for *P. juliflora* (14 ml/ 200mg DM) and highest for *L. diversifolia* (65 ml/ 200mg DM). Other species with GP below 25 ml/200mg DM were *P. cineraria* (18 ml/ 200mg DM) and *M. indica* (23 ml/ 200mg DM) from the medium and low CP group, respectively. Values above 50 ml/ 200mg DM were also found for *Moringa* spp. The weighted mean was 38 ml/ 200mg DM (SEM = 2). The lowest GP24 was found for *P. juliflora* with 10 ml/ 200mg DM. Highest GP24 was found for *M. stenopetala* and *S. sesban* with each 45 ml/ 200mg DM. *S. sesban* was the only species which had the same results for GP and GP24 (Melesse et al. 2019). The weighted mean GP24 was 27 ml/ 200mg DM (SEM = 2). The lowest CH4 volumes were found in the low and medium CP group for *P. cineraria* and *C. cajan* (8,4 and 9 l/kg DM, respectively). CH4 presented for *P. juliflora* was negative (Melesse et al. 2019). The highest CH4 volumes were found in the high CP group for *M. stenopetala* and *S. sesban* (37,7 and 30,8 l/kg DM, respectively). The weighted mean CH4 was 17,0 l/kg DM (SEM = 2, excluding the negative value). The biggest variations in presented gas volumes were found for *M. oleifera* where GP ranged from 34 to 52 ml/ 200mg DM, GP24 from 26 to 45 ml/ 200mg DM and CH_4 from 12,1 to 37,7 l/kg DM (Pal et al. 2015 and Melesse et al. 2019, respectively).

Table 11 In vitro gas production of browse leaves

Browse Species		GP	GP24	CH4
low CP	*Ailanthus excelsa*	36 [b]	31	15,3
	Combretum aculeatum	30 [a]	n.a.	n.a.
	Ficus religiosa	37 [b]	24	11
	Mangifera indica	23 [b]	18	12
	Pergularia tomentosa	45 [a]	n.a.	n.a.
	Prosopis cineraria	18 [c]	11	8,4
	Tamarindus indica	40 [b]	27	16
medium CP	*Albizia procera*	25 [c]	n.a.	n.a.
	Azadirachta indica	36 [ab] (5)[2]	26 (4) [2]	14,0 (4) [2]
	Cajanus cajan	25 [a]	17	9,0
	Cytisus proliferus	49 [a]	40	27,3
	Gliricidia sepium	41 [ac] (5)[2]	n.a.	n.a.
	Maerua crassifolia	47 [a]	n.a.	n.a.
	Morus alba	34 [b]	26	12,1
	Newbouldia laevis	33 [c]	n.a.	n.a.
	Parkia biglobosa	34 [c]	n.a.	n.a.
	Senna siamea	53 [c]	n.a.	n.a.
	Senna spectabilis	50 [c]	n.a.	n.a.
high CP	*Albizia lebbeck*	37 [bc] (4)[4]	18	13,6
	Leucaena diversifolia	65 [c]	n.a.	n.a.
	Leucaena leucocephala	39 [abc] (5)[3]	30 (5) [2]	14,3 (4) [2]
	Moringa oleifera	42 [ab] (11)[2]	35 (9) [2]	21,4 (5) [2]
	Moringa stenopetala	56 a	45	37,7
	Prosopis juliflora	14 [a]	10	-5,8
	Sesbania sesban	45 [a]	45	30,8
	Weighted Mean	38 (2)	27 (2)	17 (2)

Note: GP and GP24 in ml/ 200mg DM, CH4 in l/kg DM. Single values taken from the original sources, mean values calculated (n>1 presented in superscript numbers, SE in parentheses). See Appendix II for corresponding references. Superscript letters indicate different GP parameters, a: asymptotic GP, b: potential GP, c: GP after 96 hours of incubation. CH4: methane; GP: total gas production; GP24: gas production after 24 hours of incubation; n.a.: not available; SE: standard error of mean. (Source: own Table)

Acacia spp.

Except *A. seyal*, all acacias were analyzed. Table 12 presents the volumes of gas produced for the acacias. Abdulrazak et al. (2000) presented GP96 and potential GP as two different parameters for *A. brevispica*, *A. mellifera*, *A. nilotica*, *A. nubica* and *A. tortilis*, whereby all SE between the two parameters within this study were 1 or less. Besides in this study, two or more GP values were found for *A. nilotica* and *A. tortilis*. *A. nubica* had the highest GP (42 ml/ 200mg DM, n = 2, SE = 1), followed by *A. abysinica (*41 ml/ 200mg DM) and *A. nilotica* (38 ml/ 200mg DM, n = 4, SE = 5). GP below 25 ml/ 200mg DM was found for *A. angustissima* (23 ml/ 200mg DM). The weighted mean GP was 36 ml/ 200mg DM (SEM = 1). GP24 ranged from 19 ml/ 200mg DM (*A tortilis* and *A. tortilis subsp. raddiana*) to 37 ml/ 200mg DM (*A. nubica*). Weighted mean GP24 was 25 ml/ 200mg DM (SEM = 2). *A. abysinica* produced the most CH4 among all browse species (28,7 l/kg DM). Lower CH4 values were found for *A. tortilis subsp. raddiana* (2,8 l/kg DM) and *A. nilotica* (6,4 l/kg DM). The weighted mean was 11 l/kg DM (SEM = 3). For *A. nilotica*, GP ranged from 32 to 52 ml/ 200mg DM (Pal et al. 2015 and Melesse et al. 2019, respectively), GP24 from 19 to 32 ml/ 200mg DM (Zabré et al. 2018 and Melesse et al. 2019, respectively) and CH4 from 4,5 to 9,8 (Zabré et al. 2018 and Pal et al. 2015, respectively). For *A. tortilis*, GP ranged from 23 to 35 ml/ 200mg DM and GP24 from 13 to 26 ml/ 200 mg DM (Pal et al. 2015 and Abdulrazak et al. 2000, respectively).

Table 12 In vitro gas production of acacia leaves

	Browse Species	GP	GP24	CH4
Acacias	*A. abysinica*	41 [a]	34	28,7
	A. angustissima	23 [c]	n.a.	n.a.
	A. brevispica	33 [bc] (1)[2]	20	n.a.
	A. mellifera	37 [bc] (1)[2]	22	n.a.
	A. nilotica	38 [abc] (5)[4]	24 (3) [4]	6,4 (2) [3]
	A. nubica	42 [bc] (1)[2]	37	n.a.
	A. senegal	35 [b]	30	13,2
	A. tortilis	31 [bc] (4)[3]	19 (6) [2]	11,1
	A. tortilis subsp. raddiana	n.a.	19	2,8
	Weighted Mean	36 (1)	25 (2)	11 (3)

Note: GP and GP24 in ml/ 200mg DM, CH4 in l/kg DM. Single values taken from the original sources, mean values calculated (n>1 presented in superscript numbers, SE in parentheses). See Appendix II for corresponding references. Superscript letters indicate different GP parameters, a: asymptotic GP, b: potential GP, c: GP after 96 hours of incubation. CH4: methane; GP: total gas production; GP24: gas production after 24 hours of incubation; n.a.: not available; SE: standard error of mean. (Source: own Table)

A strong positive correlation ($R^2 = 0,80$) between GP24 and CH4 was found for all browse species including acacias (see Appendix IV). Figure 6 shows the relative proportion of CH4 in the produced gas. Relatively high amounts of CH4 in relation to total volume of produced gas were found for *M. indica*, *A. procera*, *A. proliferus*, *M. oleifera*, *M. stenopetala*, *S. sesba*n and *A. abysinica*. The opposite is the case for *F. religiosa* and *A. nilotica*.

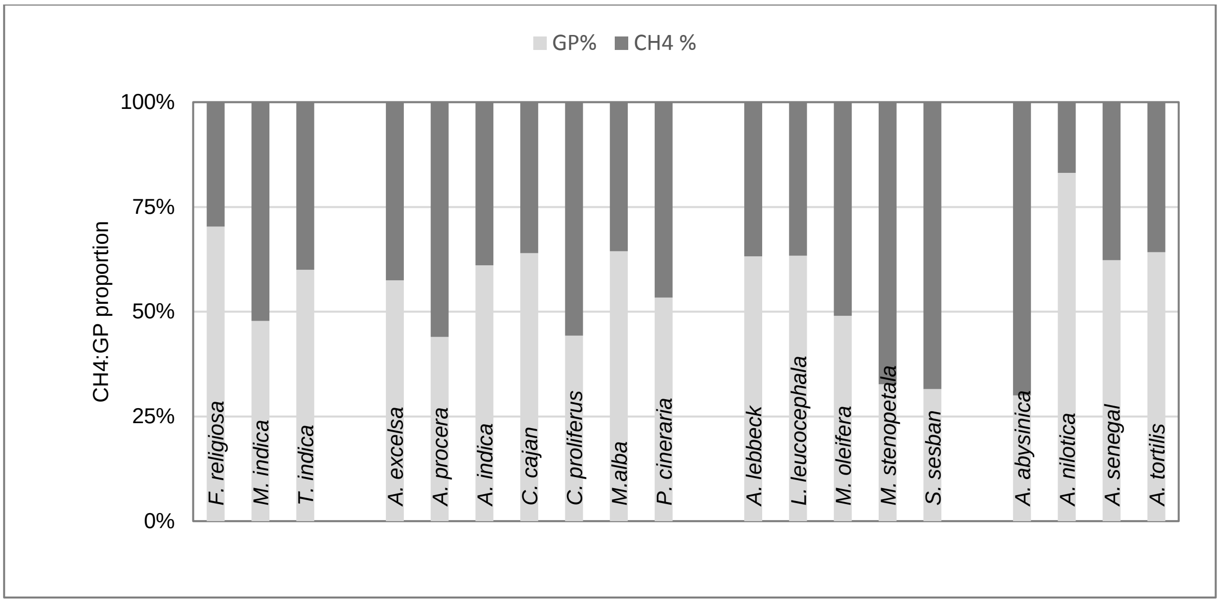


Figure 6 Proportion of CH4 in GP (in %) of incubated browse leaves.

Note: Grouped into low, medium and high CP, and acacias. CH4: methane production; CP: crude protein; GP: total gas production. (Source: own Diagram, values as found in Tables 11 and 12)

The classification of browse species according to their GP and OMDeg values is presented in Table 13. The correlation was not found ($R^2 = 0,19$). The ranking shows that most species are in the category 'OMDeg above/GP above' but that there are also some species with GP under the weighted mean and simultaneously OMDeg above.

Table 13 Classification of browse samples according to GP values and OMDeg

	OMDeg above	**OMDeg below**
GP below	*Ailanthus excelsa* *Acacia senegal* *Acacia tortilis* *Azadirachta indica* *Ficus religiosa* *Mangifera indica* *Morus alba*	*Acacia angustissima* *Acacia brevis* *Cajanus cajan* *Combretum aculeatum* *Prosopis cineraria* *Prosopis juliflora*
GP above	*Acacia abysinica* *Acacia nubica* *Albizia lebbeck* *Cytius proliferus* *Maerua crassifolia* *Moringa olifeira* *Moringa stenopetala* *Sesbania sesban* *Tamarindus indica*	*Acacia mellifera* *Acacia nilotica* *Gliricidia sepium* *Leucaena leucocephala* *Pergularia tomentosa*

Note: Entries in alphabetical order. 'above': above weighted mean; 'below': below weighted mean. GP: gas production; OMDeg: organic matter degradability. (Source: own Table based on Steingass and Arbelot 1994)

El Hassan et al. (2000) measured GP with different inclusion levels (0%, 15%, 30%, 60%) for *A. angustissima*, *C. proliferus*, *L. leucocephala* and *S. sesban* in order to detect ANFs. They showed that GP increased when higher levels of *C. proliferus* and *L. leucocephala* were included. The GP remained similar with inclusion of *S. sesban* but was lower with inclusion of *A. angustissima*. Larbi et al. (1998) reported significant differences when sampling in different seasons. In the dry season, *A. angustissima* produced 13 ml/ 200 mg DM, while in the wet season it reached 34 ml/ 200 mg DM.

The GP kinetics were tabulated by Abdulrazak et al. (2000), whereas they were shown in a figure by Calabrò et al. (2007) and Melesse et al. (2019). Abdulrazak et al. (2000) showed that GP of *A. nubica* was high after 12 hours (74% of total GP). *A. tortilis* showed fast fermentation compared to other acacias from this study (49% of total GP at 12 hours). Except *A. brevispica*, all acacias reached 90% of GP after 72 hours. In the figure of Calabrò et al. (2007), *M. crassifolia* and *P. tomentosa* stood out in comparison to other species of this study with high rates of fermentation before 12 hours. In the figure of Melesse et al. (2019), two species were highly distinguishable from others: *M. stenopetala,* which had high and fast fermentation (asymptote after 48 hours) and *P. juliflora*, which had very low but fast fermentation (asymptote after 24 hours approximately).

Pal et al. (2015) showed in their study the relation between CH4 production and OMDeg (Figure 7). They demonstrated that lower CH4 production per g degradable OM coincided with moderate to high OMDeg for *P. cineraria*, *A. nilotica*, *F. religiosa* and *A. indica,* and other species not included in this thesis. *A. tortilis* and *M. alba* were in medium ranges of CH4 production and high OMDeg.

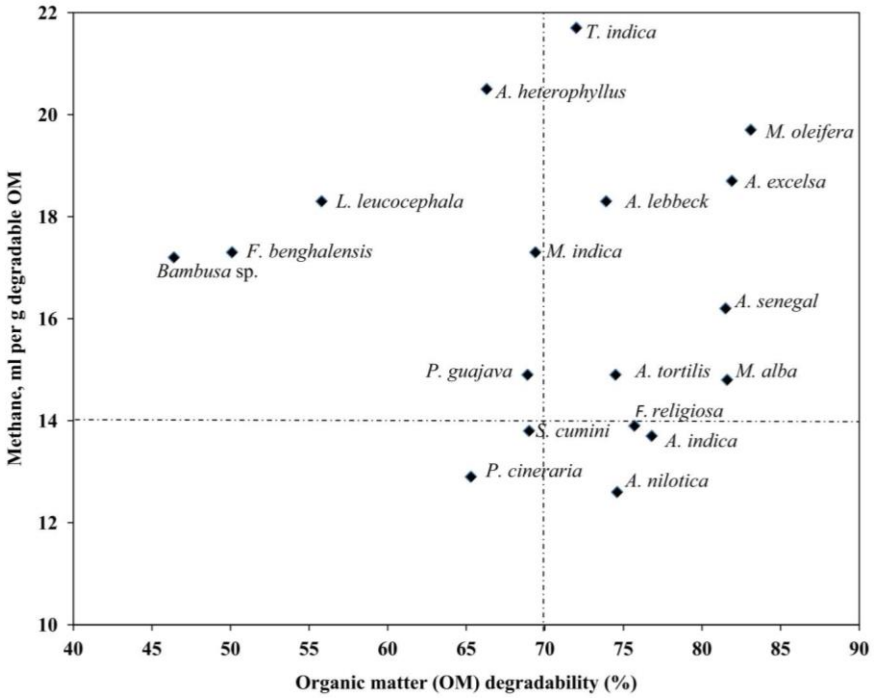


Figure 7: Plot showing relationship between organic matter (OM) degradability and methane production per g of degradable OM for different tree leaves. The horizontal dotted line separates leaves with respect to low (<14 ml g $^{-1}$ degradable OM) and high (>14 ml g $^{-1}$ degradable OM) methane production; whereas vertical dotted line separates leaves based on low (<70%) and high (>70%) OM degradability

(Source: Pal et al. 2015, p. 104)

4.3 Feeding trials

Eleven studies which evaluated browse in feeding trials were found. In all of these studies, the intake was measured. Digestibility values of the feed offered were obtained in seven studies. BWG was measured in eight. From the eleven studies, four were done in BF; two in Sahelian BF (Sanon et al. 2008a; b) and two in the Sudano-Sahel region (Ouédraogo-Koné et al. 2008; 2009). The same 15 species were subjects of intake and BWG trials (35% of all species). Of those, ten species (22% of all species) were analyzed for their effects on digestibility (with different inclusion levels of the feed ration). Appendices V and VI present detailed information on the feed rations and animals of the feeding trials (goats and sheep, respectively). The species and trials presented by Aschfalk et al. (2000), who did several intake (acceptance) trials, are shown in Appendix VII. Eight studies were done with goats and four with sheep, one study used goats and sheep in separate trials (Bosma and Bicaba 1997). In the Sahelian zone of BF, *A. senegal* and *P. lucens* were tested (Sanon et al. 2008a; b). In the Sudano region of BF, the species *A. africana* and *P. erinaceus* were tested (Ouédraogo-Koné et al. 2008; 2009). To understand the effects of browse leaves as supplement, the digestibility values found in the literature were compared to the respective control groups. The obtained values for digestibility, intake and BWG refer to feed mixtures e.g. browse offered together with hay. The apparent values are therefore not those of the browse species. Nevertheless, the differences need to be attributed to the inclusion of the browse in the feed ration. Therefore, the results are presented in comparison to the respective control groups of the individual studies. One study (Partey et al. 2018) did not present any control group. Apart from *P. laxiflora* and *F. sycomorus*, all browse species were offered as supplements. The species *A. africana*, *F. thonningii* and *P. erinaceus* were tested as supplements and as sole feeds.

4.3.1 Digestibility

Figure 8 presents the browse species subjected to digestibility evaluation in feeding trials and their relative effect on the digestibility compared to that the control diet. *P. lucens* offered at 75% with hay of *Schoenefeldia gliricidis* to goats improved CPD significantly, and ADF digestibility slightly compared to the control (hay) and had otherwise similar results (Sanon et al. 2008b). In the same study, *A. senegal* was tested at 75% inclusion. It had better DMD, OMD and CPD than the control (ibid.). In a different study, Hailemariam et al. (2010) studied *A. senegal* when fed to goats as supplement (1,2% BW). Hay (no specification) *ad libitum* was the basal and control diet. In both studies, the acacia showed the best improvement on DMD and OMD compared to the respective control diets (NDF digestibility lower in Sanon et al. 2008b). DMD was 68% and 59%, OMD was 72% and 63% and CPD was 67% and 63% (Hailemariam et al. 2010 and Sanon et al. 2008b, respectively). *A. indica* was tested in this same study at 1,2%BW supplementation level. It had higher CPD than the control and the acacia. A mixture of *A. indica* and *A. senegal* (0,6% BW each) was also offered as supplement. This combination improved DMD and OMD, but CPD remained similar to the control diet (ibid.). *A. africana* was offered to goats as sole feed (100%) and at 70% inclusion with 30% hay of *Andropogon gayanus*. Hay alone was the control diet (Ouédraogo-Koné et al. 2008). Both feed rations showed similar DMD results to the control (hay) and improved CPD. At 70%, there was better fiber digestibility. Digestibility of all fractions did not show great variation between the two tested levels (DMD 60% each, CPD 80% and 77%, with 100% or 70% browse, respectively). In the same study, *P. erinaceus* was offered to a separate group of goats at 70%. The browse showed higher CP and lower DM digestibility compared to the control diet and lower CPD compared to *A. africana*.

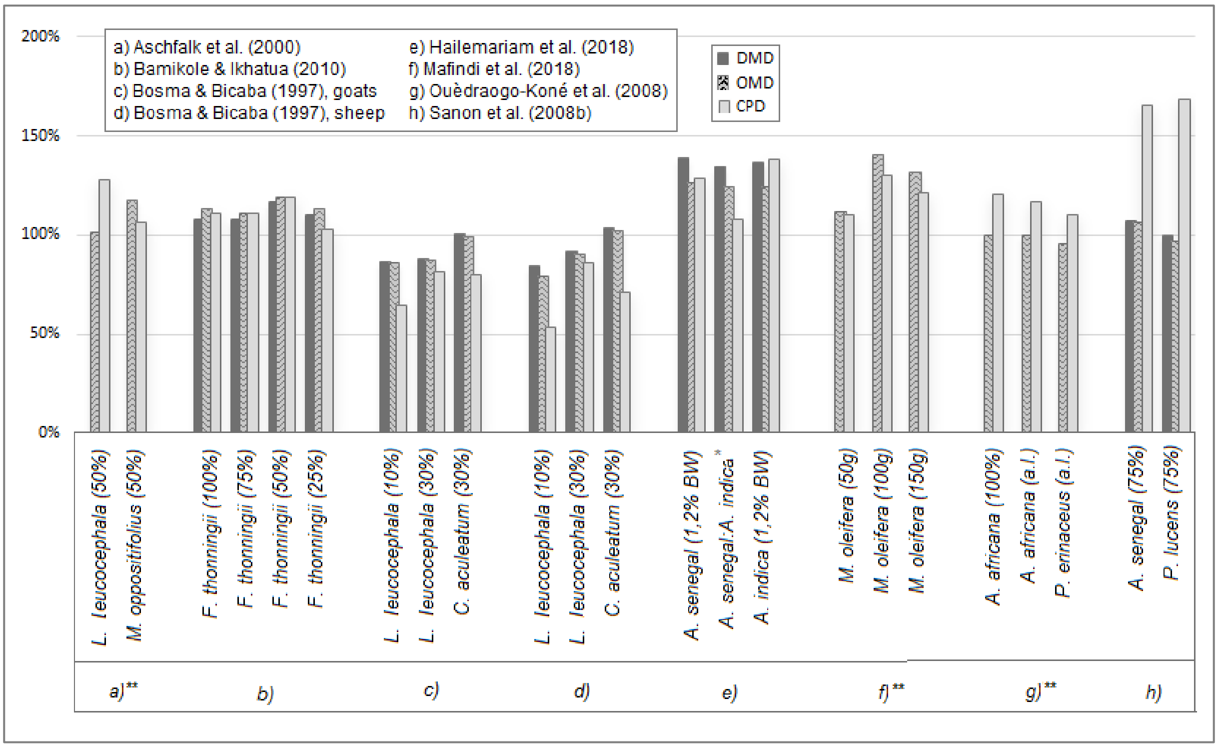


Figure 8 Relative in vivo DMD, OMD and CPD of feed including different browse forage compared to the respective control diets (100%)

*Note: Inclusion levels of forage in parentheses. Letters indicate different studies. *1:1 each at 0,6% BW; ** no DMD values. a.l.: ad libitum; CPD: crude protein digestibility; DMD: dry matter digestibility; OMD: organic matter digestibility. (Source: own Diagram)*

Different results for *L. leucocephala* were presented in two articles. In the first study, Aschfalk et al. (2000) studied the browse with sheep when the basal diet (*Panicum maximum* grass*)* was replaced with 50% browse. The digestibility of the control (*P. maximum ad libitum*) had a wide range because the trials were not all done in the same season (56% to 63% OMD and 44% to 64% CPD). Compared to the control, *L. leucocephala* at 50% had similar OMD and higher CPD. The apparent OMD and CPD of the feed offered were 59% and 69%, respectively (ibid.). The second study (Bosma and Bicaba 1997) compared *L. leucocephala* at 10% and 30% supplement level. The basal feed was *Sorghum bicolor* stover and the control included 30% concentrate. Goats and sheep were in separate trial groups. Medium to high deterioration that the control diet's DMD and OMD were found with 30% and 10% *L. leucocephala*. For the total feed offered with 30% supplement, DMD was 50% and 46%, OMD was 52% and 48%, CPD was 51% and 45% for goats and sheep, respectively. At 10% all values were lower than those of 30% supplement, and with a CPD of 28% it was especially low for sheep (ibid.). In the same study, *C. aculeatum* was tested at 30% supplementation. With goats, this feed achieved results similar in digestibility to the control, but less CPD. DMD was 57% and 52%, OMD 59% and 54%, CPD 50% and 38% for goats and sheep, respectively (Bosma and Bicaba 1997).

For *M. oleifera*, all levels of inclusion (50g, 100g, or 150g) showed similar or better results in digestibility than the compared control diet. Basal and control diets were cow pea husks *ad* *libitum*. 50g inclusion of *M. oleifera* showed similar results to the control, but improved digestibility of the ash fraction (Mafindi et al. 2018). With 100g and 150g inclusion, digestibility was significantly improved for all measured parameters. 100g showed the best improvement and the best digestibility for all fractions. 150g showed reduced ash digestibility. DMD ranged from 59% to 74% and CPD from 57% to 75% (ibid.). *F. thonningii* was tested at levels of 25%, 50% and 75% of feed ration with a basal diet of *P. maximum* grass and as sole feed (100%) (Bamikole and Ikhatua 2010). The control diet was grass as sole feed. All levels showed either similar or better results than the control. Significant improvements of DMD, OMD, CPD and fiber digestibility were found at 50% in feed ration. DMD ranged from 69% to 75%, OMD from 71% to 76% and CPD from 60% to 70%. The 50% supplement level always had the highest digestibility. *F. thonningii* as sole feed showed DMD 69%, OMD 73% and CPD 65% and had better CPD than the browse at 25% supplement level (ibid.).

4.3.2 Dry matter Intake and body weight change

Figure 9 shows the effect of the diets including browse on DMI and BWG compared to the control diets. Sanon et al. (2008b) measured the voluntary intake of goats fed *A. senegal*, *G. senegalensis* and *P. lucens*. The foliage was offered *ad libitum* and a supplement of max 30% hay (*S. gliricidis*) was included based on previous intake. In this study, DMI was higher with supplements of *A. senegal* and *P. lucens* and was lower with *G. senegalensis*. The control group fed only hay lost 1,1 kg BW. *A. senegalensis* and *P. lucens* led to positive BWG above 1kg in the three-week trial and the difference between the two supplements was not significant (1,1kg and 1,7kg, respectively). *G. senegalensis* led to higher BW loss than the control diet. Steady weight gain with *P. lucens* leaves was reported by Sanon et al. (2008a), though no significant impact compared to the control group was presented. In this study, the basal diet was hay (*S. gracilis*) and maize bran, which the control group received supplemented with cotton-seed cake. The FCR was higher than the control for goats receiving *P. lucens*. *A. senegal* was tested as supplement at 1,2%BW and the group which received this diet had significantly (P<0,001) higher DMI than the control group (Hailemariam et al. 2016). *A. indica* at 1,2%BW and the mixed supplement with both species at each 0,6%BW achieved similar results. The DMI of the group supplemented with *A. senegal* was significantly higher than that of the group with *A. indica* or the mixed supplement. The total BWG was highest for goats fed *A. senegal* supplement. Goats fed this browse and those fed the mixed supplement showed more than double BWG compared to the control group (239% and 228%, respectively). The group fed *A. indica* showed significantly higher BWG than the control, but less than the other two supplements. The FCR was significantly lower for all supplements, but among the supplements, *A. indica* showed the highest FCR (ibid).

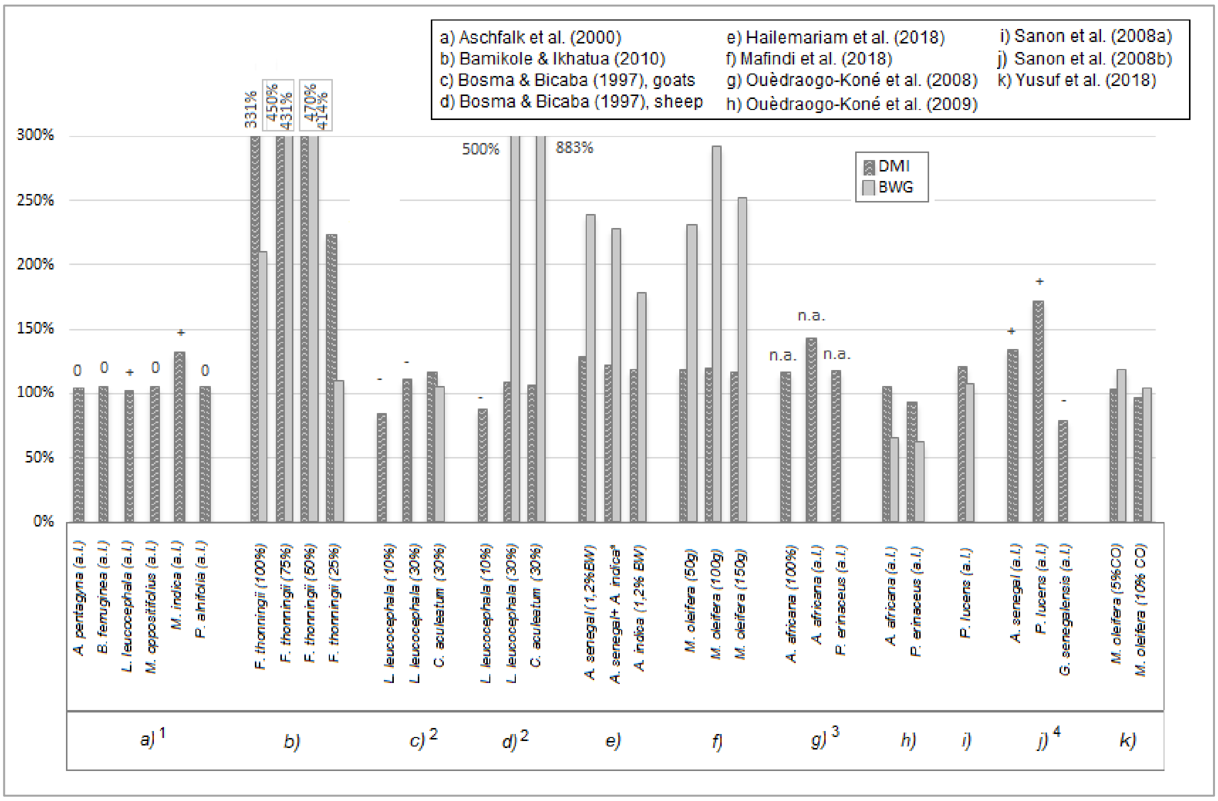


Figure 9 Relative DMI and BWG of small ruminants fed diets including browse forage compared to respective control groups (100%)

*Note: Inclusion levels of the browse in parentheses. Values >300% are presented as numbers. Letters indicate different references, superscript numbers indicate missing BWG: 1: no control group; 2: BW loss in trial groups; 3: BWG n.a.; 4: BW loss in control group. For trials without control groups or with BW loss, positive BWG (+), maintained BW (0) and BW loss (-) are presented. *1:1 each at 0,6% BW; a.l.: ad libitum; BW: body weight; BWG: body weight gain; CO: concentrate; DMI: dry matter intake; n.a.: not available. (Source: own Diagram)*

Ouédraogo-Koné et al. (2008) measured the voluntary intake of sheep fed *A. africana* and *P. erinaceus*. In this study, the DMI of *A. africana* as sole feed was higher than the control diet (hay), and when this browse was supplemented with hay the DMI was almost 1,5-times higher. *P. erinaceus* mixed with hay had similar results as *A. africana* fed alone. In another study, the same two browse species were offered to sheep and intake and BWG were measured (Ouédraogo-Koné et al. 2009). The basal diet was hay and maize bran, which the control group received supplemented with cotton-seed cake. The DMI was similar to the control with *A. africana* and slightly lower with *P. erinaceus*, but the differences in DMI between the two browse species was significant. Both species led to positive BWG, but it was less than that of the control group. Only 2/3 of the control group's BWG was reached (66% and 62%, respectively). The same two browse species were fed to goats in a participatory feeding experiment in Ghana (Partey et al. 2018). There was no information on BWG and for DMI there was no control group. It was shown that *A. africana* was consumed at approximately 240 g/day, reaching 3% BW and *P. erinaceus* at 210 g/day, which was below 3% BW (daily DMI values read from figure, p.3). In this same study, Partey et al. (2018) showed that goats fed *P. laxiflora* as sole feed did not consume at levels of 3% BW (approximately 200g/day), and *F. sycomorus* was the most consumed browse in this study (DMI above 250g/day, values read from figure, p.3).

The DMI and BWG of animals fed with different levels of *L. leucocephala* were studied in two references. One of these, Bosma and Bicaba (1997), found that compared to the control group (basal feed and 30% concentrate), DMI of *L. leucocephala* supplemented feed was lower than the control diet at 10% but similar at 30% supplementation for goats and sheep. At 10% supplementation, DMI did not reach 2% BW with goats (1,8%BW). BWG was positive in the control groups, although for sheep it was only 60g over the two-week trial period. BWG was much lower with 10% *L. leucocephala*. Sheep receiving that diet lost 1,3kg. At 30% supplementation, they gained weight which was five times higher than the control. Goats lost weight with *L. leucocephala* as supplement. With 10% supplement the weight loss was significantly higher (-0,67kg) than with 30% supplement (-0,03kg). The goat control group, which was given concentrate at 30% of the total feed ration, gained 0,28kg (ibid). Bosma and Bicaba (1997), also studied *C. aculeatum*. It was offered at 30% inclusion. For both, goats and sheep, the DMI was similar to the control. The BWG of the sheep receiving this diet was significantly higher (more than 800% compared to the control) while with goats, it was similar.

In the second study, *L. leucocephala* and five other browse species were fed to sheep in three different intake and BWG trials: free choice between browse and a mixture of grass (*P. maximum*) and wheat bran (Figure 9), free choice between six browse species and grass, and no choice between browse and grass (15% and 30% inclusion of browse, chopped and mixed with grass) (Aschfalk et al. 2000). With free choice, *L. leucocephala* was consumed at 10% of the total diet. The total DMI was similar to the control group. BWG was positive in this trial and the highest in this study. With free choice between six browse species and grass, *L. leucocephala* was not consumed. Without choice between the browse and the grass, sheep offered 15% *L. leucocephala* showed similar DMI to the control, but significantly lower DMI with 30% inclusion. In this trial, sheep maintained their BW.

Aschfalk et al. (2000) also found that, given the choice, sheep had higher total DMI when offered *M. indica* and had positive BWG. *M. indica* was consumed at 31% of the total DMI. With free choice between different browse species and grass, *M. oppositifolius* was the most consumed species (of those presented in this thesis) suitable for the Sahel climate, and the DMI was similar to that of grass. *A. pentagyna* was consumed at one-third of the amount of *M. oppositifolius*. Without choice between browse and grass, the DMI increased with 15% and 30% inclusion of *B. ferruginea* and *P. alnifolia*. Inclusion of *A. pentagyna* showed no changes, while inclusion of *M. oppositifolius* reduced the DMI. Without choice, sheep offered *B. ferruginea* had positive BWG, those offered *A. pentagyna* and *M. oppositifolius* had no BW changes and those offered *P. alnifolia* lost BW.

M. oleifera was evaluated in two studies. Mafindi et al. (2018) found that a basal diet of cow pea husks *ad libitum* supplemented with 50g, 100g and 150g improved DMI of goats compared to the control (basal diet *ad libitum*). 100g supplement showed best results but all levels were similar. Daily gains and BWG improved significantly with different levels of *M. oleifera*. Compared to the control group, BWG with 100g of *M. oleifera* supplement was almost 3-fold (293%), with 150g and 50g it was more than double (253% and 231%, respectively). The FCR was lower for all supplement levels and reflects this pattern (Mafindi et al. 2018). A different trial of supplement with the same species was tested in the study by Yusef et al. (2018), where *M. oleifera* replaced 5% or 10% of the concentrate. The basal diet was grass (*P. maximum*) *ad libitum* and concentrate was fed at 4%BW. Intake was similar to the control but slightly lower with 10% in the concentrate. The BWG improved with 5% *M. oleifera* in the concentrate but was similar with 10%. Therefore, the FCR was lower for the 10% replacement (ibid.).
In the study by Bamikole and Ikhatua (2010), *F. thonningii* was tested for voluntary intake and BWG. The basal diet was fresh *P. maximum* and feeds were offered separately. All levels of inclusion (25%, 50%, 75%) and the browse offered as sole feed (100%) had higher DMI compared to the control (*P. maximum* grass). Intake was more than twice as high at supplement level 25% and more than four times higher at levels 50% and 75% (414% and 431% DMI relative to control diet, respectively). As sole feed, the DMI was three-fold compared to the control diet. The BWG was similar to the control with 25% *F. thonningii* in the diet, doubled with the browse as sole feed and was more than four times higher with 50% and 75% inclusion. Highest BWG was found with 50% inclusion, the best FCR with 75% (ibid.).

4.4 Other results

ANFs, especially tannins and PAs, were studied in eight articles and analyzed for 31 species, including the ten acacias. All *in vitro* studies, besides Calabrò et al. 2007, obtained ANF content through different methods of analysis. Except in one (Aschfalk et al. 2000), studies with feeding trials did not obtain ANF values. Appendix VIII shows the tannin fractions presented in the studies. Seasonal variations of composition were studied by Ouédraogo-Koné et al. (2008) and Larbi et al. (1998). The latter also studied these variations for GP, degradability and ANFs. The study by Yusuf et al. (2018) was the only one with economic evaluation of the studied supplements. They found that the revenue-per-kg gain increased significantly with both 5% and 10% inclusion of *M. oleifera* in the supplementation scheme. The feed costs were reduced, and the 10% level was significantly cheaper than 5% (ibid.).

5 Discussion

To identify browse trees and shrubs of (semi-)arid regions that have the potential to enhance livestock production in the Sahel region of West Africa, a comparative literature analysis was conducted. A number of articles containing information about use of tropical browse as livestock feed was found. Verification that the MPTs can grow in the climate of the Sahel region was carried out through a database review. Chemical composition, gas production, degradability, digestibility, DMI and impact on weight performance were compared. The results in chapter four have shown that most browse species are among medium to high levels of CP and potential digestibility. The assumption that MPTs are suitable as supplementation for low-value feed was validated.

A large number of articles related to the use of browse species in the tropics came from the initial desktop research. Comparing many potential supplementary browse species was made possible by three references, which studied a great variety of MPTs, but these articles were all not from the study area. The relevance of the species studied outside of the focus area needs to be further validated. For example, *Kaya senegalensis* was afterwards found in a list of species suitable for agroforestry in the dry African climate (Sahelian Senegal), while *F. thonningii* was stated to be native to tropical semi-humid Africa (Baumer 1990). Along with the presented results in this thesis, many other parameters were measured in the studies, e.g., carcass characteristics, macro and trace-elements and rumen microbial characteristics. The literature has the potential to cover more aspects of animal nutrition and health than what was possible to present in this thesis. The information which was presented throughout this thesis was reduced to allow for a clear line leading to the answer of the given study question. Other important aspects of ruminant production were not covered by the given literature, namely reproduction parameters and milk yield/quality. These aspects warrant further research. Articles directly related to the Sahel zone as study area were found. Both nutritional value and effects on animal performance were studied in this region. Well-known supplement browse species like *L. leucocephala* and *G. sepium* were also studied in this region. These species have been introduced to the region and are not without constraints (Abdulrazak et al. 2000) so the need to identify more locally available fodder plants for sustainability reasons still exists (Melesse et al. 2019). It was possible to evaluate the potential of some of the species from this region with the help of studies from outside. Evaluating the acacias separately allowed the highlighting of their nutritional value as genus and the identification of more suitable ones. As expected, more studies evaluated the nutritional potential than the actual effects on animal performance. *In vitro* and *in situ* analyses are more favorable in terms of costs, especially for developing countries (Beever and Mould 2000).

The browse species analyzed in the literature were selected according to relevance of the individual regions. Abdulrazak et al. (2000) selected six acacias based on local knowledge of herdsmen in Kenya. *A. nilotica* was studied in four articles, suggesting its relevance for the region. In fact, Zabré et al. (2018) describes it as a frequently used feed for ruminants in BF. *A. tortilis*, *A. nilotica* and *A. senegal* are – among a variety of MPTs – available and used for ruminants in India (Pal et al. 2015). Species like *P. erinaceus* and *A. africana* which were referred to as frequently used in traditional livestock systems in sub-humid West Africa (Ouédraogo-Koné et al. 2009), were among relevant MPTs identified in a participatory process with farmers in Ghana (Partey et al. 2018).

5.1 Chemical composition

All MPTs had CP content above 90 g/kg DM. 80 g/kg DM is the minimum CP requirement for maintenance (Larbi et al. 1996b; Zabré et al. 2018), while 100 - 300 g CP/ kg DM is considered moderate to high (Jayasuriya 2002). This stresses the need to identify well-digestible MPTs because high CP content alone cannot define supplements as suitable. Jayasuriya (2002) categorized tropical MPTs as 'high fiber/ high CP' speices but in this thesis all species with the highest CP had NDF below 600 g/kg DM and, except *P. juliflora*, relatively low ADL. Most species had medium to low ADL and, if the outliers *A. procera* and *G. senegalensis* were excluded, the weighted mean ADL would have been 89 g/kg DM. High CP and low ADL combined are good criterions to identify potential CP supplements (Larbi et al. 1996a; b; Pal et al. 2015). Based on this consideration, *F. sycomorus*, *G. senegalensis*, *M. indica* and *P. laxiflora* appear unsuitable as supplements. The extremely high ADL of *A. procera* and *G. senegalensis* most likely outweigh the value of its moderate CP content. The particularly low ADL content in *M. oleifera*, *M. stenopetala* and *S. sesban* (high CP content,) as well as in *C. aculeatum*, *M. crassifolia* and *M. alba* (medium CP content) and *A. nubica* suggest that a high digestibility can be expected with these species. From *P. juliflora,* with high ADL and crude fiber content, the opposite can be expected. From those species where only the NDF and ADF values were found, impaired digestibility can be expected with *L. diversifolia*, *N. laevis* and *P. biglobosa* as their high ADF:NDF ratio suggest higher amounts of cellulose and lignin (Abdulrazak et al. 2000). CP and ADL for *A. africana*, *G. sepium*, *P. erinaceus* and *P. lucens* are ambiguous.

The differences of values found for CP, NDF, ADF and ADL between different studies could be attributed to differences in sampling material, seasons and regions of the studies. For example CP values for *G. sepium*, were much higher in the study of Larbi et al. (1998) who sampled 'leaves and small stems' compared to the study of Calabrò et al. (2007). The latter argued that the results of their study were impaired because lignified stems were used in the analysis but their sampling material was initially presented as 'leaves'. This also shows that sampling material is not always precisely described. Sampling only leaves of woody species changes the results of the feeding value (Larbi et al. 1996b). Thus, it would appear reasonable to consider which parts of the plants are actually eaten by the animals when sampling and feeding. Differences of ADL for *L. leucocephala* were extremely high; two studies presented differences between all fiber fractions, whereby Bosma and Bicaba (1997) showed much lower values than Pal et al. (2015). However, the CP values of these studies did not vary greatly. Sampling material, region and season were all different. Most likely it is the seasonal difference which caused the deviances in the fiber fraction (wet and dry season, respectively). Significant seasonal differences of chemical composition of MPTs were observed by Larbi et al. (1998). CP, NDF, ADF, and PAs were all higher in the wet season. Ouédraogo-Koné (2008) studied seasonal changes and found apparent seasonal variability of NDF and ADL, and highest CP content highest in the dry season. Nevertheless, Larbi et al. (1998) concluded that significant differences in seasonal values have little or no impact on the ranking of the species. Appropriate feeding strategies for different seasons need to be established, and Jabbar et al. (1997) mentioned that optimal time for supplementation within the production cycle need to be determined to increase the effectiveness and hence the economic benefits of supplementing.

That the composition of the fiber fraction changes while CP contents remain similar could be a reason why the correlations between fiber fractions and CP were not stronger. Abdulrazak et al. (2000) found negative correlations, especially between CP and ADF. Larbi et al. (1998) found that correlations could be strong in one season and poor in another. The strong positive correlation between NDF and ADF values for the compared browse species in this thesis is in agreement with the literature (Abdulrazak et al. 2000) but other correlations between fiber fractions were not found in this thesis. Averaging results of different seasons within one study dissevered the ADL and CP pattern.

The weighted mean CP of the acacias was similar to that of the other browse species, but the weighted mean NDF and ADF were both lower. High CP with lower amounts of fiber make acacias potentially more valuable than other MPTs. Abdulrazak et al. (2000) stated that NDF-N and ADF-N as well as the proportion of ADF to NDF were higher for acacias, which would mean that the digestibility, especially that of nitrogen, is impaired. The four cited references that studied *A. nilotica* were from different countries and from different seasons, thus showing variations in CP and fiber contents. ADL content was particularly variable, while CP content remained relatively similar. Fiber was more favorable in *A. tortilis subsp. raddiana* than that of *A. nilotica*. *A. nubica* had relatively high CP content and was low in all three fiber fractions. *A. seyal* had comparably low CP content and ADL was above average, thus suggesting its poor quality as forage. The difference of the sampling material or regional differences might explain the variation in the given fiber contents of *A. angustissima*. Along with the leaves of acacias, nutritive value of fruit and pods from some acacia species has also been observed (Sanon et al. 2008a; b; Sawe et al. 1998).

5.2 *In situ* and *in vitro* experiments

In situ and in vitro results are sufficient to predict utilization in terms of OMDeg, DMI and BWG (Larbi et al. 1998; Ørskov 2000) and allow the evaluation of a large number of species within one trial. Three studies compared most of the species found in this thesis. On one hand, this provides a lot of data to help select suitable browse species. On the other hand, the importance of further feeding experiments to investigate the true effects of the browse species was stressed by several authors (Abdulrazak et al. 2000; El Hassan et al. 2000; Larbi et al. 1996b; 1998).

Most of the degradability values of the analyzed browse species were in medium to high ranges and are comparable with results found for common browse species such as *L. leucocephala* and *G. sepium* used as supplements in developing countries (Jabbar et al. 1998; Jarasuriya 2002). The used classification for degradability was based on expert communication (Schlecht May 2021). It is in agreement with the classification by Jarasuriya (2002), where values between 40% to 60% are estimated to be of low to moderate digestibility and 60% to 80 % moderate to high. Most species had OMDeg above the weighted mean which indicates that those below it had extremely low degradability compared to the rest. There are two species which need to be pointed out here and classified with 'low degradability'. *P. juliflora* with low OMDeg and *A. angustissima* with low ND.

Especially high DMDeg, OMDeg and ND were also found among the browse species studied in the Sahel zone. *M. crassifolia*, *A. senegal* and *A. tortilis subsp. raddiana* can be classified with 'high OMDeg' and *G. sepium* with 'high ND'. For *M. crassifolia*, good nutritional value as supplement can be expected with CP content above average and high levels of degradability. Its ND can be classified as high. That it was studied in the Sahel zone shows that it is found in the region and feeding trials could help to clarify its true potential as supplement. *A. tortilis subsp. raddiana* was only analyzed in one study and, apart from comparably low CP content, it showed favorable values. Other species which can be classified as highly degradable are *A. tortilis*, *A. excelsa*, *M. alba*, *M. oleifera* (high OMDeg and DMDeg), *M. stenopetala* (high OMDeg), *A. nubica*, *A. mellifera*, *F. religiosa* and *A. indica* (high DMDeg), *S. siamea* and *S. spectabilis* (high DMDeg and ND) and *A. lebbeck* (high ND). Besides high DMDeg, the ND of *S. spectabilis* and *S. siamea* were extremely high. Larbi et al. (1998) discussed that although *Senna* spp. are known to have toxic compounds and are not acknowledged by producers in Nigeria, the ANFs appeared not to have interfered with the digestibility. The authors call for research to find out ways to utilize these species. The high ND of *G. sepium* attracts attention and indicates good potential as CP supplement, despite DMDeg and OMDeg in medium ranges. Jabbar et al. (1997) reviewed several studies concerning *G. sepium* as supplement in Nigeria and pointed out that fibrous grasses and crop residues can be sufficiently digested when supplemented with *G. sepium* and an additional energy supplement (cassava residues). The difference between OMDeg values for *M. oleifera* between two studies (82% Pal et al 2015, 76% Melesse et al. 2019) relates reversely to the different values of ADL found by the respective authors (28 and 46 g/kg DM ADL). Pal et al. (2015) concluded that lignin inhibits digestion the most. The pattern of OM degradability in different studies for *L. leucocephala* 56%, 60% and 70%, Pal et al. 2015, El Hassan et al. 2000 and Melesse et al. 2019, respectively), again, relates reversely to the pattern of ADL values (140, 94, and 55 g/kg DM ADL, respectively). The potential DMDeg for *L. leucocephala* presented by Larbi et al. (1998) was higher than those presented by El Hassan et al. (2000) and Pal et al. (2015). But each of these values relate to the CP values found by these authors (270, 197 and 174 g/kg DM CP, respectively) and this possibly reflects the positive influence of CP on digestibility. Even though the correlation between CP or ADL with OM degradability could not be proven in this thesis, Abdulrazak et al. (2000) and Larbi et al. (1996a; b) showed correlations of these fractions with degradability and gas production. Two factors might have influenced the correlations in this thesis: species with CP below the weighted mean were less represented in the degradability analyses and the results within one study for the same species were averaged.

Acacias were less degradable than the other browse species. In the case of *A. angustissima*, the low ND, despite higher OMDeg and DMDeg, indicates ANFs inhibiting CP utilization (Pal et al. 2015). *A. mellifera* and *A. brevispica* were found with OMDeg below 50%. While *A. mellifera* contained more ADL compared to *A. brevispica*, their DMDeg and OMDeg were similar. This indicates the presence of ANFs in *A. brevispica*. Moreover, *A. mellifera* had high DMDeg but low OMDeg, the same for *A. nubica*, which possibly has some indication regarding their N-utilization. *A. seyal* and *A. nilotica* were found with even lower rates of DMDeg and OMDeg (below 40%) by Abdulrazak et al. (2000), which, they argued, is less interesting for ruminant feeding. Nevertheless, Pal et al. (2015) and Zabré et al. (2018) found higher OMDeg for *A. nilotica* in their studies. No adequate explanation was found for these findings. On the contrary, Zabré et al. (2018) presented the highest fiber values for this species, but lower CP than Abdulrazak et al. (2000). All this reflects and supports the assumption of impaired utilization due to high NDF- and ADF-bound N (Abdulrazak et al. 2000). Nevertheless, extremely high OMDeg was found for *A. senegal* and *A. tortilis*, which were not studied by Abdulrazak et al. (2000), who generally presented lower OMDeg values than all the other studies.

The weighted mean GP shows that the analyzed browse species have favorable fermentation characteristics. In the high CP group, most volumes of GP were above 40 ml/ 200mg DM and for the medium and low CP groups, most volumes produced were in medium ranges. The values found fall within ranges found by Steingass and Arbelot (1994), who concluded that GP above 25 ml/ 200mg can be considered medium to high and good digestibility can be expected. Among the browse studied for GP and degradability characteristics in the Sahel zone, *P. tomentosa* had high GP but also the overall lowest CP of this thesis. Compared to the other species, it is less interesting as protein supplement. Only if it is widely distributed in the Sahel region, and/or commonly used as forage, would it be worth the effort of studying this species more. Noticeable are the low GP values found for *A. angustissima*, *M. indica*, *P. cineraria* and *P. juliflora*. Species with high degradability and simultaneously GP under the found average were *A. tortilis*, *A. excelsa*, *M. alba*. Thus, it could be expected that the energy loss through GP be lower and utilization of nutritional values be higher (Pal et al. 2015). CH_4 for all three species was average for this study but with volumes of less than 16l/kg DM, they can be classified as low (A. excelsa> M. alba> A. tortilis). Pal et al. (2015) discussed that *M. indica* and *P. cineraria* could be interesting as supplements because both species showed medium to high digestibility despite the low GP. This indicates higher utilization potential, despite having found high ADL for *M. indica*. This, in turn, shows that species cannot be evaluated based solely on their chemical content.

Pal et al. (2015) and Abdulrazak et al. (2000) found differences between GP24 (lower) and potential GP (higher), which support the assumption that digestion of these woody species is not complete after 24 hours. Therefore, 24 hours and 48 hours are not enough to estimate the full digestibility potential of woody roughages (Omed et al. 2000, pp. 148–149). Only GP24 of *A. nubica* was similar to total GP. *S. sesban* was the only species which had the same results for GP and GP24. Faster digestion due to faster fermentation in the rumen indicates higher intake potential because the rumen is emptied faster (Rymer 2000). Calabrò et al. (2007) argued that high amounts of non-structural carbohydrates caused the fast fermentation of *M. crassifolia* and *P. tomentosa* which, therefore, could also be the case for *S. sesban* and *A. nubica*. These four species were also among those with the highest GP.

The acacias produced less gas than the other browse species and only two were found with high GP (*A. abysinica* and *A. nubica*). This supports the assumption that, as was expected from the presented chemical composition, they are not as well utilized. *A. abysinica* was found with medium digestibility and high GP. On one hand, it shows that the high CP content outweighed the high ADL regarding digestibility. On the other hand, a very high CH_4:GP ratio indicates energy loss in the form of unfavorable microbial activity (Zabré et al. 2018). For *A. angustissima,* one could expect the seasonal differences to be attributed to seasonal changes in fiber, but these were not found by the cited authors. They did however find seasonal changes of ANFs (Larbi et al. 1998). GP significantly decreased with higher inclusion of *A. angustissima*. El Hassan et al. (2000) concluded that high amounts of ANFs cause anti-microbial activity, which was indicated by the deterioration of gas production. Simultaneously, they found high amounts of soluble phenolics. They stated that this acacia has been fed to animals successfully after having adapted them to it gradually (ibid.). Nevertheless, the medium to low ND allows disregarding this species as CP supplement. El Hassan et al. (2000) pointed out that the GP characteristics of *S. sesban* did not indicate the influence of ANFs but that their effects are known from other studies. *L. diversifolia* was found with the overall highest GP. This, combined with high DMDeg, OMDeg and CP, could possibly make this species appear interesting for future feeding experiments. *Leucaena* spp. have been analyzed as some of the most digestible roughages and therefore show high potential of intake (Ørskov 2000, p. 182). *A. nubica* has favorable chemical composition, degradability and fermentation characteristics. In the final ranking of acacias in the study by Abdulrazak et al. (2000), it was placed first. In contrast, based on the OMDeg of acacias compared in this thesis, *A. senegal* and *A. tortilis* need to be ranked higher.

None of the authors discussed the correlation between CH4 and GP24 which was found in this thesis. The correlation indicates that high gas production, although it means higher digestibility, must also be seen from a climate perspective, and a balance between digestibility and gas production needs to be pursued. CH4 is not only a hazard to environment. Reducing its emissions in rumen fermentation also means more energy available for the animal. Supplementing with species that reduce CH4 can improve performance of livestock production in the tropics and mitigate climate change (Pal et al. 2015). There are species which reduce CH4 without affecting the positive microbial activity. Such could be the case for *F. religiosa*, *A. indica* and *A. nilotica* as total GP is in medium ranges while CH4 is low. They are interesting for further research and supplementing or feeding with these species should be tested (Pal et al. 2015). In addition*, P. juliflora* and *C. cajan* have the potential to reduce CH4 emissions when fed as supplements, maybe due to secondary plant compounds, according to Melesse et al. (2019). *P. juliflora* has high ADL, low OMDeg and low GP so low nutritional value can be expected from this species. Despite this fact, Melesse et al. (2019) conclude that it has potential to supplement feed as CH4 mitigating ingredient. They did not however discuss the reasons for the negative CH4 values. Low CH4:GP relations also coincided with low GP for *M. alba*, *A. lebbeck*, *A. senegal* and *A. tortilis*, which are therefore all interesting species to consider when trying to reduce CH4 emissions and energy losses. *M. stenopetala* was highly degradable but produced high amounts of CH4 in relation to total GP. Additionally, the CH4:GP ratio was high. High CH4 values could be expected from *L. diversifolia* due to extremely high GP.

The extremely low CH4 values for *A. tortilis subsp. raddiana* and *A. nilotica* presented by Zabré et al. (2018) are not comparable with other results. Pal et al. (2015), who also analyzed *A. nilotica,* found similar GP24 as Zabré et al. (2018) but CH4 was less than a half for the latter. In both studies, sheep were the inoculum donors. Maybe the seasonal or regional differences caused a different concentration of ANFs which affected the methane production. Zabré et al. (2018) reasoned that the low CH4 was caused by the effects of tannins on microbes, in particular methanogens, in the rumen. They found that *A. tortilis subsp. raddiana* produced similar GP24, and even less CH4, than *A. nilotica*, which also makes it interesting for reducing CH4 emissions. The authors conclude that these acacias have good potential as supplements. Considering that both are from the Sahel region, strategies to utilize these species as supplement are of value. Feeding experiments are needed to affirm these assumptions.

GP values for *A. nilotica*. *A. indica*, *L. leucocephala* and *M. oleifera* were obtained in the two studies done by Pal et al. (2015) and Melesse et al. (2019). All were lower in the former study, except for *L. leucocephala*. This effect could have been caused by different animal species used as inoculum donors. Pal et al. (2015) used sheep and Melesse et al. (2019) used cattle. Sheep are known to digest browse better than cattle, and it is interesting that *L. leucocephala* showed a different pattern. Using cattle, El Hassan et al. (2000) found higher values for *L. leucocephala* than the other two studies in all inclusion levels tested. Here, the difference could be attributed to different feeds offered to the inoculum donors or seasons. GP for *A. lebbeck* underlies the same differences between the cited studies. Lower values found by Pal et al. (2015) and higher values by Larbi et al. (1996a; b; 1998), who used sheep and cattle, respectively. The criteria for high, medium and low GP were set according to the study of Steingass and Arbelot (1994), in which cattle were used as inoculum donors. The results show that different criteria are needed for different species. For comparisons of GP and digestibility between studies using different animal species, it would be useful to establish a correction formula to reduce the differences between values of different inoculum donors. Rymer (2000) discussed such a correction formula for digestibility but also mentioned that differences between sheep and cattle have been observed to be small and could be disregarded. Looking at the values reported for small ruminants appears more interesting for the Sahel region but references to classify these values were not found.

5.3 Feeding trials

As expected, few of the analyzed studies conducted feeding trials in the (Sudano-)Sahel. Some of the species found in these articles were also found in degradability experiments, and comparing their results helps to prove or disprove those results. The high DMDeg and OMDeg found for *A. senegal* was apparent in the digestibility trials done by Sanon et al. (2008b) and Hailemariam et al. (2016). Feeding trials should not be done standardly but to evaluate results of *in vitro* analyses (Rymer 2000), which has been done for this acacia.

In general, those studies which compared a control diet of basal feed without supplementation to experimental diets of basal feed with browse supplementation all showed improvement in DMI and BWG (Aschfalk et al.2000; Bamikole and Ikhatua 2010; Bosma and Bicaba 1997;

Hailemariam et al. 2016; Mafindi et al. 2018; Ouédraogo-Koné et al. 2008; Sanon et al. 2008b). This supports the hypothesis that browse is suitable as supplement and improves animal performance where low-value feed is offered to animals. Aschfalk et al. (2000) discussed that digestibility of browse species can be higher than that of grass and is thus a good supplement in the dry seasons when grass is of low value. The results show that especially CPD improves with inclusion of browse. Interestingly, those species which were tested at inclusion levels of 50% or more in the ration had good digestibility. This was not expected due to what was earlier said about ANFs in browse.

The effects of A. africana fed to sheep as sole feed could compete with hay fed to the control group. This is supported by the study of Partey et al. (2018) where goats receiving *A. africana* as sole feed readily consumed it. Ouédraogo-Koné (2009) confirmed that this browse species led to positive BWG with sheep but it could not compete with cotton seed cake as supplement. *A. africana* could be a replacement in cases were grass and hay are not available. Based on these results, it can be recommended as supplement in the Sahel region. The authors discussed that the nutrient intake for the group receiving *A. africana* was sufficient, while that for *P. erinaceus* was not. But, at the same time, the utilization of nutrients in *P. erinaceus* must have been higher because the FCR was lower than that of *A. Africana* (ibid.). In the three studies which evaluated *P. erinaceus* (Ouédraogo-Koné 2008; 2009; Partey et al. 2018), it was mentioned that this browse is a common fodder of the West African regions. Partey et al. (2018) pointed out that *P. erinaceus*, despite having low DMI as sole feed, is commonly available on markets in Ghana. At the same time, it is endangered due to its favorable wood qualities (CILSS 2016, p. 16). Species which are exploited in the Sahelian region should be more present in plantations to protect them from extinction (Sanon et al. 2008b). This was also said about *P. lucens* (ibid.). The best supplementation level and/or the synergy with high-energy supplements could be valuable information for these regions to promote *P. erinaceus* and *P. lucens* (Sanon et al. 2008b, Jabbar et al. 1997). *C. aculeatum* showed positive effects on intake and BWG for both goats and sheep and its effects are comparable to those of concentrate. This locally available and adapted browse could be of benefit to low-value feed rations in the Sahel region (Bosma and Bicaba 1997). Different inclusion levels should be studied to ascertain the value of this species.

The results for *A. indica* show that it can reduce the amount of feed needed and improves BWG at the same time. CP digestibility was significantly higher for the feed supplemented with *A. indica* than control and mixed supplement. At the same time, Hailemariam et al. (2016) showed that CP ingestion with this supplement was lowest in their study. The fact that *A. indica,* despite having higher CP, had less BWG than *A. senegal* indicates that its CP utilization is weak. This might be due to the ANFs (Pal et al. 2015). Leaves of *A. senegal* show good results and Sanon et al. (2008a; b) mentioned, in addition to leaves, the pods of this acacia have good impact on digestibility and DMI. The use of this species as supplement should be promoted as it also showed low CH4 production (Pal et al. 2015). The results for *G. senegalensis* prove what was expected due to the very high ADL content. It was not well-liked by animals, which is why hay was more consumed and CP requirements could not be met and led to BW loss. At the same time, the digestibility trial by Sanon et al. (2008b) was disregarded due to poor condition of the animals after intake trials with this species.

In the study of Bosma and Bicaba (1997), the results show that *L. leucocephala* was not suitable to replace concentrate for goats and the animals suffered weight loss despite the amounts of DMI. This was also found by Jabbar et al. (1997) who discussed that goats preferred the browse compared to grass but were not able to utilize it. This is again reflected by the digestibility results found by Bosma and Bicaba (1997). Nevertheless, these authors stated that the BWG in their study had a very large standard deviation and that the study was not able to evaluate the effects of the browse on BWG accurately. It was concluded that *L. leucocephala* and *C. aculeatum* improve utilization of crop residues and hence sustainable intensification (ibid.). In contrast, results obtained by Aschfalk et al. (2000) show that mature sheep supplemented with *L. leucocephala* at 15 or 30% inclusion maintain their BW. The digestibility of the feed with 50% inclusion was higher than what could have been expected from the given ND. Jabbar et al. (1997) pointed out that *L. leucocephala* improves animal production at a maximum rate of 30% of total feed. Due to its mimosine content, it should not be used as sole feed. Furthermore, they pointed out that *G. sepium* is able to reduce the toxicity of *L. leucocephala* (ibid.).

Differences in digestibility between goats and sheep found by Bosma and Bicaba (1997) were attributed to goat digestion being more adapted to forage and less susceptible to the effects of ANFs. Goats might take in less but digest more efficiently because weight gains did not vary between animals, but intake did (ibid.). The results of Bosma and Bicaba (1997) suggest that sheep and goats select according to CP content. Sheep generally had higher intake, only with *C. aculeatum* at 30% inclusion, were goats and sheep similar. Different digestion patterns among goat and sheep need to be considered when applying this information to feed ratios of particular animals (Bosma and Bicaba 1997), Aschfalk et al. (2000) concluded that each species needs to be tested with different animals as acceptance and utilization varies among animals, and according to Jabbar et al. (1997) the information obtained in feeding trials with different animal species has more value for producers.

Given the little difference of digestibility caused by *F. thonningii* as feed, the high impact on BWG is astonishing. These results could not have been expected given the high amounts of fiber fractions. But as was mentioned by van Soest (1994, 191f.), high CP levels can help to overcome the negative impact of lignin on digestibility. In the intake and BWG trials of *F. thonningii*, Bamikole and Ikhatua (2010) showed that this browse species is suitable, both as supplement and as sole feed. These authors discussed that the grass of the dry season in which the trials were performed had little value and the differences are high because of that. But again, this supports the assumptions that *F. thonningii* can be a valuable feed and supplement source in the dry season, and that dry season feed needs to be supplemented. Bamikole and Ikhatua (2010) concluded that *F. thonningii* is both suitable as profitable supplement at best levels of 50 or 75% but can also replace grass in the dry season. The same is discussed by Balehegn et al. (2014), where *F. thonningii* was found with great potential to substitute 50% basal feed and improve animal nutrition. More insight about the possible effects of this species in the Sahel region need to be obtained.

For *A. pentagyna, B. ferruginea*, *F. sycomorus*, *M. oppositifolius, P. alnifolia* and *P. laxiflora* the information found in the literature is sketchy. *P. laxiflora* had relatively low CP content and was not consumed well as sole feed. It was ranked among 20 important MPTs in Ghana in a participatory evaluation but was on rank 17 (Partey et al. 2018). *F. sycomorus* was well consumed and ranked 2nd most important MPT in this study. Digestibility of this species is expected to be low due to high values in all fiber fractions. Nevertheless, it has been observed to be among frequently consumed forages in BF (Ouédraogo-Koné et al. 2006). *M. oppositifolius*, which is one of the most fed browses in Benin and is distributed across the country (Aschfalk et al. 2000), was well-liked by sheep and had no negative impact on their weight performance but had undesirable impact on intake and FCR compared to control. Nevertheless, if it is widely available in the Sahel region, options for utilizing it should be identified. *B. ferruginea* increased intake and BW despite high amounts of tannins and low CP. Further research can improve the knowledge of understanding CP utilization of browse with high amounts of ANFs (Larbi et al. 1998). Aschfalk et al. (2000) concluded that all species of their study besides *A. pentagyna*, were suitable as supplements but that harvesting from large trees like *P. alnifolia* can be a limiting factor in utilizing a species. This consideration should be made when selecting species for supplementation.

5.4 Other results

Analyzing tannins was standardly done for most species in *in vitro* experiments. This shows the importance of these values with regard to estimating the MPTs nutritional value. Nevertheless, analyzing them in detail was not the focus of this thesis. It came through in the literature that ANFs have several influences on fermentation, digestion and health. All reviewed browse species contain different amounts of ANFs. Not all tannins compete with digestibility as shown in the results of *A. raddiana* (Zabré et al. 2018). This indicates that ANFs are not reasons to disregard species per se. Zabré et al. (2018) argued that the ANFs of acacias can be beneficial to livestock production regarding health and methane production, while CP contents improve nutrition of the animals. Leaves of *P. cineraria*, *A. nilotica* and *F. religiosa* suppressed methanogenesis and were found with high tannin content, even though the correlation was nonsignificant (Pal et al. 2015). Not only tannins reduce CH4 production, as Pal et al. (2015) pointed out in their study the example of limonoids in *A. indica* with simultaneously high GP and low CH4. Melesse et al. (2019) discussed the impact of tannins on CH4 production and concluded that there is no proof of direct influence. Aschfalk et al. (2000) advised against feeding *A. pentagyna* because of its toxicity. The authors argued that the impaired N-utilization, despite high CP content, was caused by the presence of ANFs. In this same study, *M. indica* was well accepted and had small amounts of condensed tannins while *P. alnifolia* was also well accepted and had high amounts of the same fraction (ibid.).

Unfortunately, selecting the literature with a focus on experimental studies reduced the otherwise important focus on socio-economic considerations. The excluded articles contained some valuable information on this subject, for example the preferences of farmers regarding the use of species (Bosman et al. 1996; Jabbar et al. 1997) or the preference of animals (Ouédraogo-Koné et al. 2006). Notwithstanding, the decision to focus on experimental studies allowed for a more detailed analysis of the nutritional value of species. Yusuf et al. (2018) showed in their economic evaluation that feed cost was reduced for both supplementation levels of *M. oleifera* because of the lower FCR. The assumption can be made that reduced FCR leads to economic benefits. This was the case for *F. thonningii* (75% inclusion), *A. senegal* and *A. indica*. According to Jayasuriya (2002), supplements should not compete with human nutrition. This aspect was not touched upon in the articles but is necessary to consider before suggesting species for animal consumption. The participatory study by Partey et al. (2018) aimed at identifying and analyzing species with farmers to create awareness about the benefits of browse as fodder. Regarding the farmers interest on using browse in livestock production, Jabbar et al. (1997) pointed out that, in contrast to its use as feed supplement, using browse was for mulching on cropland was preferred by farmers. Analyzing the potential of forages can help to identify species suitable for supplementation, but ultimately seasonal variations, availability and socio-economic factors will determine the effectiveness of species (Abdulrazak et al. 2000).

6 Conclusion

Immense pressure is placed on food production systems in the Sahel region. Evaluating browse trees and shrubs as forage and supplement for the region is one step towards more sustainability. MPTs stand out for their potential nutritional value and are among valued species by livestock producers and herders in Africa. Literature regarding the nutritional value of browse species for livestock keeping in the tropics is limited. Notwithstanding, the analysis of a selection of literature sources as well as the comparison of the browse species found allowed for the identification of some favorable forages. The question whether suitable browse species as supplements for livestock production in the Sahel could be identified through a literature analysis was answered positively. The use of *A. senegal*, *A. indica* and *C. aculeatum* can be promoted for livestock production without hesitation. Further research is needed on *A. africana*, *M. crassifolia*, *P. erinaceus* and *P. lucens* to find out best levels of supplementation. Among the acacias, the effects of *A. nilotica*, *A. tortilis* and *A. tortilis subsp. raddiana* on animal performance also need verification. Precise information regarding their adaptiveness to the Sahelian environment is needed for *C. cajan*, *F. thonningii* and *M. alba* before they, along with the other suggested species, can be studied according for their agronomic and socio-economic considerations as well as their true effects on animal performance within the SustainSahel project. The understanding of the effects of tannins in tropical browse is still sketchy and the study of species like *B. ferruginea*, *S. siamea* and *S. spectabilis* can be helpful in this respect. Some species have been proven unfavorable as supplements, namely *A. angustissima*, *A. seyal*, *A. pentagyna*, *G. senegalensis*, *P. juliflora* and *S. sesban*. Comparing values obtained with different animal species showed that differences between animals need to be remembered, both in the setting of feeding experiments and when suggesting species to livestock producers.

The here stated recommendations are mainly based on (potential) plant-animal interaction. They are made towards enhancing livelihoods of farmers and herders without strong considerations of socio-economic factors, which may have led to suggestions which are not truly suitable. To make appropriate suggestions for sustainable intensification of livestock production in the Sahelian region of BF, Mali and Senegal, the question whether the found species are valuable for the use in agroforestry systems must first be investigated.

7 Summary

Sustainable intensification of livestock production in the Sahelian region of Burkina Faso, Mali and Senegal is an important aim to mitigate effects of climate change, reduce land degradation and serve the increasing population in terms of income and nutrition. The inclusion of multi-purpose trees and shrubs in agropastoral systems is an attempt to fulfil these demands. Major constraints in utilizing these species are their high content of anti-nutritional factors. Through a comparative literature analysis, the question whether the available literature on MPTs as livestock feed in the tropics could be used to identify suitable MPTs for sustainable intensification of livestock production in the Sahel region was evaluated with the aim of providing information for the ongoing SustainSahel project. Relevant literature was searched and browse species adapted to the Sahelian climate were chosen. Both, the literature itself and the included data concerning the browses chemical composition, gas production and degradability as well as their *in vivo* digestibility and effects on animal performance were investigated.

Main findings showed that high CP content alone is not sufficient to judge the potential of browse as supplement. For some species, the unfavorable fiber content was reflected in *in vitro* and/or *in situ* degradability experiments. Unexpectedly, moderate to high degradability and gas production were found for many species, such as *A. indica* and *G. sepium*. This showed that high CP content can outweigh the negative effects of fiber on degradability and that anti-nutritional factors are not reasons to disregard tropical browse per se. CH4 mitigating species, such as *C. cajan* and *F. religiosa,* were identified. Using the data of feeding trials was of high value to understand the effects of some species on animal performance. The impact of ANFs, seasonal variability of nutritional value and a few socio-economic considerations were briefly reflected in this thesis.

It was possible to shed light on the usefulness of MPTs as supplements for sustainable intensification of livestock production in the Sahel with literature from within and outside the focus area. Ultimately, the use of *A. angustissima*, *A. seyal*, *A. pentagyna*, *G. senegalensis*, *M. stenopetala* and *S. sesban* as supplements has to be discouraged. *A. senegal, A. indica* and *C. aculeatum* have been identified as suitable supplements for sustainable intensification in the Sahel. Among the locally available species, *A. africana*, *A. tortilis subsp. raddiana*, *A. nilotica, M. crassifolia, P. erinaceus* and *P. lucens* warrant further research. Precise information regarding their adaptiveness to the Sahelian environment is needed for *C. cajan*, *F. thonningii* and *M. alba* before they, along with the other suggested species, can be studied, according to their agronomic and socio-economic constraints and opportunities, and their true effects on animal performance, particularly under the SustainSahel project.

8 List of References

Abdulrazak, S. A.; Fujihara, T.; Ondiek, J. K.; Ørskov, E. R. (2000): Nutritive evaluation of some Acacia tree leaves from Kenya. In *Animal Feed Science and Technology* 85 (1-2), pp. 89–98. DOI: 10.1016/S0377-8401(00)00133-4.

Aschfalk, A.; Steingass, H.; Müller, W.; Drochner, W. (2000): Acceptance and Digestibility of Some Selected Browse Feeds with Varying Tannin Content as Supplements in Sheep Nutrition in West Africa. In *Journal of veterinary medicine. A, Physiology, pathology, clinical medicine* 47 (9), pp. 513–524. DOI: 10.1046/j.1439-0442.2000.00313.x.

Balehegn, M.; Eik, L. O.; Tesfay, Y. (2014): Replacing commercial concentrate by *Ficus thonningii* improved productivity of goats in Ethiopia. In *Tropical animal health and production* 46 (5), pp. 889–894. DOI: 10.1007/s11250-014-0582-9.

Baumer, M. (1990): Agroforestry and Desertification. The Potential Role of Agroforestry in combating Desertification and Environmental Degradation. With special reference to Africa. Wageningen: CTA.

Beever, D. E.; Mould, F. L. (2000): Forage evaluation for Efficient Ruminant Livestock Production. In D. I. Givens, E. Owen, R. F. E. Axford, H. M. Omed (Eds.): Forage Evaluation in Ruminant Nutrition. New York: CABI Pub, pp. 15–42.

Bosma, R. H.; Bicaba, M. Z. (1997): Effect of addition of leaves from *Combretum aculeatum* and *Leucaena leucocephala* on digestion of Sorghum stover by sheep and goats. In *Small Ruminant Research* 24 (3), pp. 167–173. DOI: 10.1016/S0921-4488(96)00945-5.

Bosman, H. G.; Ademosun, A. A.; Koper-Limbourg, H.A.G. (1996): Goat feeding practices and options for improvement in six villages in southwestern Nigeria. In *Small Ruminant Research* 19 (3), pp. 201–211. DOI: 10.1016/0921-4488(95)00745-8.

CABI (2021): Invasive Species Compendium. Wallingford, UK: CAB International. Available online at www.cabi.org/isc, checked on 6/16/2021.

Calabrò, S.; D´Urso, S.; Banoin, M.; Piccolo, V.; Infascelli, F. (2007): Nutritional characteristics of forages from Niger. In *Ital. J. Animal Science* (6), pp. 272–274. DOI: 10.4081/ijas.2007.1s.272.

CILSS (2016): Landscapes of West Africa. A window on a changing world. Edited by U.S. Geological Survey EROS. 47914 252nd St, Garretson, SD 57030, UNITED STATES. Available online at https://eros.usgs.gov/westafrica, checked on 5/26/2021.

El Hassan, S. M.; Lahlou Kassi, A.; Newbold, C. J.; Wallace, R. J. (2000): Chemical composition and degradation characteristics of foliage of some African multipurpose trees. In *Animal Feed Science and Technology* 86 (1-2), pp. 27–37. DOI: 10.1016/S0377-8401(00)00158-9.

Fern, K. (2014): Useful Tropical Plants Database. Available online at http://tropical.theferns.info/, updated on 6/13/2019, checked on 6/16/2021.

FiBL (2021a): SustainSahel. Background and approach. Institut de recherche de l'agriculture biologique FiBL (1). Available online at https://www.sustainsahel.net/about/background-and-approach.html, updated on 6/10/2021, checked on 6/16/2021.

FiBL (2021b): SustainSahel. Project profile SustainSahel. Institut de recherche de l'agriculture biologique FiBL (2). Available online at https://www.sustainsahel.net/about/project-profile.html, updated on 6/10/2021, checked on 6/16/2021.

Hailemariam, S.; Urge, M.; Menkir, S. (2016): Effect of feeding Neem (*Azadirachta indica*) and Acacia (*Acacia senegal*) tree foliage on nutritional and carcass parameters in short-eared Somali goats. In *Tropical animal health and production* 48 (2), pp. 461–464. DOI: 10.1007/s11250-015-0953-x.

Jabbar, M. A.; Reynolds, L.; Larbi, A.; Smith, J. (1997): Nutritional and economic benefits of Leucaena and Gliricidia as feed supplements for small ruminants in humid West Africa. In *Tropical animal health and production* 29 (1), pp. 35–47. DOI: 10.1007/BF02632347.

Jayasuriya, M. C. N. (2002): Principles of Ration Formulation for Ruminants. AFRA - African Regional Co-operative Agreement for Research, Development and Training related to Nuclear Science and Technology. Available online at https://www.osti.gov/etdeweb/biblio/20265861, checked on 5/14/2021.

Larbi, A.; Smith, J. W.; Adekunle, I. O.; Kurdi, I. O. (1996a): Studies on multipurpose fodder trees and shrubs in West Africa: variation in determinants of forage quality in *Albizia* and *Paraserianthes* species. In *Agroforest Syst* 33 (1), pp. 29–39. DOI: 10.1007/BF00122887.

Larbi, A.; Smith, J. W.; Kurdi, I. O.; Adekunle, I..O.; Raji, A. M.; Ladipo, D. O. (1998): Chemical composition, rumen degradation, and gas production characteristics of some multipurpose fodder trees and shrubs during wet and dry seasons in the humid tropics. In *Animal Feed Science and Technology* 72 (1-2), pp. 81–96. DOI: 10.1016/S0377-8401(97)00170-3.

Larbi, A.; Smith, J. W.; Kurdi, I. O.; Adekunle, I. O.; Raji, A. M.; Ladipo, D. O. (1996b): Feed value of multipurpose fodder trees and shrubs in West Africa: edible forage production and nutritive value of *Millettia thonningii* and *Albizia lebbeck*. In *Agroforest Syst* 33 (1), pp. 41–50. DOI: 10.1007/BF00122888.

Mafindi, U. M.; Kibon, A. U.; Zaklag, D. U.; Buba, I. G. (2018): Growth Performance of Red Sokoto Goats Fed Cowpea Husk Supplemented with graded Levels of *Moringa oleifera* Leaves. In *Nigerian J. Anim. Sci.* 20 (2), pp. 173–182.

Melesse, A.; Steingass, H.; Schollenberger, M.; Holstein, J.; Rodehutscord, M. (2019): Nutrient compositions and in vitro methane production profiles of leaves and whole pods of twelve tropical multipurpose tree species cultivated in Ethiopia. In *Agroforest Syst* 93 (1), pp. 135–147. DOI: 10.1007/s10457-017-0110-9.

Omed, H. M.; Lovett, D. K.; Axford, R. F. E. (2000): Faeces as a Source of Microbial Enzymes for Estimating Digestibility. In D. I. Givens, E. Owen, R. F. E. Axford, H. M. Omed (Eds.): Forage Evaluation in Ruminant Nutrition. New York: CABI Pub, pp. 135–154.

Ørskov, E. R. (2000): The *In Situ* Technique for the Estimation of Forage Degradability in Ruminants. In D. I. Givens, E. Owen, R. F. E. Axford, H. M. Omed (Eds.): Forage Evaluation in Ruminant Nutrition. New York: CABI Pub, pp. 175–188.

OSS (Ed.) (2019): Sahel and West Africa - Atlas of land cover maps. Building Resilience through Innovation, Communication and Knowledge Services - BRICKS (Benin, Burkina Faso, Chad, Ethiopia, Ghana, Mali, Mauritania, Niger, Nigeria, Senegal, Sudan and Togo). Sahara and Sahel Observatory (OSS).

Ouédraogo-Koné, S.; Kaboré-Zoungrana, C. Y.; Ledin, I. (2006): Behaviour of goats, sheep and cattle on natural pasture in the sub-humid zone of West Africa. In *Livestock Science* 105 (1-3), pp. 244–252. DOI: 10.1016/j.livsci.2006.06.010.

Ouédraogo-Koné, S.; Kaboré-Zoungrana, C. Y.; Ledin, I. (2008): Intake and digestibility in sheep and chemical composition during different seasons of some West African browse species. In *Tropical animal health and production* 40 (2), pp. 155–164. DOI: 10.1007/s11250-007-9075-4.

Ouédraogo-Koné, S.; Kaboré-Zoungrana, C. Y.; Ledin, I. (2009): Effect of feeding some West African browse foliages on growth and carcass composition in sheep. In *Tropical animal health and production* 41 (7), pp. 1243–1252. DOI: 10.1007/s11250-009-9307-x.

Pal, K.; Patra, A. K.; Sahoo, A.; Kumawat, P. K. (2015): Evaluation of several tropical tree leaves for methane production potential, degradability and rumen fermentation in vitro. In *Livestock Science* 180, pp. 98–105. DOI: 10.1016/j.livsci.2015.07.011.

Partey, S. T.; Avornyo, F.; Ouédraogo, M.; Zoughmoré, R. (2018): Candidate fodder species for goat production in Northern Ghana. Findings from a participatory evaluation excercise within the climate-smart villages of Ghana. Edited by CGIAR. Climate Change, Agriculture and Food Security. Ghana.

Reed, Jess D. (1995): Nutritional Toxicology of Tannins and Related Polyphenols in Forage Legumes. In *Journal of Animal Science* (73), pp. 1516–1528. DOI: 10.2527/1995.7351516x.

Royal Botanic Gardens, Kew; Missouri Botanical Garden (2021): The Plant List. A working list of all plant species. Available online at http://www.theplantlist.org, updated on 3/4/2021, checked on 6/16/2021.

Rymer, C. (2000): The Measurement of Forage Digestibility *In Vivo*. In D. I. Givens, E. Owen, R. F. E. Axford, H. M. Omed (Eds.): Forage Evaluation in Ruminant Nutrition. New York: CABI Pub, pp. 113–154.

Sanon, H. O.; Kaboré-Zoungrana, C.; Ledin, I. (2008a): Growth and carcass characteristics of male Sahelian goats fed leaves or pods of *Pterocarpus lucens* or *Acacia senegal*. In *Livestock Science* 117 (2-3), pp. 192–202. DOI: 10.1016/j.livsci.2007.12.011.

Sanon, H. O.; Kaboré-Zoungrana, C.; Ledin, I. (2008b): Nutritive value and voluntary feed intake by goats of three browse fodder species in the Sahelian zone of West Africa. In *Animal Feed Science and Technology* 144 (1-2), pp. 97–110. DOI: 10.1016/j.anifeedsci.2007.10.004.

Sawe, J. J.; Tuitoek, J. K.; Ottaro, J. M. (1998): Evaluation of common tree leaves or pods as supplements for goats on range area of Kenya. In *Small Ruminant Research* 28 (1), pp. 31–37. DOI: 10.1016/S0921-4488(97)00059-X.

Schlecht, E. (2021): Digestibility Classification. Expert Communication to H. Grund-Magomu, May 2021.

Schwarz, F. J. (2014): Rinderfütterung. In M. Kirchgeßner, G. I. Stangl, F. J. Schwarz, F. X. Roth, K.-H. Südekum, K. Eder (Eds.): Tierernährung. Leitfaden für Studium, Beratung und Praxis. 14th edition. Frankfurt am Main: DLG Publishers, pp. 357–510.

Stangl, G. I. (2014a): Die Zusammensetzung von Nahrung und Tier. In M. Kirchgeßner, G. I. Stangl, F. J. Schwarz, F. X. Roth, K.-H. Südekum, K. Eder (Eds.): Tierernährung. Leitfaden für Studium, Beratung und Praxis. 14th edition. Frankfurt am Main: DLG Publishers, pp. 20–45.

Stangl, G. I. (2014b): Energiehaushalt. In M. Kirchgeßner, G. I. Stangl, F. J. Schwarz, F. X. Roth, K.-H. Südekum, K. Eder (Eds.): Tierernährung. Leitfaden für Studium, Beratung und Praxis. 14th edition. Frankfurt am Main: DLG Publishers, pp. 135–176.

Steingass, H.; Arbelot, B. (1994): *In Vitro* Studies for the Prediction of Digestibility, Metabolisable Energy Content and Protein Fermentability of Shrub and Tree Fodders. Chapter VII. In H. Guerin (Ed.): Valeur alimentaire des fourrages ligneux consommés par les ruminants en Afrique centrale et de l'Ouest.

SustainSahel (2021): Literature study. Task/Deliverable 6.1: Identifying the most suitable shrub foliage types relevant for livestock feeding and animal health care (M1-M8). FiBL (unpublished internal project document).

UNDESA (2019): World Population Prospects 2019: Data Booklet (ST/ESA/SER.A/424). Available online at https://population.un.org/wpp/Publications/Files/WPP2019_DataBooklet.pdf, checked on 4/27/2021.

van Soest, Peter J. (1994): Nutritional Ecology of the Ruminant. Second Edition. Ithaca, NY: Cornell University Press.

Wilkins, R. J. (2000): Forages and Their Role in Animal Systems. In D. I. Givens, E. Owen, R. F. E. Axford, H. M. Omed (Eds.): Forage Evaluation in Ruminant Nutrition. New York: CABI Pub, pp. 1–14.

Williams, B. A. (2000): Cumulative Gas-production Techniques for Forage Evaluation. In D. I. Givens, E. Owen, R. F. E. Axford, H. M. Omed (Eds.): Forage Evaluation in Ruminant Nutrition. New York: CABI Pub, pp. 189–213.

Yusuf, A. O.; Mlambo, V.; Iposu, S. O. (2018): A nutritional and economic evaluation of *Moringa oleifera* leaf meal as a dietary supplement in West African Dwarf goats. In *SA J. An. Sci.* 48 (1), pp. 81–87. DOI: 10.4314/sajas.v48i1.10.

Zabré, G.; Kaboré, A.; Bayala, B.; Spoto Correa, P.; Leando, N. L.; Niderkorn, V. et al. (2018): *In vitro* Rumen Fermentation Characteristics, Methane Production and Rumen Microbial Community of two major *Acacia* Species used in Sahelian Region of Burkina Faso. In *Tropical and Subtropical Agroecosystems* 21, pp. 357–366.

Cover Picture: AfriPics.com / Alamy Stock Photo

9 Appendices

Appendix I Methodology of the literature study by the SustainSahel Task/Deliverable 6.1

Information sources used for the literature searches:

Electronic catalogues and databases	Search engines	Scientific journals (in alphabetical order)
• Kasseler Recherche-, Literatur- und Auskunftsportal (KARLA)[1] • WorldCat • Publication database of the World Agroforestry Centre (ICRAF)	• CAB Direct • Google Scholar • ResearchGate • Scopus • Web of Science	• Agriculture, Ecosystems and Environment • Agriculture and Allied Sciences • Agroforestry • Agroforestry Systems • AJOL (African journal online) • Biodiversity and Conservation • Cahiers Agricultures • Environmental and Experimental Botany • Ethology • Ethology, Ecology and Evolution • Ethnobotany Research and Applications • Frontiers in Plant Science • Forests • Journal of Ethnopharmacology • Journal of Ethnobiology and Ethnomedicine • Plant and Soil • Plant Ecology and Diversity • Plants • PloS One • Sécheresse • Sustainability • Trees

Note: All databases were searched using full search.

[1] Search possibility in the inventory of the library of the University of Kassel, as well as in 126 databases (as of 15 November 2020) including Academic Search Index, Agris FAO, Bielefeld Academic Search Engine (BASE), Directory of Open Access Journals (DOAJs), JSTOR, OAister, ScienceDirect

Classification categories for the selection process:

1) Relevant: Literature sources related to the use of trees/shrubs for livestock feeding and/or animal health care, and related to the chemical composition of parts of trees/shrubs, with a regional focus on the AEZ of the study sites in the three partner countries;
2) Potentially relevant: Literature sources related to the use of trees/shrubs for livestock feeding and/or animal health care, but outside the regional focus areas, or studies that provided additional information on relevant tree species (e.g. ecology, propagation techniques);
3) Irrelevant: Literature sources not related to the use of trees/shrubs for livestock feeding and/or animal health care, and outside the regional focus area.

(Source: SustainSahel 2021, unpublished)

Appendix II List of all browse species with all presented parameters

On the following pages, a list of all browse species with their full scientific names and all parameters is presented.

Chemical composition in g/kg DM, degradability in %, gas production in ml/200g DM, CH4 in l/kg DM. 'x' is for values which were compared but not presented and can be found in the respective references.

Browse Species Reference	CP	NDF	ADF	ADL	DMDeg	OMDeg	ND	GP	GP24	CH4	DMD	OMD	CPD	DMI	BWG	ANF
Acacia abysinica Benth.																
Melesse et al. 2019	277	n.a.	n.a.	176	n.a.	65	n.a.	41	45	28,7	n.a.	n.a.	n.a.	n.a.	n.a.	x
Acacia angustissima (Mill.) Kuntze																
El Hassan et al. 2000	255	364	179	82	n.a.	52	42	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x
Larbi et al. 1998	274	553	454	n.a.	44	n.a.	48	23	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x
Acacia brevispica Harms																
Abdulrazak et al. 2000	213	308	210	114	72	48	n.a.	33t 34p	20	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x
Acacia mellifera (M.Vahl) Benth.																
Abdulrazak et al. 2000	194	269	192	77	77	49	n.a.	36t 38p	22	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x
Acacia nilotica (L.) Delile																
Abdulrazak et al. 2000	172	312	217	99	64	48	n.a.	34t 34p	22	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x
Melesse et al. 2019	168	n.a.	n.a.	43	n.a.	51	n.a.	52	32	5,3	n.a.	n.a.	n.a.	n.a.	n.a.	x
Pal et al. 2015	159	336	214	116	74	75	n.a.	32	21	9,4	n.a.	n.a.	n.a.	n.a.	n.a.	x
Zabré et al. 2018	159	520	338	250	n.a.	60	n.a.		19	4,5	n.a.	n.a.	n.a.	n.a.	n.a.	x
Acacia nubica Benth.																
Abdulrazak et al. 2000	213	154	114	51	88	64	n.a.	43t 42p	37	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x
Acacia senegal (L.) Willd.																
Hailemariam et al. 2016	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	x	n.a.
Pal et al. 2015	141	310	168	71	81	82		35	30	13,2	n.a.	n.a.	n.a.	n.a.	n.a.	x
Sanon et al. 2008b	170	322	181	53	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	x	x	x	x	n.a.
Acacia seyal Delile																
Abdulrazak et al. 2000	134	230	168	121	66	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x
Acacia tortilis (Forssk.) Hayne																
Abdulrazak et al. 2000	172	296	251	110	80	52	35t 35p	n.a.	26	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x
Pal et al. 2015	153	322	215	101	75	75	n.a.	23	13	11,1	n.a.	n.a.	n.a.	n.a.	n.a.	x
Acacia tortilis subsp. raddiana (Savi) Brenan																
Zabré et al. 2018	120	272	118	71	n.a.	81	n.a.	n.a.	19	2,8	n.a.	n.a.	n.a.	n.a.	n.a.	x

Browse Species Reference	CP	NDF	ADF	ADL	DMDeg	OMDeg	ND	GP	GP24	CH4	DMD	OMD	CPD	DMI	BWG	ANF
Afzelia africana Pers.																
Ouédraogo-Koné et al. 2008	134	497	384	152	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	n.a.	x	x	n.a.	n.a.
Ouédraogo-Koné et al. 2009	197	540	390		n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	x	n.a.
Partey et al. 2018	137	645	401	129	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	n.a.	n.a.
Agelaea pentagyna (Lam.) Baill.																
Aschfalk et al. 2000	131	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	n.a.	x	x	x
Ailanthus excelsa Roxb.																
Pal et al. 2015	146	369	219	65	83	82	n.a.	n.a.	18	23,4	n.a.	n.a.	n.a.	n.a.	n.a.	x
Albizia lebbeck (L.) Benth.																
Larbi et al. 1996a	227	417	304	61	71	n.a.	85	37	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x
Larbi et al. 1996b	256	359	72		80	n.a.	94	44	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x
Larbi et al. 1998	257	457	351		72	n.a.	90	39	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x
Pal et al. 2015	184	320	202	93	70	74	n.a.	n.a.	31	35,6	n.a.	n.a.	n.a.	n.a.	n.a.	x
Albizia procera (Roxb.) Benth.																
Larbi et al. 1996a	188	648	565	324	61	n.a.	68	25	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x
Azadirachta indica A.Juss.																
Hailemariam et al. 2016	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	x	n.a.
Melesse et al. 2019	222	n.a.	n.a.	119	n.a.	61	n.a.	40	30	17,6	n.a.	n.a.	n.a.	n.a.	n.a.	x
Pal et al. 2015	149	324	234	122	78	77	n.a.	n.a.	18	25,4	n.a.	n.a.	n.a.	n.a.	n.a.	x
Bridelia ferruginea Benth.																
Aschfalk et al. 2000	99	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	n.a.	x	x	x
Cajanus cajan (L.) Millsp.																
Melesse et al. 2019	200	n.a.	n.a.	125	n.a.	49	n.a.	25	17	9,0	n.a.	n.a.	n.a.	n.a.	n.a.	x
Combretum aculeatum Vent.																
Bosma & Bicaba 1997	161	285	217	38	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	x	x	x	x	n.a.
Calabrò et al. 2007	95	333	274	60	n.a.	63	n.a.	45	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Cytisus proliferus L.f.																
El Hassan et al. 2000	208	388	217	76	n.a.	72	68	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x
Melesse et al. 2019	209	n.a.	n.a.	68	n.a.	70	n.a.	49	40	27,3	n.a.	n.a.	n.a.	n.a.	n.a.	x
Ficus religiosa L.																
Pal et al. 2015	125	402	291	73	78	76	n.a.	n.a.	22	31,2	n.a.	n.a.	n.a.	n.a.	n.a.	x

Browse Species Reference	CP	NDF	ADF	ADL	DMDeg	OMDeg	ND	GP	GP24	CH4	DMD	OMD	CPD	DMI	BWG	ANF
Ficus sycomorus L.																
Partey et al. 2018	116	669	506	146	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	n.a.	n.a.
Ficus thonningii Blume																
Bamikole & Ikhatua 2010	205	558	402	114	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	x	x	x	x	n.a.
Gliricidia sepium (Jacq.) Walp.																
Calabrò et al. 2007	150	426	334	171	n.a.	57	n.a.	30	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Larbi et al. 1998	254	381	305	n.a.	74	n.a.	84	47	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x
Guiera senegalensis J.F.Gmel.																
Sanon et al. 2008b	105	590	401	234	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	x	n.a.
Leucaena diversifolia (Schltdl.) Benth.																
Larbi et al. 1998	232	414	338	n.a.	74	n.a.	76	65	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x
Leucaena leucocephala (Lam.) de Wit																
Aschfalk et al. 2000	270	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	x	x	x	x
Bosma & Bicaba 1997	184	211	149	33	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	x	x	x	x	
El Hassan et al. 2000	197	346	192	94	n.a.	60	48	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x
Larbi et al. 1998	270	414	308	n.a.	70	n.a.	76	38	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x
Melesse et al. 2019	245	n.a.	n.a.	55	n.a.	70	n.a.	48	34	18,3	n.a.	n.a.	n.a.	n.a.	n.a.	x
Pal et al. 2015	174	303	202	140	53	56	n.a.	n.a.	24	37,0	n.a.	n.a.	n.a.	n.a.	n.a.	x
Maerua crassifolia Forssk.																
Calabrò et al. 2007	193	231	170	35	n.a.	83	n.a.	35	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Mallotus oppositifolius (Geiseler) Müll.Arg.																
Aschfalk et al. 2000	161	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	x	x	x	x
Mangifera indica L.																
Aschfalk et al. 2000	97	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	n.a.	x	x	x
Pal et al. 2015	106	364	211	118	69	71	n.a.	n.a.	25	30,4	n.a.	n.a.	n.a.	n.a.	n.a.	x
Moringa oleifera Lam.																
Mafindi et al. 2018	258	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	n.a.	x	n.a.
Melesse et al. 2019	256	n.a.	n.a.	46	n.a.	76	n.a.	52	44	26,4	n.a.	n.a.	n.a.	n.a.	n.a.	x
Pal et al. 2015	296	266	124	28	82	83	n.a.	n.a.	26	30,8	n.a.	n.a.	n.a.	n.a.	n.a.	x
Yusuf et al. 2018	315	355	253	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	n.a.	n.a.

Browse Species Reference	CP	NDF	ADF	ADL	DMDeg	OMDeg	ND	GP	GP24	CH4	DMD	OMD	CPD	DMI	BWG	ANF
Moringa stenopetala (Baker f.) Cufod.																
Melesse et al. 2019	296	n.a.	n.a.	37	n.a.	83	n.a.	56	45	37,7	n.a.	n.a.	n.a.	n.a.	n.a.	x
Morus alba L.																
Pal et al. 2015	184	285	159	52	79	82	n.a.	n.a.	26	33,8	n.a.	n.a.	n.a.	n.a.	n.a.	x
Newbouldia laevis (P.Beauv.) Seem.																
Larbi et al. 1998	171	627	457	n.a.	66	n.a.	71	33	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x
Parkia biglobosa (Jacq.) G.Don																
Larbi et al. 1998	163	539	398	n.a.	73	n.a.	65	34	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x
Pergularia tomentosa L.																
Calabrò et al. 2007	99	418	371	73	n.a.	68	n.a.	47	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Pericopsis laxiflora (Baker) Meeuwen																
Partey et al. 2018	102	676	576	103	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	n.a.	n.a.
Pouteria alnifolia (Baker) Roberty																
Aschfalk et al. 2000	133	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	n.a.	x	x	x
Prosopis cineraria (L.) Druce																
Pal et al. 2015	134	431	282	135	66	65	n.a.	n.a.	11	18,4	n.a.	n.a.	n.a.	n.a.	n.a.	x
Prosopis juliflora (Sw.) DC.																
Melesse et al. 2019	261	n.a.	n.a.	119	n.a.	44	n.a.	14	10	-5,8	n.a.	n.a.	n.a.	n.a.	n.a.	x
Pterocarpus erinaceus Poir.																
Ouédraogo-Koné et al. 2008	181	581	387	163	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	n.a.	x	x	n.a.	n.a.
Ouédraogo-Koné et al. 2009	226	552	383		n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	x	n.a.
Partey et al. 2018	105	617	349	86	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	n.a.	n.a.
Pterocarpus lucens Guill. & Perr.																
Sanon et al. 2008a	149	494	358	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	x	n.a.
Sanon et al. 2008b	147	477	351	180	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x	x	x	x	x	n.a.

Browse Species Reference	CP	NDF	ADF	ADL	DMDeg	OMDeg	ND	GP	GP24	CH4	DMD	OMD	CPD	DMI	BWG	ANF
Senna siamea (Lam.) H.S.Irwin & Barneby																
Larbi et al. 1998	173	444	285	n.a.	79	n.a.	92	53	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x
Senna spectabilis (DC.) H.S.Irwin & Barneby																
Larbi et al. 1998	212	414	319	n.a.	80	n.a.	94	50	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x
Sesbania sesban (L.) Merr.																
El Hassan et al. 2000	243	206	139	43	n.a.	68	67	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	x
Melesse et al. 2019	228	n.a.	n.a.	66	n.a.	73	n.a.	45	45	44,5	n.a.	n.a.	n.a.	n.a.	n.a.	x
Tamarindus indica L.																
Pal et al. 2015	119	431	308	147	72	72	n.a.	n.a.	27	40,2	n.a.	n.a.	n.a.	n.a.	n.a.	x

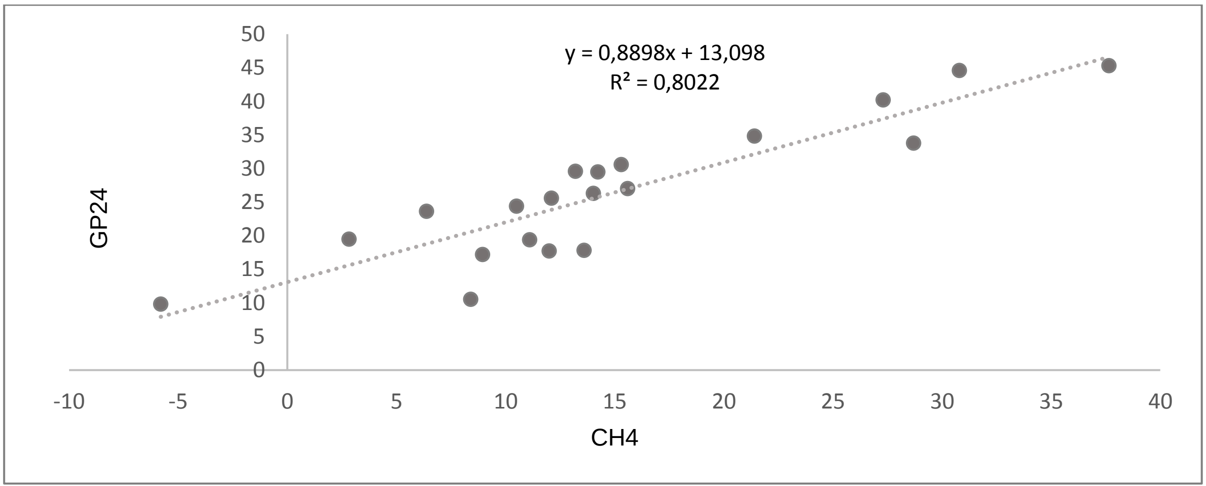
ADF: acid detergent fiber; ADL: acid detergent lignin; BWG: body weight gain; CP: crude protein; n.a.: not available; NDF: neutral detergent fiber; CPD: crude protein digestibility; DM: dry matter; DMD: dry matter digestibility; DMDeg: dry matter degradability; DMI: dry matter intake; GP: gas production; GP24: gas production after 24 hours of incubation; ND: nitrogen degradability; NDF: neutral detergent fiber; OMD: organic matter digestibility; OMDeg: organic matter degradability; p: potential; t: true.

Appendix III Animal species and breeds used for *in vitro* and *in situ* experiments

Animal species	Breeds	References
buffalo	*B. bubalis*	Calabrò et al. 2007
cattle	Jersey Zebu X Fresian Zebu (steers)	Melesse et al. 2019 El Hassan et al. 2000 Larbi et al. 1996a; b; 1998
sheep	n.a. Malpura sheep Santa Inês	Abdulrazak et al. 2000 Pal et al. 2015 Zabré et al. 2018

Note: n.a.: not available.

Appendix IV Correlation between GP24 and CH4 of browse species



Note: CH4: methane (in l/kg DM); DM: dry matter; GP24: gas production measured after 24 hours of incubation (in ml/ 200mg DM).

Appendix V Different amounts of browse foliage and additional feed offered to goats in different feeding trails

Browse Species	Level	Feed	Goat Breed	initial BW	Trial	References
Acacia senegal	1,2% BW	1	Short-eared Somali	15,7 - 16,9	intake, digestibility, BWG	Hailemariam et al. 2016
	75%	2	Sahelian	23,3	intake, digestibility	Sanon et al. 2008b
	a.l.	3	Sahelian	23,3	intake, BWG	Sanon et al. 2008b
Afzelia africana	100%	-	West African Dwarf	n.a.	intake	Partey et al. 2018
Azadirachta indica	1,2% BW	1	Short-eared Somali	15,7 - 16,9	intake, digestibility, BWG	Hailemariam et al. 2016
Combretum aculeatum	30%	4	Voltaique X Fouta Djallon	24,8 - 29,4	intake, digestibility, BWG	Bosma & Bicaba 1997
Ficus thonningii	100%	-	West African Dwarf	5 - 7,5	intake, digestibility, BWG	Bamikole & Ikhatua 2010
	75%	5				
	50%	6				
	25%	7				
Guiera senegalensis	a.l.	3	Sahelian	23,3	intake, BWG	Sanon et al. 2008b
Leucaena leucocephala	10%	4	Voltaique X Fouta Djallon	24,8 - 29,4	intake, digestibility, BWG	Bosma & Bicaba 1997
	30%	4				
Moringa oleifera	50g	8	Red Sokoto	10,5 - 10,6	intake, digestibility, BWG	Mafindi et al. 2018
	100g	8				
	150g	8				
	5% of CO**	9	West African Dwarf	7,0 kg	intake, BW change	Yusuf et al. 2018
	10% of CO**	9				
Pterocarpus erinaceus	100%	-	West African Dwarf	n.a.	intake	Partey et al. 2018
Pterocarpus lucens	a.l.	10	Sahelian	15,6	intake, BWG	Sanon et al. 2008a
	75%	2		23,3	intake, digestibility	Sanon et al. 2008b
	a.l.	3		23,3	intake, BWG	Sanon et al. 2008b

Note: Numbers 1 – 10 represent different feed rations, total amount of these in parentheses. 1: hay (no specification) (a.l.); 2: hay (SG) (25%); 3: hay (SG) (30%); 4: 70:30 stover (SB) and CO (70%); 5: grass (PM) (25%); 6 grass (PM)(50%); 7: grass (PM)(75%); 8: cow pea husks (a.l.); 9: grass (PM) (a.l.) and CO (4%BW)**; 10: CSC, MB and hay (SG) (each 200g). No additional feed where 100% browse was offered. Amounts needed to feed browse a.l. were established in adaptation periods before the here mentioned trials. AG: Andropogon gayanus, a.l.: ad libitum; BW: body weight in kg; BWG: body weight gain; CO: concentrate; DM: dry matter; MB: maize bran; PM: Panicum maximum, SB: Sorghum bicolor. *ingredients: wheat bran 52,5%, cotton seed cake 25%, molasses 12,5%, fish meal 5%, NaCl 5%. **ingredients: palm kernel cake 19,25%, wheat offal 20%, rice bran 40%, oatmeal 20%, premix 0,25%, salt 0,5%.*

Appendix VI Different amounts of browse foliage and additional feed offered to sheep in different feeding trails

Browse Species	Levels	Feed	Breeds	Initial BW	Trials	References
Afzelia africana	100% *a.l.* *a.l.* *a.l.*	- 1 2 3	West African Djallonké	20 20 20 15,7 - 16,9	intake, digestibility intake digestibility intake, BWG	Ouédraogo-Koné et al. 2008 Ouédraogo-Koné et al. 2008 Ouédraogo-Koné et al. 2008 Ouédraogo-Koné et al. 2009
Combretum aculeatum	30%	4	Djallonké	24,8 - 29,4	intake, digestibility, BWG	Bosma & Bicaba 1997
Leucaena leucocephala	10% 30%	4	Djallonké	24,8 - 29,4	intake, digestibility, BWG	Bosma & Bicaba 1997
Pterocarpus erinaceus	*a.l.*	1 2 3	West African Djallonké	20 20 15,7 - 16,9	intake digestibility intake, BWG	Ouédraogo-Koné et al. 2008 Ouédraogo-Koné et al. 2008 Ouédraogo-Koné et al. 2009

Note: Numbers 1 – 4 represent different feed rations, total amount of these in parentheses. 1: hay (AG) (200g); 2: hay (AG) (max. 30%); 3: hay (AG) and MB (each 200g); 4: 70:30 stover (SB) and CO (70%). No additional feed where 100% browse was offered. Amounts needed to feed browse a.l. were established in adaptation periods before the here mentioned trials. AG: Andropogon gayanus, a.l.: ad libitum; BW: body weight; BWG: body weight gain; CO: concentrate; DM: dry matter; MB: maize bran; PM: Panicum maximum, SB: Sorghum bicolor. *ingredients: wheat bran 52,5%, cotton seed cake 25%, molasses 12,5%, fish meal 5%, NaCl 5%.*

Appendix VII Different browse foliage offered to West African Dwarf sheep in different feeding trials by Aschfalk et al. 2000)

Browse Species	Level	Amount PM	Trials	Parameters
Agelaea obliqua *Bridelia ferrugines* *Mangifera indica* *Mallotus oppositifolius* *Leucaena leucocephala* *Pouteria alnifolia*	a.l.	*a.l.* + wheat bran (200g)	acceptance (free choice between one browse and PM)	intake, BWG
Agelaea obliqua *Mallotus oppositifolius* *Leucaena leucocephala*	a.l.	a.l.	acceptance (free choice between six species and PM)	intake
Agelaea obliqua *Bridelia ferrugines* *Mallotus oppositifolius* *Leucaena leucocephala* *Pouteria alnifolia*	15%	85%	acceptance (no choice between one browse and PM)	intake, BWG
Agelaea obliqua *Bridelia ferrugines* *Mallotus oppositifolius* *Leucaena leucocephala* *Pouteria alnifolia*	30%	70%	acceptance (no choice between one browse and PM)	intake, BWG
Mallotus oppositifolius *Leucaena leucocephala*	50%	50%	partial digestibility	digestibility

Note: Initial BW of the animals were between 17,0 and 23,7 kg. a.l.: ad libitum; BW: body weight; PM: Panicum maximum.

Appendix VIII List of studies with tannin and phenol values

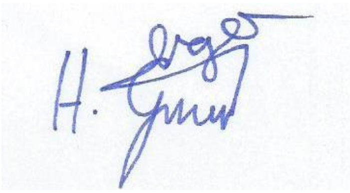
This list presents all studies in which tannins and phenols were measured and presented. 'x' is for values found in the respective references. Kindly refer to articles for more information.

Reference	TT	EST	TCT	TET	SCT	SOPH
Abdulrazak et al. 2000	X	n.a.	X	X	n.a.	n.a.
Aschfalk et al. 2000	X	X	n.a.	X	n.a.	n.a.
El Hassan et al. 2000	n.a.	n.a.	X*	n.a.	n.a.	X
Larbi et al. 1996a	n.a.	n.a.	X*	n.a.	n.a.	n.a.
Larbi et al. 1996b	n.a.	X	X*	n.a.	n.a.	X
Larbi et al. 1998	n.a.	n.a.	X*	n.a.	n.a.	X
Melesse et al. 2019	X	n.a.	n.a.	X	X	n.a.
Pal et al. 2015	X	n.a.	X	X	n.a.	n.a.
Zabré et al. 2018	X	n.a.	X	X	n.a.	n.a.

*Note: n.a.: not available; SCT: soluble condensed tannins; SOPH: soluble phenols; TT: total tannins; EST: extractable condensed tannins; TCT: total condensed tannins; TET: total extractable tannins. *proanthocyanidins*

10 Declaration of Oath

I hereby declare, in lieu of oath, that I have composed the enclosed bachelor's thesis myself without use of any other than the cited sources and aids. Sentences or parts of sentences quoted literally are marked as such; other references with regard to statements and scope are indicated by full details of the publications concerned. The thesis in the same or similar form has not been submitted to any examination body and has not been published. This thesis has not been, even in part, used in another examination or as a course performance. Furthermore, I declare that the submitted bound written copies of the present thesis and the version submitted as electronic soft copy are consistent with each other in content.



Witzenhausen, 21st June 2021