Performance of Sorghum (*Sorghum bicolor* L. Moench) as an Energy Crop for Biogas Production

ATHAR MAHMOOD

A thesis submitted for the requirement of doctoral degree in agriculture
from Faculty of Agricultural and Nutritional Sciences,
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submitted by

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Dedicated to

MY MOTHER
(Kishwar Sultana)

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Abbreviations and definitions used in this thesis.

ADF:	Acid Detergent Fiber
NDF:	Neutral Detergent Fiber
XL:	Lipid Concentration
XP:	Protein Concentration
XZ:	Sugar Concentration
DMC:	Dry Matter Content
DMY:	Dry Matter Yield
ADL:	Acid Detergent Lignin
LAI:	Leaf Area Index
Ph:	Plant Height
XA:	Ash Concentration
LSD:	Least Significant Difference
P:	Probability Level
NIRS:	Near Infra Red Reflectance Spectroscopy
PAR:	Photosynthetically Active Radiation
VS:	Volatile Solid
GG:	Gross-Gerau
GI:	Giessen
RH:	Rauischholzhausen
RS:	Row Spacing
CV:	Cultivar
ST:	Sowing Time
PD:	Plant Density
AT:	Air Temperature
LAT:	Long Term Air Temperature
PS:	Precipitation Sum
LPS:	Long Term Precipitation Sum
BGY:	Biogas Yield
MY:	Methane Yield
XM:	Methane Concentration
nl:	Norm Litter

1. Introduction

The European Union is emphasizing to reduce the CO_2 emissions, increase energy efficiency and the proportion of renewable energy sources in total energy production to 0.20 by 2020 (Richter et al. 2009). Biogas production from agricultural biomass is gaining importance as it offers environmental benefits (Chynoweth 2004). Energy crops, used for biogas production, include maize, sorghum, sunflower, sudan grass, fodder beet, poor oat grass meadows, small-sedge poor-fen, meadow, and montane hay meadow (Jerger and Chynoweth 1987, Chynoweth et al. 1993, Weiland 2003, Amon et al. 2007, Richter et al. 2009, Schittenhelm 2010). Biogas consists mainly of methane (CH_4) and carbon dioxide (CO_2), CH_4 being the energy-carrying compound. Biogas production systems are therefore aimed to optimize the methane yield.

Maize silage is a key substrate for agricultural biogas production in Germany (Widdicombe and Thelen 2002, Schnittenhelm 2008). In Germany, growing of maize for biogas production is common in the catchment area of biogas plants. For that reason mono-cropping of maize is increasing, which is threatening the agricultural systems owing to decrease in crop species diversity, increasing pest pressure and nutrient losses (Schittenhelm 2010). Alternate crops are being evaluated to overcome these problems. It is hypothesized that, owing to compositional identity, sorghum can be used for biogas production.

Sorghum (*Sorghum bicolor* L. Moench) is a C_4 annual grass which can produce high forage biomass yields per unit of land (Fribourg 1995, Rooney et al. 2007). The most important producers of grain sorghum are USA, India, Nigeria and China (FAO 2009). Within the species *Sorghum bicolor* which is characterized by a diploid set of chromosomes ($2n = 20$) are several subspecies or races with different morphological and physiological characteristics (Zeller 2000). Since plant breeders found first lines with cytoplasmatic male sterility in 1950ies years hybrid breeding technology is established in *Sorghum bicolor* too. Sorghum biomass is variously used for the production of energy, fiber or paper, as well as for syrup and animal feed in several regions (Steduto et al. 1997).

Cultivars and hybrids of sorghum are available that have been selected specifically for high forage biomass (Redfearn et al. 2000, Trostle 2004, Blumenthal et al. 2007). Cultivars differ in their chemical composition, including content of water soluble carbohydrate (Habyyarimana 2004, Zhao et al. 2009) and protein, as well as in their structural fibrous ingredients, including neutral detergent fiber acid detergent fiber and acid detergent lignin (Miron et al. 2006, Beck et al. 2007). Consequently, clear differences between varieties with respect to dry matter and NDF digestibility of the silage have been found (Hanna et al. 1981, Pedersen et al. 1982, Ashbell et al. 1999).

Plant configuration can affect leaf area index (LAI) and canopy closure, altering partitioning of available evapotranspiration between the plant and the soil surface. Higher dry matter yields were recorded from narrow rows than from wide rows under favorable conditions (Steiner 1986, Staggenborg et al. 1999). At the same plant population, double-row planting resulted in reduced dry matter, tillering and LAI during early plant growth compared to single-row planting due to increased intra-specific plant competition (Blum and Naveh 1976). However, Karchi and Rudich (1966) found that under dryland conditions superior yields resulted from narrow rows combined with wide intra row seedling spacing. At low yield potential, clumping greatly increased yields compared to uniform spacing (Bandaru et al. 2006).

Higher biomass yield of *Sorghum bicolor* in South Texas was observed when planting date is adjusted to take advantage of maximum radiation (Hipp et al. 1970). The planting date should be as early possible in order to take advantage of favorable growing conditions and accumulate biomass (Kucharik 2008), but a crop planted too early can be exposed to adverse environmental conditions. Early planting affected plant phenology altering water use patterns resulting in increased yields when soil moisture is limited (Blum 1972). The soil water is the primary consideration when determining planting date and the decision to plant is determined by the probability that additional moisture will be received in the future (Muchow et al. 1994).

Plant density can affect forage yield (Cusicanqui and Lauer 1999) and quality (Defoor et al. 2001). An increase in plant density can reduce water availability to the individual and lead to water deficiency (Berenguer and Faci 2001), followed by yield reduce. Plant density can also affect the plant morphology (Lafarge and Hammer 2002), DM content (Rosenthal et al. 1993) and chemical composition (Widdicombe and Thelen 2002). Under dryland conditions, dry matter yield of Sudan grass hybrids was not influenced by different seeding rates (Iptas et al. 2002).

Susceptibility to chilling injury imposes late plantings or prevents the cultivation of many crops in regions where temperatures can drop below the optimal growth temperatures for individual plant species. Early planting could contribute to a longer growing season, a more efficient utilization of late spring and early summer rainfall, and to an improved yield potential.

However, sorghum is very sensitive to cold stress and often expresses poor early-season vigor and reduced competitive ability against weeds, owing to low temperatures after sowing. The effects of chilling stress on sorghum have been studied in relation to chilling-induced declines in photosynthetic capacity. However, there are many conditions, i.e. cloudy conditions or darkness, where the photosynthetic apparatus of sorghum may not be affected by low temperatures (Taylor and Rowley 1971).

Sorghum is a new crop in Germany and still not well adapted to the local climate. So there is a dire need to optimize various breeding and husbandry practices like sowing date, harvesting date, row spacing and plant density etc. This study was therefore conducted to clarify the effect of different sowing times, row spacing and plant densities on dry matter production, chemical composition, and biogas production of sorghum under local conditions in Germany (Hessen).

Hypothesis

The aims of the experiments described in this thesis were to point out the best row spacing, sowing time, plant density and cultivars for maximum dry matter yield (DMY), and maximum biogas and methane productivity via anaerobic digestion. In doing so the following hypothesis were put forward: In doing so the following hypothesis were put forward:

1. Narrow row spacing (keeping number of plant constant) and higher plant density increase the leaf area index (LAI) and number of tillers per plant of sorghum.

2. Dry matter yield, biogas and methane productivity of sorghum is influenced by cultivars and row spacing.

3. Higher plant density increases dry matter yield and biogas production of sorghum.

4. Different plant densities and sowing times affect the chemical composition of sorghum biomass.

5. Delayed sowing cause a decline in dry matter yield and methane productivity of sorghum.

2. Literature Review

2.1 Botany of sorghum

Taxonomy

Sorghum (*Sorghum bicolor* L. Moench) is belonging to the Tribe *Andropogonae* of the family *Poaceae*. The genus *Sorghum* has been classified into five subgenera: *Eusorghum*, *Chaetosorghum*, *Heterosorghum*, *Para-sorghum* and *Stiposorghum* (Garber 1950). Although this classification is convenient, however it does not stand for evolutionary relationships (Dillon et al. 2004). The *Eu-sorghum* comprises the cultivated species *S. bicolor* (L.) Moench and its subspecies are *drummondii, arundinaceum*, and wild species includes *S.* x *alum* Parodi, *S. halepense* (L.) Pers. and *S. propinquum* (Kunth) Hitchc (deWet 1978). The *Eu-sorghum* section is originated from Africa or Asia (Doggett 1976, DuVall and Doebley 1990). Sections *Chaetosorghum* and *Heterosorghum* consist of *S. macrospermum* and *S. laxiflorum* and both of these species are annuals and polyploids (Lazarides et al. 1991, Wu 1990). Section *Stiposorghum* includes ten species indigenous to northern Aus and tralia (Lazarides et al. 1991). *Para-sorghum* Section is comprised seven African, Asian, Australian and Central American species. The basic number of chromosome of species in each section is five. The species belong to *Parasorghum* and *Stiposorghum* are mostly diploid (2*n* = 10), however a few species are tetraploid or hexaploid.

Sorghum includes three species, *S. halepense, S. propinquum* and *S. bicolor Sorghum halepense* is also known as Johnsongrass, derived from a natural cross between *S. arundinaceum* and *S. propinquum* (Doggett 1976). *Sorghum propinquum* is a perennial species related to *S. bicolor* (Chittenden et al. 1994, Sun et al. 1994). By using Harlan and deWet’s system which is based on spikelet morphology, *Sorghum bicolor* has been classified into five races. These races consist of *Bicolor, Guinea, Caudatum, Kafir, and Durra*. Owing to the variability found in each race an additional classification scheme was developed. This new classification amalgamates the Harlan and deWet’s classification with working groups (sub-races) based on “head opening” which resulted in the classification of seventy working groups (Dahlberg et al. 2004). Early *bicolor* sorghum is believed to have arisen from the subspecies *verticilliforum* in central Africa (Dahlberg 1995). The races; Caudatum, Kafir, Guinea, and Durra were created by the crossing of early *bicolor* with the wild forms of sorghum. It is believed that the Guinea race has been evolved when the Bicolors came into contact with the wild *S. arudinaceum*. The Caudatum race is also believed to develop from a cross between an early domesticated Bicolor and wild sorghum (Dahlberg 2000). The Kafir race is thought to be developed from crosses between Bicolor in northern Africa with wild verticilliflorum that was carried from east toward south by the Bantu speakers of Africa (Dahlberg 1995). The Durra race is thought to be originated in Ethiopia as a result of crossing between early bicolor and with wild *S. aethiopicum* which allowed it to cope with drier conditions (Dahlberg 1995).

2.2 Physiological characteristics of sorghum

Drought tolerance

The C_4 cereals, like sorghum are originated from the tropics and can tolerate heat and drought condition more effectively as compared with C_3 plants (like wheat), which originated from temperate regions (Blum et al. 1990, Chapman and Carter 1976). Under arid environmental conditions, osmotic adjustment is imperative in the drought resistance of many C_4 plants (Slatyer 1963) and may enable sorghum to grow when leaf water potential is low (Craufurd et al. 1993). Due to several morphological and physiological properties, sorghum is better drought resistant in comparison with maize (Purseglove 1972). They are:

1. The plant grows slowly until the root system is established.
2. As compared with maize, it can produce two time higher secondary roots.
3. During drought stress, Silica deposits in the endodermis of the root avoid tissue collapse.
4. Leaf area is about half that of equivalent maize.
5. Evapotranspiration from sorghum is about half as compared with maize.
6. Leaves contain a thicker cuticle and they in- roll completely under drought conditions.

Sorghum leaves subjected to wilting for 1 week recover quickly after watering, with normal diurnal stomatal rhythm being restored in 5 days. Contrary to that normal stomatal function is permanently impaired, with no restoration of normal diurnal pattern in maize (Doggett 1988). Where the crop is dependent on stored soil water, deeper root systems result in superior yield. Sorghum has an advantage, by penetrating the soil faster and to greater depths. Under similar conditions maize roots grew to about 1 m depth whereas sorghum roots penetrated more than 2 m, thus allowing extraction of significantly more water (Squire 1990).

Cold tolerance

Sorghum plant is considered sensitive to cold temperatures at germination and seedling stage of growth. Under cold temperature, poor emergence and seedling loss results in reduced plant population and grain yield. Improvement in cold tolerance during germination and early seedling development can potentially allow expansion of sorghum cultivation into regions of colder climates. Germination, emergence and seedling growth have been shown to be independently sensitive to cold temperature (Alegre De La Soujeole and Miller 1984). Singh (1985) found that the intensity of cold tolerance in sorghum differs with the stage of plant growth. The chilling stress induced declines in photosynthetic capacity of sorghum (Taylor and Rowley 1971). Author also argued that there are many conditions, i.e. cloudy conditions or darkness, where the photosynthetic apparatus of sorghum may not be influenced by low temperatures.

Nutrient use efficiency

Although sorghum plants (C_4) use N more efficiently than most C_3-type crops and are more tolerant to drought and high temperature stresses compared to corn (Young and Long 2000), N deficiency can suppress plant growth and DM accumulation and allocation. Lower plant biomass production due to N shortage was linked with reductions in both LA and leaf photosynthetic capacity (Sinclair 1990) and was mainly attributed to a smaller LA in sorghum. Nitrogen deficiency decreased LA, chlorophyll content, and Pn of sorghum plants that resulted in lower DM accumulation (Zhao et al. 2005).

Lemaire et al. (1996) concluded that sorghum has greater ability to satisfy its nitrogen requirement, with better uptake of N from the soil, gives this species an undeniable agronomic advantage over maize, due to its greater adaptation to growing condition in limiting in water and nitrogen. Examining the relative aerial/ underground growth kinetics of two species provide grid for analyzing the balance between the nitrogen supply characterized by the uptake capacities of roots system and the nitrogen demand which is determined mainly by the dynamics of the leaf area development.

With irrigation and high nitrogen fertilizer application, maize dry matter accumulation was higher than that of sorghum, due to earlier development of leaf area in maize, leading to a larger quantity of intercepted radiation (Lemaire et al. 1996). But when nitrogen was limiting, the capacity of sorghum to take up N from the soil was always higher than that of maize. An early study in Australia under irrigation and a wide range of N applications showed no difference between both species (Muchow and Davis 1988).

2.2 Uses of sorghum

Rooney and Waniska (2000) provide a tremendous overview of the uses of sorghum in food and industry. Worldwide, sorghum has been used for human food, animal feed, building material and fencing (House 1985, Doggett 1988). Traditionally, sorghum is used in unfermented and fermented breads, porridges, couscous, rice-like products, snacks, and malted alcoholic and non-alcoholic beverages in many African and Asian countries. Sorghum can be used to produce foods that are gluten-free and in this respect the potential for new food uses exists for both the US and Europe.

Broomcorn is a classical example of industrial use of sorghum in Europe (Berenji and Kisgeci 1996). The demands of ecological and natural products have led to renewed interest in old fashioned, biodegradable, wooden-handled brooms, which have had a positive effect on broomcorn production.

The use of sorghum as forage crop is gaining importance in many region of the world (Zerbini and Thomas 2003). Sweet sorghum stalks consist of sugars, mainly sucrose that amounts up to 55% of dry matter and in glucose (3.2% of dry matter). They also contain fiber contents like cellulose (12.4%) and hemicelluloses (10.2%) (Billa et al. 1997). Sugar in biomass of Sweet sorghum is readily fermentable and thus it can be considered as a tremendous raw material for fermentative hydrogen production. Although sorghum has been thoroughly investigated as an energy crop for bioethanol and methane production (Jackman 1987, Richards et al. 1991, Mamma et al. 1996), it can also be used as a potential source for hydrogen production. Sorghum biomass could be fully exploited for hydrogen production since both soluble and complex carbohydrates can be utilized, either in a single step or separately after extraction. Fermentative hydrogen production from biomass can be attained either by using mixed acidogenic microbial cultures or a pure culture of a saccharolytic strain. *Ruminococcus albus* is a non spore-forming, obligatory anaerobic, coccoid bacterium (Hungate 1966), the natural habitat of which is the first stomach (rumen) of the ruminants. It produces extracellular hydrolytic enzymes (exoglucanases and endoglucanases), which break down cellulose (Ohmiya et al. 1985, Ohmiya et al. 1987, Ohmiya et al. 1988) and hemicelluloses (Dehority 1973). On the other hand, itcannot break down pectin and starch (Hungate 1960). The oligosaccharides produced from cellulose and hemicellulose degradation – cellobiose, glucose, pentoses, xylose and arabinose, are further metabolized (Lou et al. 1997, Thurston et al. 1999).

2.3 Cultivation

Planting Method

Higher dry matter yields were found by drilling sorghum compared to hand sowing and broadcasting (Kim et al. 1989). Highest green fodder yield was reached for planting in single row followed by double row and triple row strips (Nazir et al. 1997). Sorghum is sensitive to planting depth. In general, plant depth ranges from 2.5 to 7.5 cm. Hergert et al. (1993) concluded that planting to deep (>3.8 cm) caused a poor seedling survival and vigor, while planting too shallow (<1.3 cm) caused poor rooting therefore lodging of the mature crop was occurred.

Plant density

An optimum seeding rate of 30 – 40 kg ha^{-1} is suggested for forage sorghum (Kim et al. 1989). The higher seed rate enhanced the non-structural carbohydrate content in sorghum (Mohamed and Hamd 1988), whereas height increased with higher seeding rate for the first cut but decreased with increasing seeding rate for second cut. By decreasing plant density of sorghum i.e. increasing within row spacing from 5 to 60 cm reduced dry matter yield, total NDF and lignin concentrations, while forage digestibility and protein content enhanced (Caravetta et al. 1990). Significant reduction in dry matter yields was observed as row spacing increased from 15 to 90 cm. An optimum plant density of 40–50 plants m^{-2} (in rows 25 cm apart) was suggested for silage of highest quantity and quality in previous study (Corleto et al. 1990). Another study showed that the mixture of sorghum and soybean (*Glycine max* L.) were most advantageous for obtaining greater dry matter yields under high planting densities (Kawamoto et al. 1987).

Planting date

The appropriate planting date for sorghum depends on different factors like soil temperature, air temperature, soil moisture, and near term weather predictions. These factors have an effect not only on planting density but also on hybrids selection as well. Sorghum needs at least 10 °C soil temperatures; below this it can not germinate (Anda and Pinter 1994). Authors suggested that sorghum planting should be delayed until the soil temperature at the planting depth has reached at 10 ° C for three consecutive days, combined with an acceptable five days forecast. Soil moisture content is a critical factor in deciding the proper planting date. Grain yields of sorghum markedly influenced by soil water content at planting (Unger 1991).

Previous study suggests that sorghum planted with adequate moisture can grow four times faster than sorghum planted in dry soil at the same soil temperature (Anda and Pinter 1994).

The planting date should be as early possible in order to take advantage of favorable growing conditions and accumulate biomass but a crop planted too early can be exposed to adverse environmental conditions (Kucharik 2008). The soil water has primary importance when determining planting date, and that the decision to plant is determined by the probability that additional moisture will be received in the future (Muchow et al. 1994). When soil moisture was sufficient, maximum biomass production by sweet sorghum was observed when planting date is adjusted to take advantage of maximum solar radiation in South Texas (Hipp et al. 1970).

However, sowing date had no clear impact on digestibility, plant crude protein and fiber (El-Hattab and Harb 1991). Under the climatic conditions of India, Poornima et al. (2008) found that among the different dates of sowing, June 8th sowing led to extensively higher grain yield and millable cane yield over other dates of sowing. Increase in yield under June 8th sowing might be due to the favourable environment prevailed during the crop growing season.

Fertilizer applications

Nitrogen requirement

Nitrogen is considered to have a greater importance in improving the yield and quality of fodder. Nitrogen (N) application increased CP (crude protein), ash and HCN content but lowered the non-structural carbohydrate content in sorghum (Mohamed and Hamd 1988). Application of N up to 120 kg ha^{-1} enhanced the green forage, dry matter and CP contents and reduced NDF contents in sorghum (Bebawi 1988, Patil et al. 1992). In sudan grass and sorghum x sudan grass hybrids, the impact of N fertilization on dry matter yield varied with time of harvest. According to Iptas and Brohi (2003) Increasing N fertilizer rates from 60 to 240 kg ha^{-1} had no significant effect at the first and third cuttings, but the highest dry matter yield was obtained with 80 kg N ha^{-1} at the second cutting of sorghum x Sudan grass hybrids. Increasing N fertilization up to 100 or 150 kg ha^{-1} resulted in more forage and dry matter production (Turgut et al. 2005). However, when the fertilization levels were lower or higher than those levels, the forage and dry matter yields were decreased. Seed yield also showed similar trends as with forage and dry matter yield, and maximized at N fertilization regimes.

The grain yield of sorghum increased with higher levels of N (Poornima et al. 2008). The highest grain yield was recorded with 150 kg N ha^{-1} (2173 kg ha^{-1}) which was similar to 120 kg N ha^{-1} (2063 kg ha^{-1}). The increase in grain yield was 62, 54 and 43 per cent higher under 150 kg N ha^{-1}, 120 kg N ha^{-1} and 90 kg N ha^{-1} respectively over control. The increased grain yield at high N levels might be caused by the boost up of yield attributing characters and nutrient uptake under these treatments.

Phosphorous requirement

Phosphorus (P) is critical for the early development of young sorghum plant. A phosphorus deficiency can cause a restricted of root development and delayed flowering and maturity in sorghum. To take more benefits, phosphorus should be applied as a band at planting so that seedlings have immediate access to this element. Phosphorus does not have similar significant effects on fodder yield and quality as nitrogen. It was observed that protein content and yield were not affected by P_2O_5 application (Patel et al. 1993). A previous study showed that crude fiber decreased with increasing N but was not influenced by P application (Patel et al. 1994).

Potassium requirement

Potassium (K) is taken up in large quantities by the sorghum plant. Potassium plays an important role in the water relations within the plant and vigor, disease resistance and grain quality. Sorghum takes up 50% of its potassium requirements during the vegetative period prior to floral initiation (Pacific seeds, 2007/2008). Adequate supplies of potassium are therefore essential for the establishment of a healthy stand of grain sorghum.

Irrigation requirement

Water can affect crop performance not only directly but also indirectly by influencing nutrient availability, timing of cultural operations, and other factors. Sorghum can respond to additional irrigation by stem elongation and increase of yield (Saeed and El-Nadi 1998, Singh and Singh 1995). But on the other hand, better water status can enhance lignin content and reduce forage sorghum digestibility (Amaducci et al. 2000). The amount of moisture needed to produce an acceptable yield of grain sorghum is approximately 400 to 500 mm, which may be provided from a combination of stored soil moisture, rainfall and irrigation. Fresh weight yields of forage sorghum ranged from 38.3 t ha^{-1} with no irrigation to 88.4 t ha^{-1} with 560 mm of irrigation (Naescu and Nita 1991).

Weed control

Weed control within the four to five weeks after germination of sorghum plants is most critical: infact the seedlings of sorghum grow slowly and have not ability to cope well with weeds until a canopy develops (Benini et al. 1994, Buhler et al. 1998). After this stage, the competitiveness of sorghum enhanced owing to high plants density and height, reducing subsequent weed emergence and growth (Covarelli 1999). As a result of this, severe uncontrolled weed infestations at the early growth stages of sorghum often cause poor crop establishment or complete crop failure; however an effective pre-emergence weed control can help to overcome this problem (Martin et al. 1982). The most common weeds of sorghum in Taxas are; Amaranthus spp., Texas panicum, barnyardgrass [*Echinochloa crusgalli* (L.) Beauv.] and crabgrass [*Digitaria sanguinalis* (L.) Scop] (Webster 2000, Moore and Murray 2000, Smith et al. 1990).

The increasing interest of farmers on biomass sorghum grown for renewable energy production should be supported with scientific information on how to optimize chemical weed control strategies and improve the efficacy minimizing application costs (Hallam et al. 2001, Monti and Venturi 2003). The herbicides such as Atrazine, pendimethalin, and trifluralin are commonly used in Texas grain sorghum production to control many weeds which caused serious problem (Grichar et al. 2005). Most producers include atrazine (pre emergence) in their sorghum weed control program. To control annual grasses effectively, a dinitroaniline herbicide can be included with atrazine. Post application of atrazine is generally not recommended unless broadleaf weeds emerge subsequent to the crop. Chenault et al. (1992) reported that pendimethalin or trifluralin can provide greater than 78% barnyardgrass control depending on incorporation method. Munoz et al. (1986) reported that pendimethalin plus atrazine showed consistently better results for control of broadleaf signalgrass than pendimethalin alone when applied (post emergence).

Insect pest control

Sorghum [*Sorghum bicolor* (L.) Moench] is an important cereal crop in America, Asia, Africa, and Australia. Almost 150 species of insects have been reported as pests of sorghum (Reddy and Davies 1979, Jotwani 1980, Young and Teetes 1980). Among these the major pests are; sorghum shoot fly (*Atherigona soccata* Rond.), armyworm (*Mythimna separata* Walk.), stem borer (*Chilo partellus* Swin.), sorghum midge (*Stenodiplosis sorghicola* Coq.), aphid (*Melanaphis sacchari* Zehnt.), earhead bug (*Calocoris angustatus* Leth.), shoot bug (*Peregrinus maidis* Ashmead) and head caterpillars (*Helicoverpa, Eublemma*, and *Cryptoblabes*) (Sharma 1993). Cultural practices, host-plant resistance, natural enemies and insecticides are most common recommendations for integrated pest management (IPM) in sorghum. Stem borer larvae can cause a serious crop damage by defoliation, boring into the stem and dead-heart at early growth stage of sorghum crop, stem tunneling and chaffy heads in late infestation (Nye 1960, Harris 1962, Young and Teetes 1977, Reddy 1983). In Africa south of the Sahara, stem borer species like *Busseola fusca* Fuller, *Chilo partellus* Swinhoe, *Sesamia calamistis* Hampson and *Eldana saccharina* Walker are most important (main) pests of sorghum and maize (Swaine 1957, Ingram 1958, Nye 1960, Mathez 1972, Reddy 1983, Harris 1989, PätsPäts 1992). Different techniques are used to control stem-borer including cultural, biological, plant resistance, and uses of insecticides have been developed in Africa and Asia. Insecticides have been also used for the control of stem borer in Africa and Asia (Ajayi 1989, Nwanze and Mueller 1989, Sithole 1990). Among these insecticides, both granules (carbaryl, carbofuran, trichlorphor) and spray (malathion and diazinon), have been proved to be effective against stem borer (Walker 1960, Warui and Kuria 1983).

Disease control

Anthracnoses caused by *Colletotrichum graminicola* and maize stripe viral disease (MStV), caused by a tenuivirus are prevalent diseases of sorghum in most parts of India (Navi et al. 2001, Indira et al. 2002, Narayana et al. 2002). Anthracnose can attack all plant parts. Premature leaf area demolition and infection of developing grains caused a clear decline in stover and grain yield (Thomas et al. 1996). MStV systemically infects plants causing stunting. Depending on the growth stage, infected plants do not produce panicles or some time set few seeds incase panicles are produced (Narayana et al. 2002). The virus is can be spread by the plant hopper (*Peregrinus maidis)* that is well known pest of sorghum (Narayana et al. 2002). To control the diseases of sorghum integrated disease management (IDM) should be adopted.

Harvesting

The bloom stage is an optimal harvesting stage regarding the yield of forage DM, in vitro DM digestibility (IVDMD), and CP per hectare (Snyman and Joubert 1996). At this stage, the quality of forage quality was also higher and would meet, the energy requirements set for the roughage component of most dairy diets (NRC 1989). Forage sorghum harvested at the ripening stage, tended to be of inferior quality which jointly with the lesser yield of DM, IVDDM, and CP, would make utilization less economical at this stage. According to De Brouwer et al. (1991) forage sorghum harvested at the early- to medium dough stage (at DM content = 29.9%) should be considered as a medium to low quality roughage that could possibly be used in maintenance rations or as a source of fiber in high concentrate finishing rations.

2.4 Anaerobic digestion

"Anaerobic digestion is a process that takes place in the presence of biodegradable biomass (substrate), anaerobic micro-organisms (facultative as well as obligatory), and a milieu (digester) free of molecular oxygen (O_2)".The process converts the biomass into energy in a gaseous mixture otherwise known as biogas. The composition of biogas consists of gases mainly methane (CH_4) and carbon dioxide (CO_2) together with small to minute concentrations of other gases. This composition depends on quality of the substrate, conditions of digestion environment and the type of microorganisms involve in this process. In the present global energy crises, many none oil producing countries like Germany sees the employment of anaerobic digestion as a means to convert waste material and energy crops into methane that can reduce their dependency on petroleum and natural gas. The complex process of anaerobic digestion can be divided into four phases of degradation, such as hydrolysis, acidogenesis, Acetogenesis, and Methanogenesis.

Stage 1: Hydrolysis

Hydrolysis is first step in which undissolved compounds like cellulose, proteins, and fats are degraded into monomers (water soluble fragments) such as amino acids, glucose, fatty acids, and glycerol by consortia of anaerobic bacteria which excrete extracellular enzymes like cellulases, proteases, and lipases. The monomers (amino acids, glucose, fatty acids, and glycerol) are directly available to the next group of bacteria. Hydrolysis is a comparatively slow and can be the rate limiting stage in anaerobic digestion especially when the organic matter contains high concentration of lignin and cellulose. Lipids hydrolysis at a much faster rate in comparison with proteins and carbohydrates (Pavlosthatis and Giraldo-Gomez 1991, Angelidaki et al. 1995). Contrary to that other researchers dismissed this and claimed lipid hydrolysis to be the slowest and hence rate limiting reaction of hydrolysis (Hanaki et al. 1987, Rinzema et al. 1993, Beccari et al. 1996).

Stage 2: Acidogenesis

The microorganisms engaged in hydrolysis are generally the same which carries out acidogenesis. Usually hydrolysis and acidogenesis are together referred to as fermentation reactions. Species of the genera *Bacteriods, Eubacterium, Clostridium, Bifidobacterium, lactobacillus* and *Butyrivibrio* are considered to dominate the fermentation reactions (McDonald et al. 1991). The products of hydrolysis are converted into organic acids by microorganism these organic acids are usually termed as volatile fatty acids (VFA). Acetic acid, formic acid, lactic acid, propionic acid, succinic acid and buteric acid are the major VFA formed during this process.

Only glycerol, amino acids and sugars undergo acidogenesis (Batstone 2000). He observed that the long chain fatty acids degrade only at the acetogenesis because they require an external acceptor for oxidation.

On the other hand Glycerol produces acetate, lactate and 1, 3 propandiol. The products of this stage (acidogenesis stage) are generally converted into acetate, hydrogen and carbon dioxide which are considered as potential methanogenic substrates.

Stage 3: Acetogenesis

The products from the acidogenic phase serve as substrate for other bacteria, those of acetogenic phase. This stage involves the action of acetogenic bacteria that convert the volatile fatty acids and alcohols formed during acidogenesis into acetate, hydrogen, and carbon dioxide. Two groups of acetogenic bacteria have been isolated which are known as hydrogen and acetate producers (Boone et al.1980, McInerney et al. 1981).

Both acetogens and methanogens are sensitive to higher hydrogen concentrations (pH acidic), therefore it is essential to strictly monitor the concentrations of hydrogen during the anaerobic digestion process. When the hydrogen partial pressure is low, H_2 and CO_2 and acetate are predominantly formed. The higher hydrogen partial pressure reduced acetate formation whereas the formation of propionic acid, butyric acid and ethanol increased. While the formation of acetate indicates good potentials for methane formation, the production of butyrate and propionate are deemed as disturbances. According to Boone et al. (1980) the hydrogen producing groups have the potentials of breaking down propionate and other organic acids into acetate and hydrogen. This break down of propionate helps to prevent the accumulation of propionate that otherwise would have antimicrobial influences on vital microorganisms (methanogens).

Stage 4: Methanogenesis

Methanogenesis is the final phase of the anaerobic digestion process. In this stage, methane and carbon dioxide (biogas) are produced by various methane-producing microorganisms termed as methanogens. The most important substrates for these organisms are hydrogen gas, carbon dioxide, and acetate, which are formed during anaerobic oxidation (Schnürer and Jarvis 2009). Some other substrates like methyl amines, alcohols, and formates can also be used for methane production (Liu and Whitman 2008). Several types of microorganisms are active in this stage like other stages of the anaerobic digestion. “The methane-producing group that usually dominates in a biogas process is the so-called acetotrophic methanogens”, which use acetate as substrate. In their metabolism, acetate is broken into two parts in which one of the carbons is used to form methane and the other to form carbon dioxide. Hence, acetotrophic methane producers are sometimes also named as acetate-splitting methanogens. Normally, Acetate is the source of about 70% of the biogas produced in a digester (Zinder 1993). Hydrogentrophs are the methanogens which used carbon and hydrogen gas as primary source for the formation of methane. Presently there are only two well recognized groups of methanogens that break down acetate: *Methanosaeta* and *Methanosarcina*, though there are also other groups of methanogens which use hydrogen gas, such as *Methanococcus*, *Methanobacterium*, *Methanobrevibacter* and *Methanogenium* (Garcia et al. 2000, Liu and Withman 2008). *Methanosarcina* and *Methanosaeta* have different growth rates and also differ regarding their capability to use acetate (Westermann et al. 1989). Methanosarcina grows faster, but finds it difficult to use acetate at low concentrations, while Methanosaeta has an advantage. Because methane producers usually grow very gradually, for that reason this is also the rate-limiting stage of the biogas process (Liu and Withman 2008). Generation time, i.e. the time required for a microorganism to divide itself in two, is between 1 and 12 days for methane producers. Methanosaeta grow the slowest.

$$\mathbf{CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O}$$

On the other hand, acetotrophic methanogens converts acetate into methane and carbondioxde.

$$\mathbf{CH_3COOH \rightarrow CH_4 + CO_2}$$

The methanogens can be influenced by various diverse conditions like pH changes or by the presence of toxic compounds including heavy metals and organic pollutants (Chen et al. 2008, Liu and Withman 2008). Because these organisms are also of immense importance to the function of anaerobic oxidation, inhibition/disruption of methanogens can critically affect the entire process.

3. Materials and methods

3.1. Overview of field experiments

Two different field experiments were carried out to study the effect of different agronomic and abiotic factors on biomass, chemical composition and biogas yield in 2008 and 2009. These experiments were conducted at research stations of the Institute of Agronomy and Plant Breeding I in Giessen, Gross Gerau and Rauischholzhausen. An overview of all experiments conducted for the study is shown in table 3.1.

Table 3.1: Overview of the field experiments conducted in 2008 and 2009

Year	Location	Study Factor	Treatment
2008	GI, GG, RH	Plant density, Sowing times & Cultivars	16, 24, 32 plants m^{-2} 1st sowing: mid May, 2nd sowing: end May, 3rd sowing: 1st week of June Cv. Goliath, cv. Bovital
2009	GI, GG, RH		
2008	GI, GG	Row spacing & cultivars	75cm, 37.5cm, 75cm (DR) Cv. Goliath, cv. Bovital (2008)
2009	GI, GG		Same row spacing Cv. Goliath, cv. Bovital, cv. Aron, cv. Rona 1, cv. Akklimat (2009)

GI = Giessen, GG = Gross-Gerau, RH = Rauischholzhausen

3.2. Planting density and sowing time field experiments

Three different sowing dates, three plant densities (16, 24, 32 plants m^{-2}) and two cultivars; Goliath (late maturing, *S. bicolor* x *S. bicolor*) and Bovital (early maturing, *S. bicolor* x *S. sudanense*) were included in these experiments. The experiment design was a RCBD under factorial arrangement with four replications. Each plot had an area of 10 m^2. Weeds were controlled by the application of herbicide Gardo Gold (chloroacetinelide) at rate of 3.5 L/ha and additionally by manual practices. An overview about sowing and harvest times is shown in table 3.2.

Table 3.2: Overview about sowing and harvesting dates in the executed field experiments in Giessen, Gross-Gerau and Rauischholzhausen in 2008 and 2009

Sowing time	**Giessen**		**Gross-Gerau**		**Rauischholzhausen**	
	2008	**2009**	**2008**	**2009**	**2008**	**2009**
	Sowing dates					
1st sowing	16.05	20.05	13.05	14.05	09.05	13.05
2nd sowing	29.05	29.05	27.05	10.06	19.05	27.05
3rd sowing	07.06	08.06	10.06	23.06	29.05	10.06
Harvesting dates						
1st sowing	11.08	06.10	02.09	09.09	16.09	28.09
2nd sowing	25.08	06.10	17.09	05.10	16.09	28.09
3rd sowing	08.09	06.10	09.10	20.10	17.09	13.10

3.3. Row spacing and cultivar field experiments

Three row spacing: 1st 75 cm, 2nd 37.5 cm and 3rd double row (75 cm apart with strip rows of 10-15 cm) and two cultivars Goliath (*S. bicolor x S. bicolor*) and Bovital (*S. bicolor x S. sudanense*) were included in 2008, while same row spacing and five cultivars Goliath, Bovital, Aron (*S. bicolor*), Rona 1 (*S. bicolor*) and Akklimat (*S. sudanense*) were tested in 2009. The most appropriate and symmetrical row spacing occurs for 37.5 cm, followed by double row 75 cm apart and 10-15 cm with in row, with the most compressed pattern 75 cm single row spacing. The experimental design was a split-plot arrangement of a randomized complete block design with row spacing as main plots and cultivars as subplots in four replications. Each plot area was 10 m^2. The sowing time of sorghum in experimental station Giessen was 8th May (2008) and 20th May (2009). Crop was harvested on 9th September in 2008 and 6th October in 2009 when it reached approximately 25% of dry matter. In Gross Gerau the sowing time of sorghum was 8th May 2008 and 20th May 2009. Harvesting was done on 18th August in 2008 and 22nd September (early maturing stage) in 2009. Plant density of 20 plants m^{-2} was maintained by thinning. Weeds were controlled by the application of herbicide Gardo Gold (chloroacetinelide) at rate of 3.5 L/ha (at five leaf stage) and additionally by manual practices.

3.4. Soil conditions in the stations

Experimental station Giessen

The experimental station Giessen (50°°35°N, 8°°40°E) is located in the valley of the Lahn River about 1° 12’ northward displacement. Topographically the station is generally even with homogenous soils rich in clay. These mainly fluvogenic (river side) soils are best described as having a silty clay consistency. The soil is characterized by the following parameters: clay content 30% (0 – 30 cm) humus content 2% (0 – 30 cm), available field capacity 202 mm (0 – 100 cm) and pH 6.0.

Soil analyses and fertilization

Soil nutrient contents were determined from top soil to 90 cm deep. Before sowing potassium and phosphorus (Thomaskali) fertilization was done in accordance with soil analysis. Fertilizer Kalkammonsalpeter (NH_4NO_3 + $CaCO_3$) was applied directly after sowing to meet the nitrogen requirement of the crop. The results of soil analyses and amount of fertilizers have been shown in table 3.3. Phosphorous and potassium fertilizer were applied in form of P_2O_5 and K_2O respectively.

Table 3.3: Soil analyses and fertilization at experimental station Giessen 2008 and 2009

Parameter	Unit	2008	2009
Nmin [1)]	kg ha^{-1}	34 (14.02.2008)	43 (16.02.2008)
P	mg $100g^{-1}$	5.0 (14.01.2008)	10.5 (16.02.2008)
K	mg $100g^{-1}$	10.7 (14.01.2008)	20.7 (16.02.2008)
Mg	mg $100g^{-1}$	11.1 (14.01.2008)	26.1 (16.02.2008)
Fertilization			
N	kg ha^{-1}	120 (24.04.2008)	120 (21.04.2009)
P & K	kg ha^{-1}	80:80 (24.04.2008)	47:70 (21.04.2009)

Nmin: NO_3^--N+NH_3^+-N in 0-90 cm soil depth

Experimental station Gross-Gerau

Experimental station Gross-Gerau (49°55'N 8°28'E) is located in the upper Rhine valley with the river Main to the north, the river Rhine to the west and the Odenwald Mountains to the East. With elevations ranging from 83.2 m to 145 m above sea level, this location is generally low lying. The soils are mainly alluvial with a predominantly sandy but also loamy texture. The soils are hence best described as having a slightly loamy to loamy sand consistency. Its sandy soils reduce its water retention capacity thereby limiting crop cultivation. Row spacing field experiments were given supplemental irrigation of 46mm in sequence of 16, 16, 20mm (29th May, 25th June and 10th July) in 2008 and 30mm in sequence of 10 and 20mm (25th May, 6th August) in 2009. Different plant densities and sowing times experiments were applied with irrigation of 40 in sequence of 20 (14 July) and 20mm (25th July) in 2008 while 36 mm in sequence of 20 (6th August) and 16mm (17 August) in 2009.

Soil conditions and fertilization

Soil nutrient contents were determined from top soil to 90 cm deep. Before sowing potassium and phosphorus (Thomaskali) fertilization was done in accordance with soil analysis. Fertilizer Kalkammonsalpeter (NH_4NO_3 + $CaCO_3$) were applied to meet the nitrogen requirement of the crop. The soil analyses and doses of fertilizers are given in table 3.4.

Table 3.4: Soil analyses and fertilization at experimental station Gross-Gerau 2008 and 2009

Parameter	Unit	2008	2009
Nmin [1)]	kg ha^{-1}	18.0 (20.02.2008)	37.0 (02.03.2009)
P	mg $100g^{-1}$	8.7 (06.09.2007)	14.0 (03.10.2008)
K	mg $100g^{-1}$	12.5 (06.09.2007)	21.7 (03.10.2008)
Mg	mg $100g^{-1}$	3.6 (06.09.2007)	5.4 (03.10.2008)
Fertilization			
N	kg ha^{-1}	120 (13.05.2008)	120 (22.05.2009)
P & K	kg ha^{-1}	70:210 (20.02.2008)	54:162 (18.02.2009)

Nmin: NO_3^--N+NH_3^+-N in 0-90 cm soil depth

Experimental station Rauischholzhausen

The research station Rauischholzhausen (50° 45´N and 8° 39´E, 220 m above sea level) is characterized by silty loam soils. Soil nutrient contents were evaluated from top soil to 90 cm deep. Kalkammonsalpeter (NH_4NO_3 + $CaCO_3$) as N fertilizer was applied directly after sowing to meet the need nitrogen requirement of crop. Previous crops were winter wheat and rapeseed in 2008 and 2009 respectively.

Table 3.5: Soil analyses and fertilization at experimental station Rauischholzhausen 2008 and 2009

Parameter	Unit	2008	2009
P	mg $100g^{-1}$	7.4	10.4
K	mg $100g^{-1}$	19.2	23.3
Mg	mg $100g^{-1}$	5.0	-
Fertilization			
N	kg ha^{-1}	120 (08.05.2008)	120 (12.05.2009)

3.5. Climatic conditions in the stations during the field experiments

Experimental station Giessen

The weather conditions during the growing period of sorghum were characterized by precipitation of 300, 315 mm and mean air temperature of 15.8, 15.1 °C in 2008 and 2009 respectively. In 2008 higher amounts of rainfall were measured in the phase May to July whereas relatively homogenous distribution was observed in 2009 (table 3.6).

Table 3.6: Weather conditions during crop growing season at experimental station Giessen 2008 and 2009

Months	2008				2009			
	AT	LAT	PS	LPS	AT	LAT	PS	LPS
	°C	°C	mm	mm	°C	°C	mm	mm
May	16.7	12.9	50	58	15.1	12.9	82	58
June	13.4	16.0	60	62	11.8	16.0	73	62
July	20.5	17.8	43	66	18.5	17.8	77	66
August	18.6	17.2	70	59	18.5	17.2	44	59
September	9.7	13.7	75	50	11.4	13.7	39	50
Sum/Mean	**15.8**	**15.5**	**298**	**295**	**15.1**	**14.3**	**315**	**295**

AT: Air temperature (°C), LAT: Long term air temperature (°C), PS: Precipitation sum (mm), LPS: Long term precipitation average (mm)

Experimental station Gross-Gerau

Average temperatures of Gross Gerau in 2008 and 2009 are compared with long term averages in table 3.7. It can be observed that in most of cases temperatures were above the long term averages for the months within the growing season. Months July and August were characterized by higher average temperature in both years. Maximum pricipitation was measured in June (115 mm in 2008 and 109 mm in 2009).

Table 3.7: Weather conditions during crop growing season at experimental station Gross-Gerau in 2008 and 2009

Months	**2008**				**2009**			
	AT	LAT	PS	LPS	AT	LAT	PS	LPS
	°C	°C	mm	mm	°C	°C	mm	mm
April	8.8	9.4	76	41	15.1	9.5	36	41
May	17.0	14.0	39	57	15.7	14.0	55	57
June	18.3	17.2	115	64	17.1	17.2	109	65
July	19.4	19.0	30	67	19.7	19.0	72	67
August	18.4	18.2	72	64	20.2	18.2	46	64
September	12.6	14.4	56	47	15.6	14.4	40	47
October	9.6	9.5	60	50	9.4	9.5	47	50
Sum/Mean	**14.9**	**14.5**	**448**	**390**	**16.2**	**14.5**	**405**	**391**

AT: Air temperature (°C), LAT: Long term air temperature (°C), PS: Precipitation sum (mm), LPS: Long term precipitation average (mm)

Experimental station Rauischholzhausen

The weather conditions of the experimental station Rauischholzhausen are given in table 3.8. This station was characterized by mean temperature of 15, 14.9 °C and precipitation 302, 342 mm during the crop season in 2008 and 2009 respectively. Higher mean temperatures were observed in the month of July and August during both years. On the other hand, higher amount of precipitation was received in the month of June 2008 and July 2009.

Tab. 3.8: Weather conditions during crop growing season at experimental station Rauischholzhausen in 2008 and 2009

Months	**2008**				**2009**			
	AT	LAT	PS	LPS	AT	LAT	PS	LPS
	°C	°C	mm	mm	°C	°C	mm	mm
May	15.0	12.2	61.4	57.3	14.2	12.2	68.6	57.5
June	17.1	15.4	73.8	63.0	15.4	15.4	50.3	62.8
July	18.4	16.7	27.7	63.7	18.5	16.7	90.1	65.1
August	17.8	16.8	58.5	73.8	18.3	16.8	37.6	72.9
September	12.6	13.2	42.2	47.8	14.6	13.2	49.3	47.9
October	9.2	8.8	38.0	49.8	8.6	8.8	45.7	49.6
Sum/Mean	**15.0**	**13.9**	**301.6**	**355.4**	**14.9**	**13.9**	**341.6**	**355.8**

AT: Air temperature (°C), LAT: Long term air temperature (°C), PS: Precipitation sum (mm), LPS: Long term precipitation average (mm)

3.6. Biomass and plant stand parameters

Leaf area indexes (LAI)

Leaf area index (LAI) was measured by using a pre-calibrated Sun Scan canopy analysis system from Delta T Company. Sun Scan measures the incident and transmitted photosynthetic active radiations (PAR) in crop canopies. It provides valuable information about LAI and biomass production. It provides an opportunity to quickly sample vast areas of land.

The advantage of using Sun Scan lies in its capability to function in both steady as well as changing light conditions. The system consists of a probe, a beam fraction sensor (BFS), and a data collection terminal (also called a Psion or Workabout) containing Sun data software for programming the system. The BFS contains two photodiodes, one of which could be shaded from the direct solar beam by the shade ring.

This allowed the direct and diffuse components of PAR to be separated. BFS therefore measured the actual solar light incident on the canopy. The Sun Scan probe is a 1 meter long light sensitive rectangular rod containing 64 photodiodes equally spaced along the 1m length. It ends in a handle containing batteries and ports to which the workabout and BFS are connected. It also contains electronics that function in converting the photodiode output from the “Wand „into digital PAR readings. The readings are then sent to the data collection terminal (Psion Workabout) via an RS232 link (cables). In these experiments readings directly represented the true leaf area indices of sorghum plants.

LAI measurements procedures constituted mounting the beam fraction sensor to a tripod and connecting to the probe via cables. From the probe the workabout was connected via the RS232 link. By positioning the BFS in an unshaded position and inserting the probe beneath the canopy shadow of targeted plants of sorghum, the leaf area index was obtained by directly reading the values displayed on the workabout.

Height of sorghum plants

At same day when sorghum leaf area indices were measured, sorghum heights were also measured by using a normal bricklayer ruler. Heights of sorghum plants from each plot were measured from the soil surface to the tip of the panicle. From each plot, two readings were measured for plant heights and the average was calculated.

Fig. 3.1: Height measurement of sorghum plants at experimental station Giessen

Number of tillers

Two meter area was harvested from middle rows of the plot and tillers (side stems) were separated from the main stems of sorghum plants. Number of tillers were counted and then calculated on m^{-2} basis.

Dry matter yields of sorghum

Sorghum was harvested using a silage plot harvester driven by the power take off shaft of a tractor. The harvesting was done plot by plot across the block from replication one to replication four until the whole experimental block (corresponding to a harvest time) was completely harvested. The same harvesting and sampling methods were used in all years and stations. At first edges were harvested and thrown away into the field as manure. This was followed by the second pass by which the two inner rows were harvested and sampled for further analysis and processing.

Fig. 3.2: Harvesting of sorghum in experimental station Giessen

The samples were collected for dry matter yield and moisture content determinations, sorghum silage chemical composition analyses and for anaerobic digestion. All samplings were prepared manually at all experimental stations. Immediately after harvest dry matter and moisture concentration of samples were determined. Samples intended for NIRS analyses of sorghum chemical composition were dried, finely grounded, packaged into dry paper sachets and stored. Those for biogas production were immediately deep-frozen at -20°C at experimental station Rauischholzhausen.

Total dry matter yield and dry matter content

One hundred grams each of the samples were weighed out and kept into a laboratory drying oven at a constant temperature of 105°C. The samples were intended to dry over a period of 48 hours. At intervals samples were taken out and weighed until no weight change was recorded between consecutive intervals. Water was considered to be the only volatile substance present in samples of sorghum and so the constant weight indicated a complete evaporation of water. Thus it was recorded as the dry matter concentration (DMC). By subtracting this final constant weight (DMC) from the weight of the sample originally put into the drying oven, the moisture content of each sample was also calculated.

$$\text{Moisture Content [\%]} = \frac{\text{(sample mass [g] - dried mass [g])}}{\text{sample mass [g]}} \times 100$$

$$\text{Dry matter Content [\%]} = \frac{\text{dried mass [g])}}{\text{sample mass [g]}} \times 100$$

3.7. Laboratory analyses

Samples from experimental fields of sorghum were analyzed for chemical composition, biogas and methane productivity at respective laboratories in Giessen at plant breeding laboratory and experimental station Rauischholzhausen.

The chemical composition of sorghum dry matter was determined by using a near infra red reflectance spectroscopy (NIRS). Biogas production was measured anaerobically digesting sorghum samples using a laboratory mesophilic digester, measuring the total biogas volumes produced by means of a wet Ritter gas meter. Methane concentration was determined by using Non-dispersive Infrared (NDIR) sensor GS IRM-100.

Near infra red reflectance spectroscopy (NIRS) analysis

The chemical composition of sorghum dry matter was analyzed spectroscopically by measuring the ability of components to reflect wave lengths in the near infra red region of the light. Near-infrared radiation is the region of the electromagnetic spectrum between the visible and the infrared region (Sheppard and Walsh 2002). By convention it is characterized as the region containing the wavelengths (λ) from 780 to 2500 nm (Workman and Shenk 2004).

Fig. 3.3: FOSS NIRS Systems Model 6500

It has been known for a long time that biological materials interact with near infrared radiation (NIR). The near infrared reflectance spectroscopy (NIRS) technology exploit the ability of chemical components of biomass to absorb and reflect specific wavelengths over the infrared range (750 to 2500 nm). Scientists found out that for a substance to absorb wavelengths, the radiation of the wavelength must match the vibration or rotational frequency of the chemical bond within a particular substance. This technology therefore enables information about the physical-optical and chemical composition of biological matter to be obtained. Generally samples are supplied in the dried and ground form but fresh material can also be used.
Infrared wavelengths are known to be particularly absorbed by:

- C-H bonds; common in carbohydrates
- N-H bonds; common in proteins, amides and amino acids
- O-H bonds; common in water, alcohols, organic acids etc.

Statistical procedures are being used to correlate the reflectance of one or more specific wavelengths to the true level of a chemical entity (Molecules, free radicals etc) as would be determined by wet laboratory methods. By using this they develop a regression equation that estimates the quantity of a chemical entity based on the entity’s strength to reflect infrared wavelengths. This equation forms the calibration equation for the material having such chemical entities (Shenk and Westerhaus 1991). After that it is entered into the computer software for use by NIRS on future samples where wet laboratory analysis will not be conducted (Carrow 2000). In Germany these experts are at the “Verband Deutscher Landwirtschaftlicher Untersuchungs und Forschungsanstalten (VDLUFA)”. The chemical composition of sorghum samples from all experiments was determined by using a FOSS NIRS Systems Model 6500 (Fig. 3.6).

Sample preparation

The samples of sorghum were prepared by drying the biomass for 24 hours, at 60°C in an oven with forced ventilation. After that samples were grounded. The finely grounded materials were then put into dried sachets and further analyzed for starch, sugar (XZ), crude protein (XP), crude lipids (XL), neutral detergent fiber (NDF), acid detergent fiber (ADF) and ash (XA) contents. The values of each of these parameters were expressed as percentages (%) of the dry matter content.

Analytical procedure

Fixed amounts of the grounded samples of sorghum were taken as required by the size of the sample ring cups (cuvettes). After that these samples were inserted into the NIRS system operating at the reflectance module. The samples were scanned from 400 to 2500 nm in a computer controlled NIRS system, model 6500 scanning monochromator. The results were displayed on an attached computer screen.

3.8. Anaerobic digestion of sorghum samples

All samples of sorghum for biogas production were deep frozen at -20°C. Keeping in mind that only the organic portion of the dry matter is digestible and that specific biogas and methane productivity are calculated on the basis of organic matter (volatile solids), it was necessary to measure the organic matter content of each sample before digestion. Because the freezing can alter sorghum dry matter contents, the dry matter concentrations determined at harvest were not more very valid.

Determination of dry matter content

Dry matter contents were determined gravimetrically in conformity with the prescriptions in section two of the German industrial standard 47 (DIN 38 414 Teil 2). The samples which had been subjected to a constant temperature of –20°C since the day of harvest were chopped up 60 seconds long using a Thermomix operating at 12000 revolutions per minute. Hundred grams of the chopped sorghum samples were weighed out and oven dried until a constant weight was reached.

Dry porcelain crucibles were weighed out by using a laboratory balance and individual weights of the crucibles were also recorded. Hundred grams (100g) each of the selected chopped sorghum samples were weighed out into the porcelain crucibles and put into a laboratory drying oven at a constant temperature of 150°C. Sample were taken out at regular intervals and weighed. When the weight from two consecutive intervals remained constant, the porcelain containing the samples were taken out of the oven, cooled in a desiccator and finally weighed out to determined the “as received” dry matter weights. This was done by subtracting the known weights of the crucible from the sum weight of crucible and sample originally put into the oven. When this weight is expressed as a percentage (%) of the fresh weight it is called the dry matter concentration (DMC). The calculations were done in the same way as in field experiments.

Determination of volatile solids contents

It is well known that volatile solids are easily oxidized (combustible or digestible) as compared with the mineral solids. Hence by burning the total dry matter (total solids) of a given biomass, all the organic matter present will be burnt away and the residues (representing the mineral solids) can be directly measured. This allows an easy calculation of both fractions by simple subtraction. The experiments described in this thesis all used this procedure to separate the volatile solids from the inorganic (mineral) solids (ash).This was done in accordance with the prescriptions in section three of the German industrial standards (DIN 38 414 chapter 3).

Sample preparation and weighing procedures were the same as for total solids determination described above. In this case however known weights of sorghum samples in crucibles were kept into a muffle furnace operating at a constant temperature of 500°C and allowed to burn completely to ashes.

The burning led to a lost in the organic components due to volatilization. For that reason this portion is referred as the volatile solids (VS). As soon as the combustion process was completed, the crucibles containing the ashes were taken out and put into in desiccators for cooling and then weighed out. By subtracting the known weight of each crucible from the combined weight of crucible and ash, the rest weight was the weight of the ash. By further subtracting the amount of ash produced from the amount of sample initially put into the furnace, the volatile solids could be determined. Volatile solids can also be expressed in grams as well as percentages (volatile solid contents) of the specific sample masses.

$$\text{Volatile solids content (\%VS)} = \frac{(\text{DM [g] - ash [g]})}{\text{DM [g]}} \times 100$$

Mesophilic anaerobic digestion of sorghum samples

Biogas measurements were executed in laboratory digesters at mesophilic conditions (38°C). Liquid manure was used as a source of bacteria for anaerobic digestion process in pots. 300 g of sorghum sample and 16 kg of liquid manure were put into different digesters having capacity of 20 L/pot. This material was allowed to digest over a predetermined retention time of 19 days at the research station Rauischholzhausen. The digesters were kept at constant temperature by standing them in a constant temperature (38°C) water bath. The temperature was regulated by using a thermostat attached to the bath. The digester had a filling and an emptying outlet, an automatic electric stirrer and a gas out let via which the gas collecting sacs were connected.

Fig. 3.4: Laboratory mesophilic digesters in the research station Rauischholzhausen

Biogas measurements with a Ritter Wet Gas Meter

A Ritter wet meter was used for the measurements of biogas volumes. It consists of a multi-chamber rotary measuring drum containing water. The drum is attached to a counting mechanism consisting of scales and needle-dials. It functions upon the principle of positive displacement. It contains an inlet and outlet for connecting the gas sac and expelling the measured gas respectively.

The meter was connected to a Bunsen burner and gas sac by means of a PVC tube with the intention that the sampled biogas flew from the sac through the meter chambers and out into the Bunsen burner where it was burnt away. When biogas flew from one chamber of the drum to the other, the drum rotated. This rotated the needle-dials clock wise around the scales so that the positions of the needles on the scales were read directly as the volume of gas that has flown through the meter. The larger needle on the larger scale gave full volumes and the smaller needles on the smaller scales showed fractions of the volumes. By combining the readings of the two scales the total biogas volumes produced by digesting 300g of each sorghum sample was calculated. By using the calculated volatile solids, the specific biogas (biogas / kg VS) of the corresponding sorghum samples were calculated.

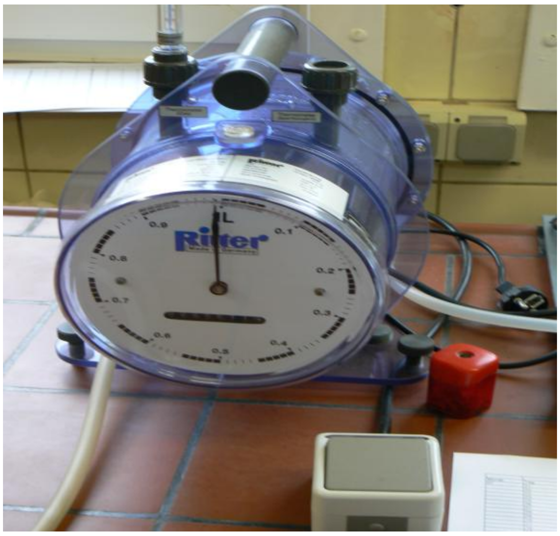

Fig. 3.5: Ritter wet gas meter used in biogas laboratory in Rauischholzhausen

Measurement of methane concentration in sorghum samples

The methane concentration was measured by using non-dispersive Infrared (NDIR) sensor GS IRM-100 which is simple spectroscopic device often used for gas analysis. It consists of an infrared source (lamp), a sample chamber or light tube, a wavelength filter, and an infrared detector. The gas is pumped into the sample chamber, and gas concentration is determined electro-optically by its absorption of a specific wavelength in the infrared (IR). The IR light is directed through the sample chamber towards the detector. The detector has an optical filter in front of it that prevent all light except the wavelength that the selected gas molecules can absorb.

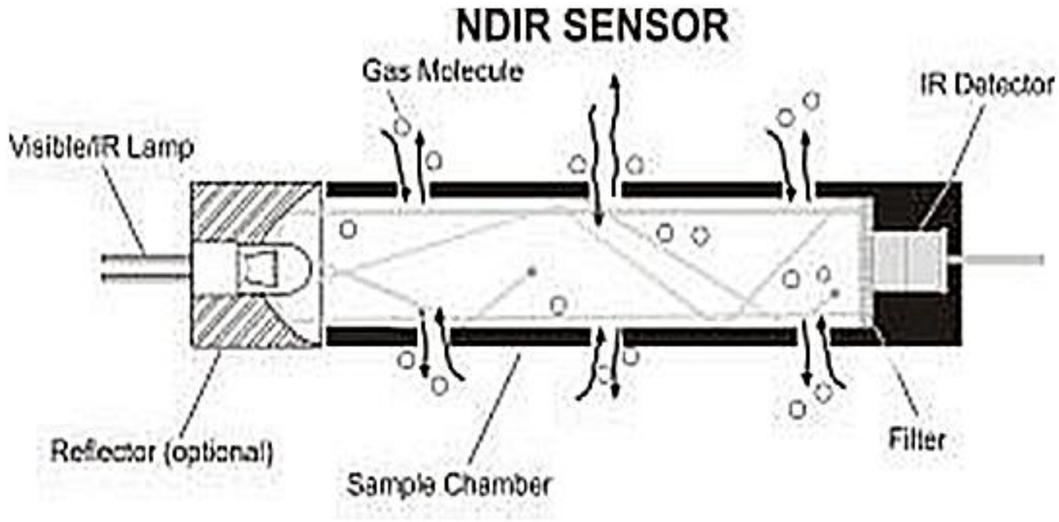

Fig. 3.6: Structure of NDIR sensor
Source: http://www.intl-lighttech.com/applications/light-source-apps/ndir-gas-sensor/ndir-gas-sensor-index

Other gas molecules do not absorb light at this wavelength, thus cannot influence the amount of light reaching the detector. The IR signal from the source is usually chopped or modulated so that thermal background signals can be offset from the desired signal. For the enhancement of optical efficiency, a reflector assembly can surround the lamp used for the NDIR sensor. The reflector is usually parabolic in shape to collimate the IR light through the sample chamber towards the detector. The use of a reflector can increase available light intensity by two to five times. The intensity of IR light that reaches the detector is inversely related to the concentration of target gas in the sample chamber. When the concentration in the chamber is zero, the detector will receive the full light intensity. The intensity of IR light striking the detector decreases as the concentration of gas increases. Beer's Law explains the exact relationship between IR light intensity and gas concentration.

Beer's Law: $I = I_0 e^{kP}$

Where:

I = the intensity of light striking the detector
I_0 = the measured intensity of an empty sample chamber
k = a system dependent constant
P = the concentration of the gas to be measured

3.9. Statistical analysis

The statistical analyses of the results were carried out by using the statistical program PIAF (Planning information analysis program for field trials) for checking the significance of the different treatments. General Linear Model (GLM) and multiple comparisons were performed using T test at $p < 0.05$. Correlation analysis was performed by PASW (version 18) to determine the relationship among the studied parameters according to Spearman's rho methods. The standard deviations (SD) showed in figures were calculated by using Microsoft Excel.

4. Results

4.1 Plant density and sowing time experiment Giessen 2008

4.1.1 Biomass yield and plant stand parameters

Leaf area index

The leaf area index (LAI) of sorghum plant stand ranged from 1.4 to 2.4 (30 days after germination) until 3.2 to 4.2 (60 days after germination) and 4.6 to 5.7 (90 days after germination) (table 4.1). In 1st sowing, leaf area index was not affected by cultivars at all three stages of measurement. On the other hand, cv. Goliath led to significantly higher LAI as compared to cv. Bovital at 30 and 60 days after germination in 2nd and 3rd sowing. An increasing trend in LAI was observed with higher plant density except in 1st sowing measured at 90 days after germination. In 1st sowing plant density had no clear effect on LAI at 30 and 60 days after germination (DAG) but medium level of plant density (24 plants m^{-2}) exhibited considerably higher LAI followed by 16 plants m^{-2} while lowest value was determined for higher plant density (32 plant m^{-2}). Opposite trend was noticed at 60 (2nd sowing) and 90 DAG (2nd and 3rd sowing) where lower plant density (16 plants m^{-2}) induced a decline in LAI of sorghum. There was no interaction between cultivars and plant density with respect to LAI of sorghum.

Table 4.1: Effect of different cultivars (CV) and planting densities (PD) on leaf area index (LAI) of sorghum at different sowing times in Giessen 2008

Cv	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		LAI 1	LAI 2	LAI 3	LAI 1	LAI 2	LAI 3	LAI 1	LAI 2	LAI 3
1		2.3a	3.4a	5.1a	1.8a	3.4a	5.4a	2.0a	4.2a	5.2a
2		2.4a	3.4a	4.8a	1.4b	3.3a	5.0a	1.9a	3.7b	4.8a
	1	2.2a	3.3a	4.9ab	1.4a	3.2b	4.6b	1.7a	3.6b	4.9a
	2	2.4a	3.5a	5.3a	1.6a	3.3ab	5.3a	2.0a	4.1a	5.0a
	3	2.3a	3.3a	4.8b	1.7a	3.6a	5.7a	2.1a	4.2a	5.2a
Means		2.3	3.4a	4.9	1.6	3.3	5.2	1.9	3.9	5.0
LSD $_{0.05}$										
PD		ns	ns	0.4	ns	0.3	0.6	ns	0.3	ns
CV		ns	ns	ns	0.3	ns	ns	ns	0.3	ns
PD x CV		ns	ns	ns	ns	ns	ns	ns	ns	ns

1st sowing = 16.05.2008, 2nd sowing = 29.05.2008, 3rd sowing = 07.06.2008, LAI 1 = 30 days after germination, LAI 2 = 60 days after germination, LAI 3 = 90 days after germination, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2

Plant height

The range of plant height was from 49 (3rd sowing) to 101 cm (1st sowing), 118 (3rd sowing) to 169 cm (1st sowing) and 261 (3rd sowing) to 299 cm (1st sowing) at 30 days of germination (DAG), 60 DAG and 90 DAG respectively (table 4.2). After 30 days of germination plant density had no clear effect on plant height in 1st and 3rd sowing whereas plant height was pronouncedly altered by plant density in 2nd sowing (p value < 0.000). It could be observed that higher plant density caused an increase in plant height of sorghum in 2nd sowing time. In all three sowing times plant density led to similar plant height (table 4.2). Plant height significantly affected by plant density in 1st and 3rd sowing at 90 DAG but did not clearly influence the plant height of sorghum in 2nd sowing. Cultivars had a clear impact on plant height in all three sowings at all stages of measurements except 30 DAG (1st sowing) and 60 DAG (3rd sowing) (table 4.2). Cv. Goliath show considerably higher plant height than that of cv. Bovital in 1st sowing (60 and 90 DAG), 2nd sowing (30, 60 and 90 DAG), 3rd sowing (30 and 90 DAG). On the other hand cv. Goliath and cv. Bovital led to comparable averages of plant height at 30 and 60 DAG in 1st and 3rd sowing time respectively (table 4.2).

Table 4.2: Effect of different cultivars (CV) and planting densities (PD) on plant height (Ph) of sorghum at different sowing times in Giessen 2008

Cv	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		Ph 1	Ph 2	Ph 3	Ph 1	Ph 2	Ph 3	Ph 1	Ph 2	Ph 3
		cm	cm	cm	cm	cm	cm	cm	cm	cm
1		101a	179a	324a	79a	157a	315a	53a	120a	275a
2		101a	160b	275b	70b	141b	281b	45b	117a	247b
	1	100a	168a	310a	70b	142a	304a	48a	113a	262ab
	2	104a	174a	295bc	76ab	152a	298a	49a	121a	268a
	3	99a	169a	293c	77a	153a	292a	51a	123a	253b
Mean		101	169	299	74	149	298	49	118	261
LSD $_{0.05}$										
PD		ns	ns	14	6	ns	ns	ns	ns	9
CV		ns	7	12	5	8	14	4	ns	8
PD x CV		ns	ns	ns	ns	ns	ns	ns	ns	ns

1st sowing = 16.05.2008, 2nd sowing = 29.05.2008, 3rd sowing = 07.06.2008, Ph 1 = 30 days after germination, Ph 2 = 60 days after germination, Ph 3 = 90 days after germination, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2

Tillers, dry matter concentration and dry matter yield

The number of tillers m^{-2} varied between 20 (3rd sowing) and 39 (2nd sowing). Cultivars had clear impact on the numbers of tillers m^{-2} in all three sowing times tested in the present study. Cv. Bovital led to higher numbers of tillers than that of cv. Goliath in all three sowing times. In 1st and 2nd sowing, plant density did not significantly affect the numbers of tillers however plant density of 32 plants m^{-2} produced markedly higher numbers of tillers m^{-2} while lower value was attained with lower plant density (16 plants m^{-2}). It could be observed that plant density did not affect dry matter concentration but cultivar clearly influenced the DM concentration except in 2nd sowing time. Early maturing cv. Bovital exhibited considerably higher dry matter concentration of 26.5 %, 20.5 % while significantly lower values of 24.3 and 16.5 % were determined for cv. Goliath in 1st and 3rd sowing respectively. Dry matter yield was ranged from minimum 5.50 t/ha (3rd sowing) to maximum 10.39 t/ha (1st sowing). In all three sowing times, plant density led to comparable averages with respect to dry matter yield of sorghum. On the other hand, cv. Goliath induced an increase in dry matter yield in all three sowing times tested in our experiment. However an interaction between cultivar and plant density was noticed in 3rd sowing. Cv. Goliath led to maximum dry matter yield with medium plant density followed by higher level while cv. Bovital produced comparable dry matter yield with medium and lower plant density which were significantly lower (fig. 4.1).

Table 4.3: Effect of different cultivars (CV) and planting densities (PD) on number of tillers (m^{-2}), dry matter concentration (DMC) and dry matter yield (DMY) of sorghum at different sowing times in Giessen 2008

CV	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		Till./m^2	DMC	DMY	Till./m^2	DMC	DMY	Till./m^2	DMC	DMY
		No.	%	t/ha	No.	%	t/ha	No.	%	t/ha
1		26b	24.3b	11.22a	34b	24.2a	11.25a	13b	16.5b	6.20a
2		37a	26.5a	9.55b	46a	25.8a	9.12b	27b	20.5a	4.80b
	1	30a	24.8a	9.60a	38a	24.3a	9.80a	16c	18.7a	5.47a
	2	33a	25.5a	10.68a	40a	25.4a	10.39a	19b	18.6a	5.63a
	3	31a	25.9a	10.90a	43a	25.3a	10.37a	24a	18.2a	5.51a
Means		32	25.4	10.39	39	25.0	10.19	20	18.5	5.50
$LSD_{0.05}$										
PD		ns	ns	ns	ns	ns	ns	2	ns	ns
CV		6	1.4	1.32	7	ns	1.37	3	1.8	0.46
PD x CV		ns	ns	ns	ns	ns	ns	ns	ns	0.80

Till = tillers, 1st sowing = 16.05.2008, 2nd sowing = 29.05.2008, 3rd sowing = 07.06.2008, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2

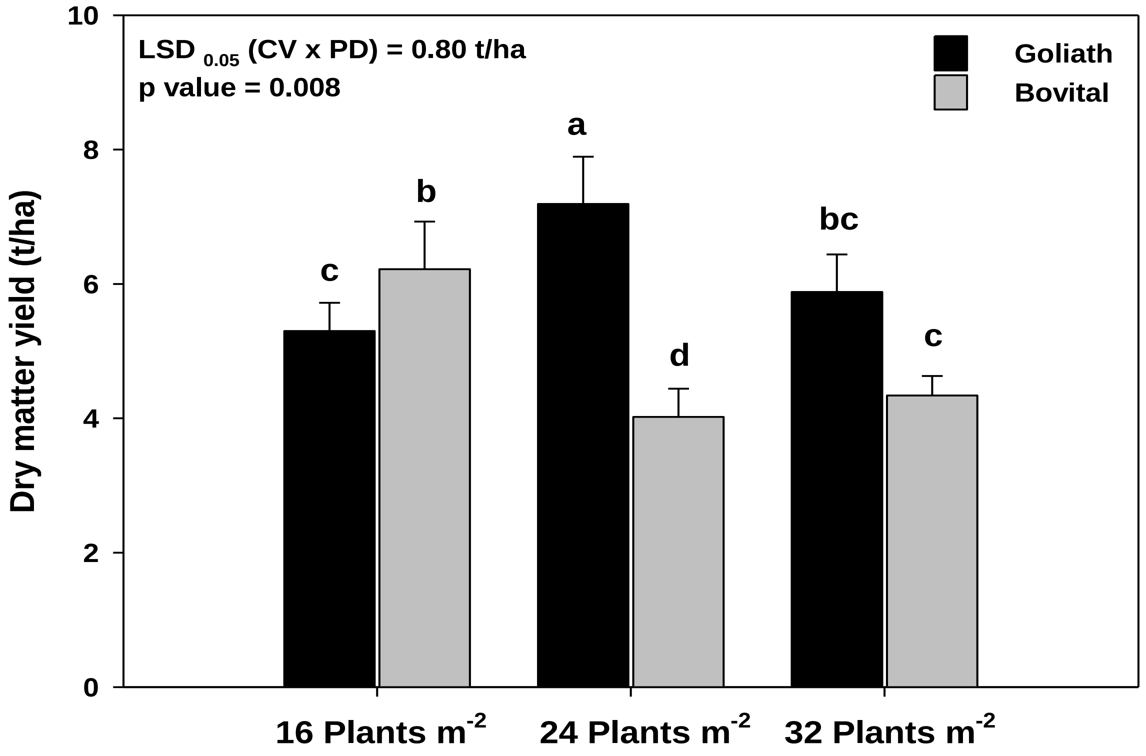

Fig. 4.1: Interaction between cultivars (CV) and plant density (PD) regarding dry matter yield of sorghum in 3rd sowing at experimental station Giessen 2008 (T = SD)

4.1.2 Data of NIRS analyses

Protein, sugar and ash concentration

Within the three field experiments which were carried out at three different sowing times the protein concentration of sorghum ranged from minimal 7.8 (1st sowing) to maximal 10.4 % (3rd sowing) (table 4.4). Plant density had clear effect on protein concentration in 2nd (p value = 0.001) and 3rd sowing (p value = 0.005) while in 1st sowing all level of plant density led to similar averages of protein concentration.

Table 4.4: Effect of different cultivars (CV) and planting densities (PD) on protein (XP), sugar (XZ) and ash concentration (XA) of sorghum at different sowing times in Giessen 2008

CV	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		XP	XZ	XA	XP	XZ	XA	XP	XZ	XA
		% DM	% DM	% DM	% DM	% DM	% DM	% DM	% DM	% DM
1		7.5b	6.9a	8.4a	8.1b	9.5a	8.8a	10.4a	13.1a	9.8a
2		8.0a	7.4a	8.3a	9.1a	7.2a	9.1a	10.4a	11.5a	9.4b
	1	7.8a	6.9a	8.5a	8.6b	7.6a	9.0a	10.9a	11.7a	9.8a
	2	7.5a	7.4a	8.1b	9.3a	8.0a	8.9a	10.0b	12.0a	9.6a
	3	7.9a	7.1a	8.5a	8.0b	9.3a	9.0a	10.4ab	13.3a	9.6a
Mean		7.8	7.1	8.3	8.6	8.3	9.0	10.4	12.3	9.6
LSD$_{0.05}$										
PD		ns	ns	0.3	0.6	ns	ns	0.5	ns	ns
CV		0.4	ns	ns	0.5	ns	ns	ns	ns	0.4
PD x CV		0.7	ns	0.4	0.9	ns	1.0	ns	ns	0.6

1st sowing = 16.05.2008, 2nd sowing = 29.05.2008, 3rd sowing = 07.06.2008, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2

However PD x CV interaction was observed for protein concentration in 1st and 2nd sowing (fig. 4.3 and 4.4). In first sowing cv. Bovital produced higher protein concentration with 32 plants m^{-2} while considerably lower protein was determined for cv. Goliath in combination with 24 plants m^{-2} (fig. 4.2). Both cultivars had different reaction on increase the plant densitiy (PD). In first sowing cv. Goliath did not change the protein concentration by increasing the PD from 16 to 24 and 32 plants/m^{-2}. Contrary to that protein concentration of the samples of cv. Bovital increased clearly by higher PD. In second sowing comparable protein concentration was obtained with Bovital (16, 24, 32 plants m^{-2}) and cv. Goliath (32 plants m^{-2}) but clearly lower protein concentration of cv. Goliath was found in smaller PD of 16 and 24 plants m^{-2} (fig. 4.3). Sugar concentration was influenced neither by cultivar nor by plant density in all three sowing times (table. 4.4). Ash concentration varied between minimal 8.3 (1st sowing) and maximal 9.6 % (3rd sowing) (table 4.4). In all three sowing times CV x PD interaction was noticed regarding ash concentration of sorghum (fig. 4.5 – 4.7). In all three sowing times cv. Bovital reached smaller ash concentration as cv. Goliath. 1st sowing cv. Goliath with 16 and 24 plants m^{-2} led to significantly higher ash concentration while minimum value was attained with cv. Bovital in lower level of plant density (16 plants m^{-2}) (fig. 4.4). Cv. Goliath in combination with 16 and 32 plants m^{-2} exhibited markedly higher ash concentration followed by cv. Goliath (16 plant m^{-2}) and cv. Bovital (24, 32 plants m^{-2}) in 2nd sowing (fig. 4.5). In 3rd sowing with all levels of plant density cv. Goliath showed comparable ash concentration which was significantly higher as compared to cv. Bovital in combination with all three plant densities (fig. 4.6).

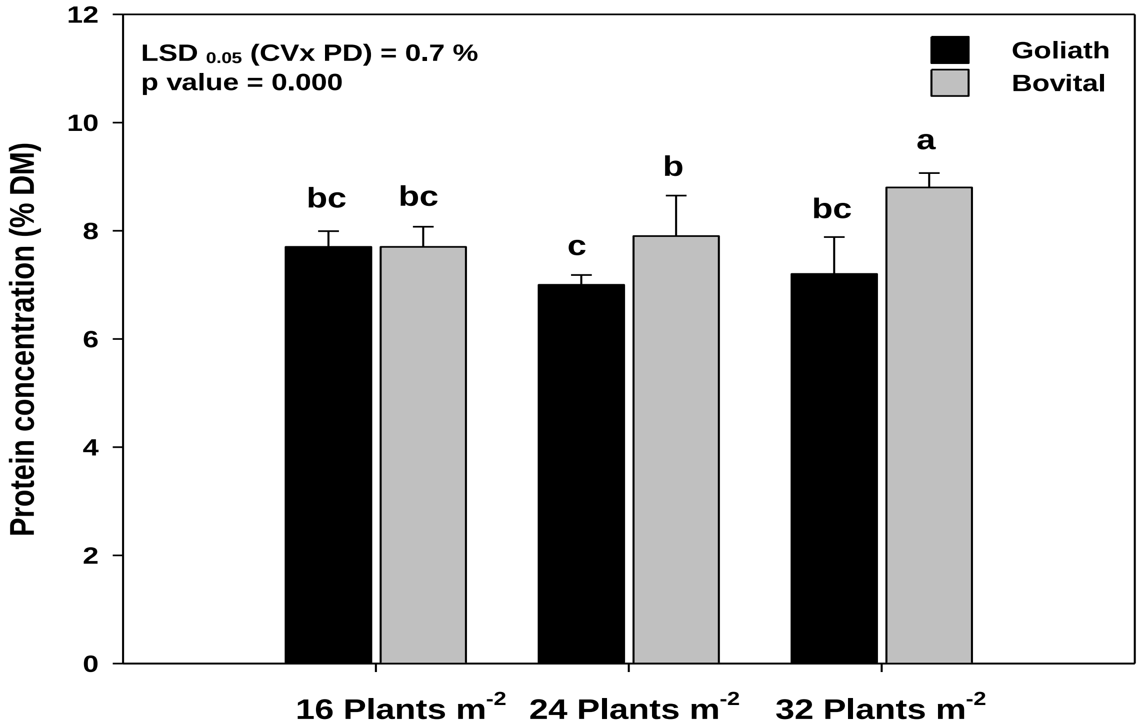

Fig. 4.2: Interaction between cultivars (CV) and plant density (PD) regarding protein concentration (XP) of sorghum in 1st sowing at experimental station Giessen 2008 (T = SD)

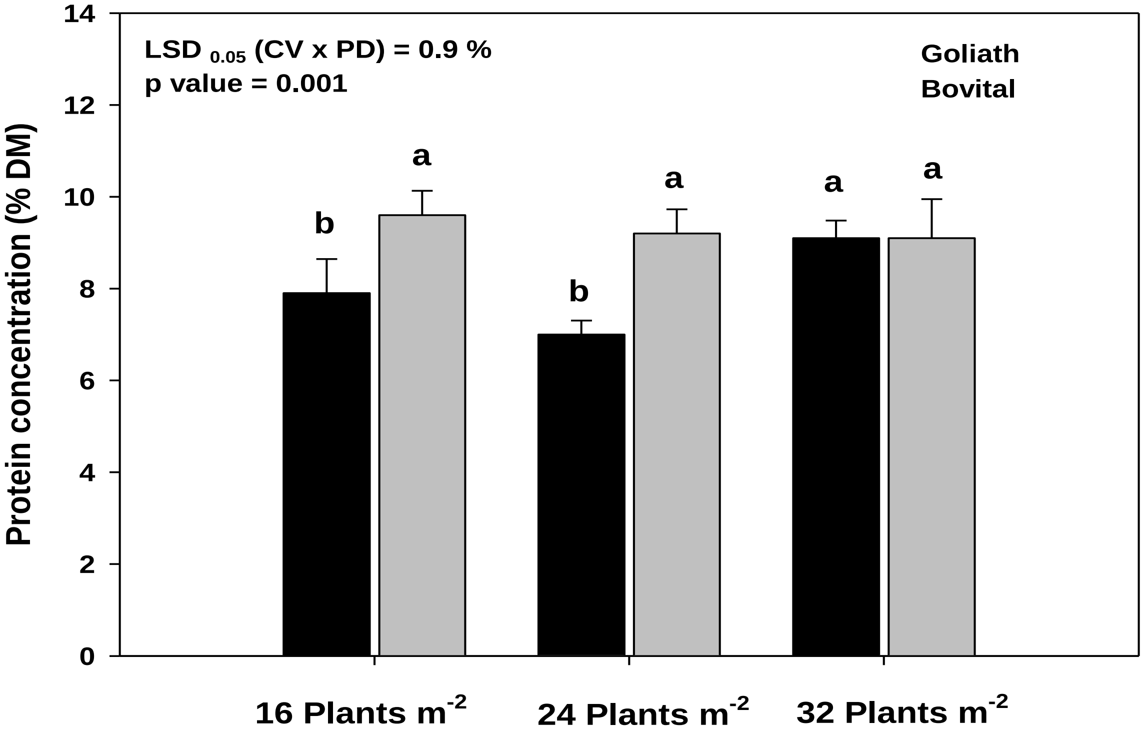

Fig. 4.3: Interaction between cultivars (CV) and plant density (PD) regarding protein concentration (XP) of sorghum in 2nd sowing at experimental station Giessen 2008 (T = SD)

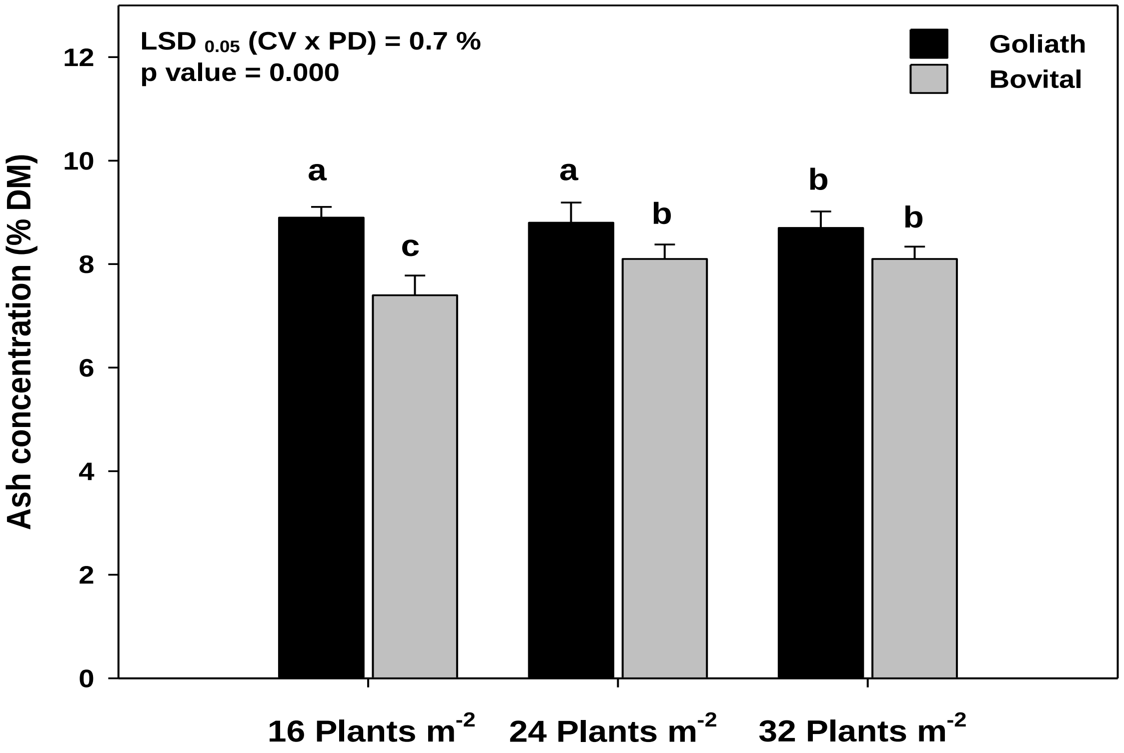

Fig. 4.4: Interaction between cultivars (CV) and plant density (PD) regarding ash concentration (XA) of sorghum in 1st sowing at experimental station Giessen 2008 (T = SD)

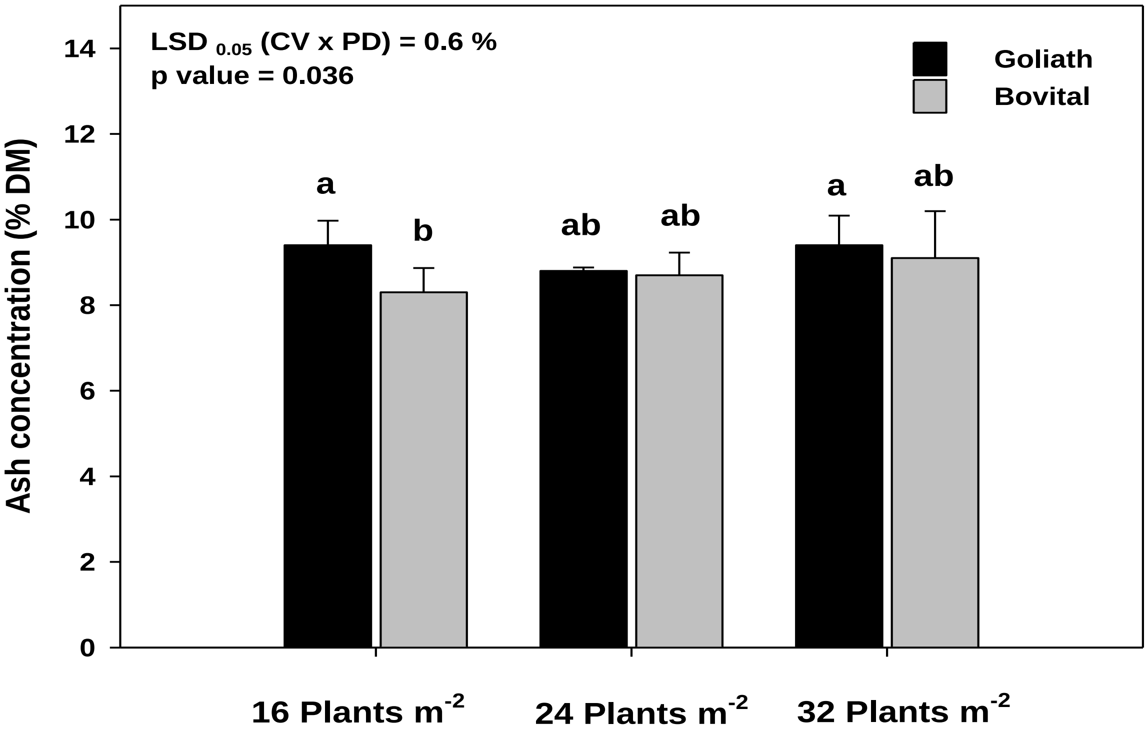

Fig. 4.5: Interaction between cultivars (CV) and plant density (PD) regarding ash concentration (XA) of sorghum in 2nd sowing at experimental station Giessen 2008 (T = SD)

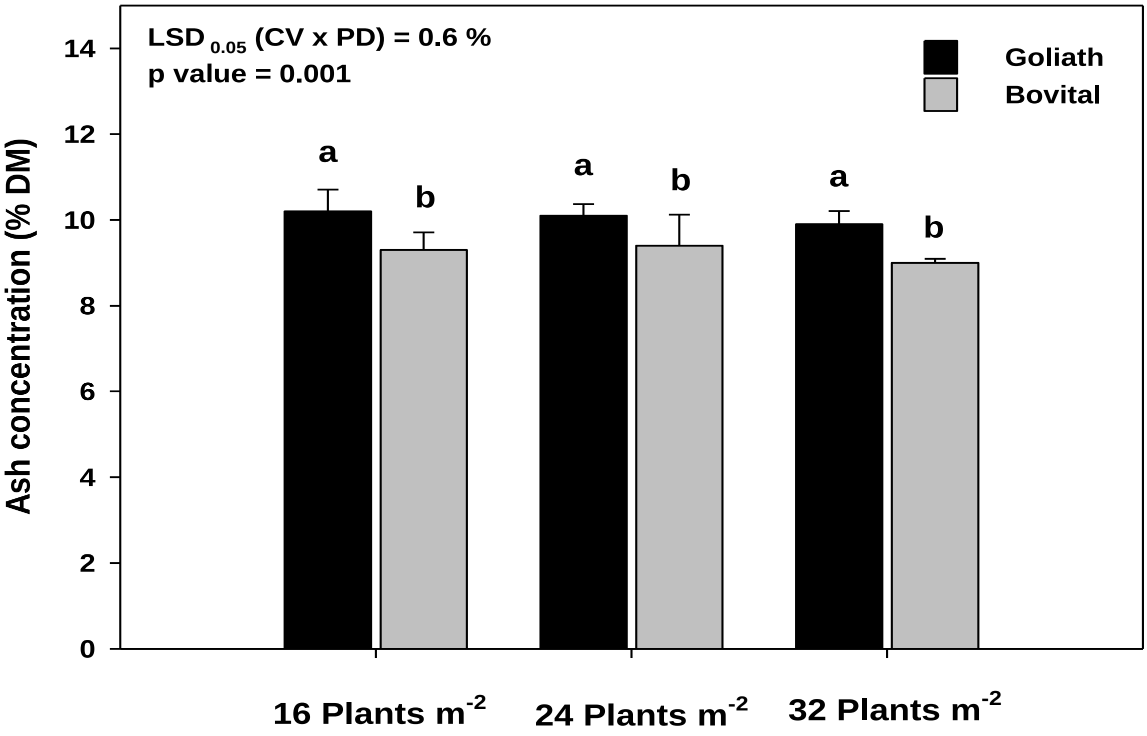

Fig. 4.6: Interaction between cultivars (CV) and plant density (PD) regarding ash concentration (XA) of sorghum in 3rd sowing at experimental station Giessen 2008 (T = SD)

Acid detergent fiber, neutral detergent fiber and acid detergent lignin

ADF concentration varied between 35 (3rd sowing) and 40.0 % (1st sowing) (table 4.5). Plant density did not significantly differ in all three sowing times. However interaction of CV x PD was observed in 1st (p value = 0.000) and 2nd sowing (p value = 0.000) with respect to ADF concentration. In 1st sowing cv. Bovital exhibited considerably lower ADF concentration than that of cv. Goliath in all three levels of plant density (fig. 4.7). Similar trend was observed in 2nd sowing time regarding ADF concentration (fig. 4.8). Cultivar as well as plant density did not affect the ADF concentration in 3rd sowing. The range of NDF concentration was from 53.7 (3rd sowing) to 60.4 % (1st sowing). Interaction between cultivar and plant density regarding NDF concentration was observed in 1st and 2nd sowing but not in 3rd sowing. Cv. Goliath (16, 24, 32 plants m^{-2}) led to pronouncedly higher NDF concentration while cv. Bovital with 32 plant m^{-2} showed significantly lower value in 1st sowing (fig. 4.9). In 2nd sowing cv. comparable NDF concentration was observed in cv. Goliath with all levels of plant density and cv. Bovital (32 plants m^{-2}) whereas clearly lower value was determined for cv. Bovital with 16 plants m^{-2} (fig. 4.10). The ADL concentration varied between 4.2 (3rd sowing) and 5.3 % (1st sowing) (table 4.5). There was a significant interaction (CV x PD) regarding ADL concentration in 1st (p value = 0.000) and 2nd sowing (p value = 0.000). Similar ADL concentration was determined for cv. Goliath with all levels of plant density in 1st sowing. Cv. Bovital also showed comparable averages of ADL concentration with all three level of plant density which was significantly lower (fig. 4.11). Almost same trend was noticed in 2nd sowing except in case of cv. Bovital with higher plant density (fig. 4.12).

Table 4.5: Effect of different cultivars (CV) and planting densities (PD) on acid detergent fiber (ADF), neutral detergent fiber (NDF) and acid detergent lignin (ADL) concentration of sorghum at different sowing times in Giessen 2008

CV	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		ADF	NDF	ADL	ADF	NDF	ADL	ADF	NDF	ADL
		% DM	% DM	% DM	% DM	% DM	% DM	% DM	% DM	% DM
1		40.8a	61.4a	5.4a	39.4a	57.9a	5.3a	34.5a	53.1a	4.1a
2		39.2b	59.5b	5.2b	38.7a	58.7a	5.0a	36.2a	54.3a	4.4a
	1	40.3a	60.9a	5.3a	38.8a	57.8a	5.1a	35.0a	53.5a	4.1a
	2	40.0a	60.3a	5.3a	38.7a	57.2a	5.0a	36.0a	54.5a	4.4a
	3	39.7a	60.2a	5.3a	39.7a	60.0a	5.3a	35.1a	53.1a	4.4a
Mean		40.0	60.4	5.3	39.0	58.3	5.1	35.3	53.7	4.2
$LSD_{0.05}$										
PD		ns	ns	ns	ns	ns	ns	ns	ns	ns
CV		1.2	1.1	0.2	ns	ns	ns	ns	ns	ns
PD x CV		2.0	2.0	0.3	3.2	6.0	0.6	ns	ns	ns

1st sowing = 16.05.2008, 2nd sowing = 29.05.2008, 3rd sowing = 07.06.2008, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2

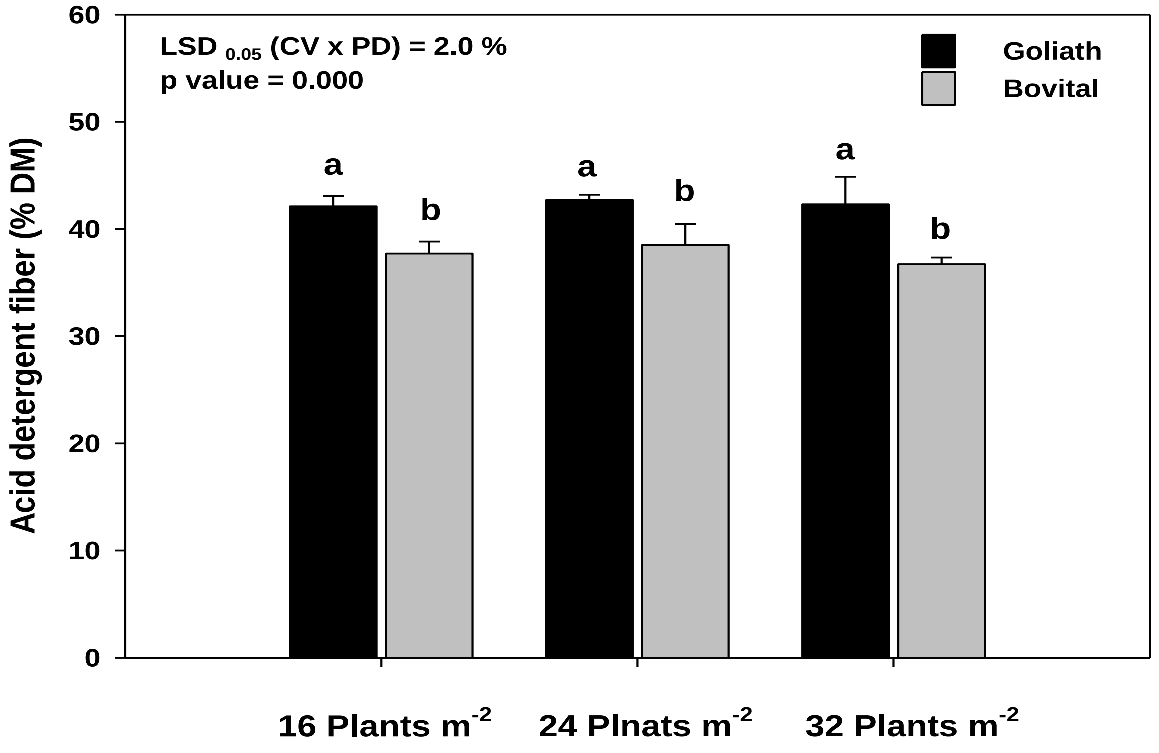

Fig. 4.7: Interaction between cultivars (CV) and plant density (PD) regarding acid detergent fiber (ADF) of sorghum in 1st sowing at experimental station Giessen 2008 (T = SD)

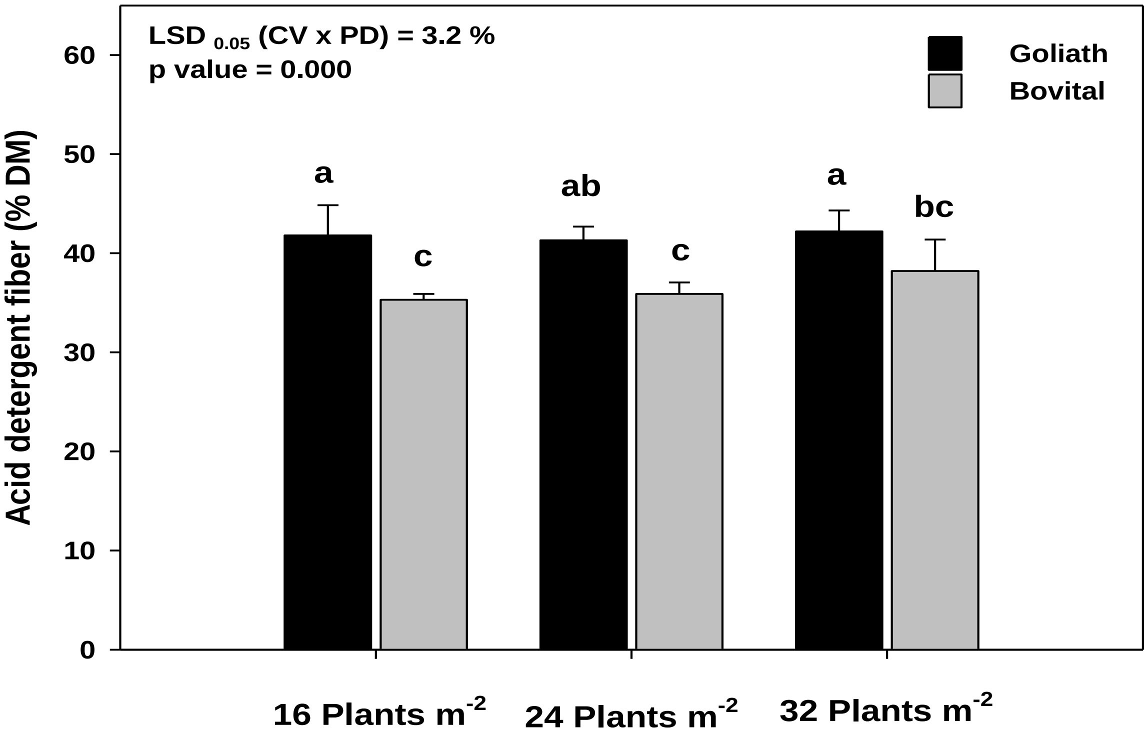

Fig. 4.8: Interaction between cultivars (CV) and plant density (PD) regarding acid detergent fiber (ADF) of sorghum in 2nd sowing at experimental station Giessen 2008 (T = SD)

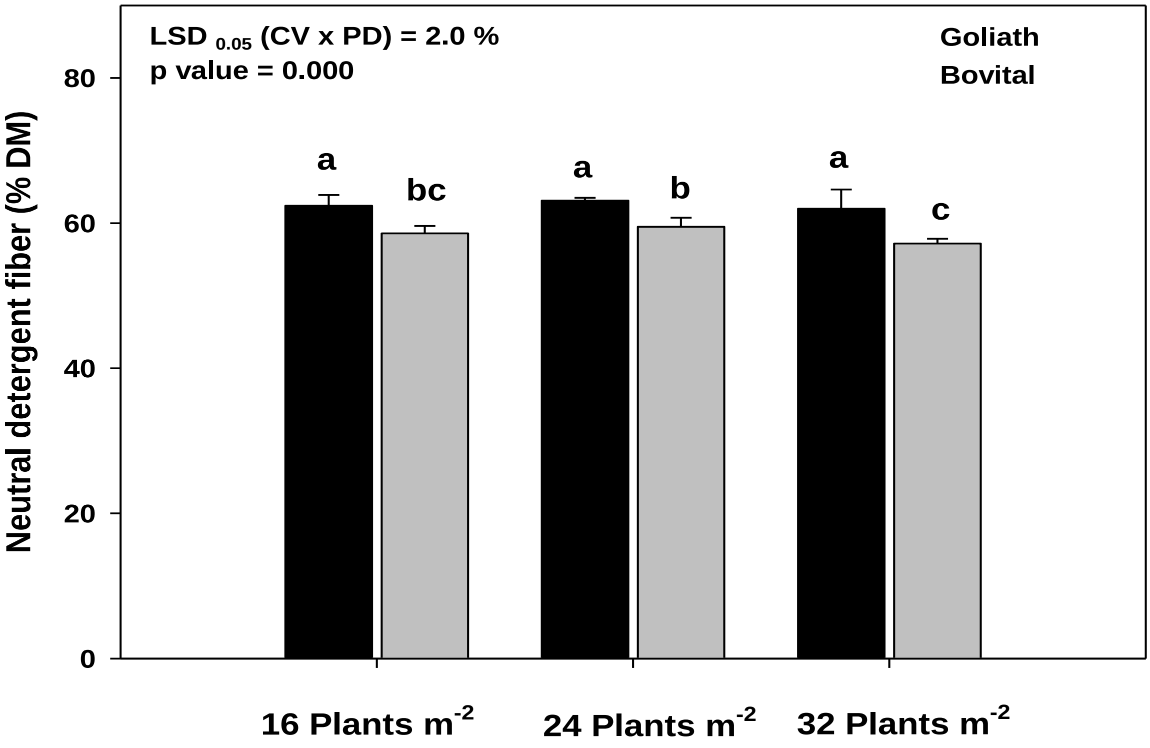

Fig. 4.9: Interaction between cultivars (CV) and plant density (PD) regarding neutral detergent fiber (NDF) of sorghum in 1st sowing at experimental station Giessen 2008 (T = SD)

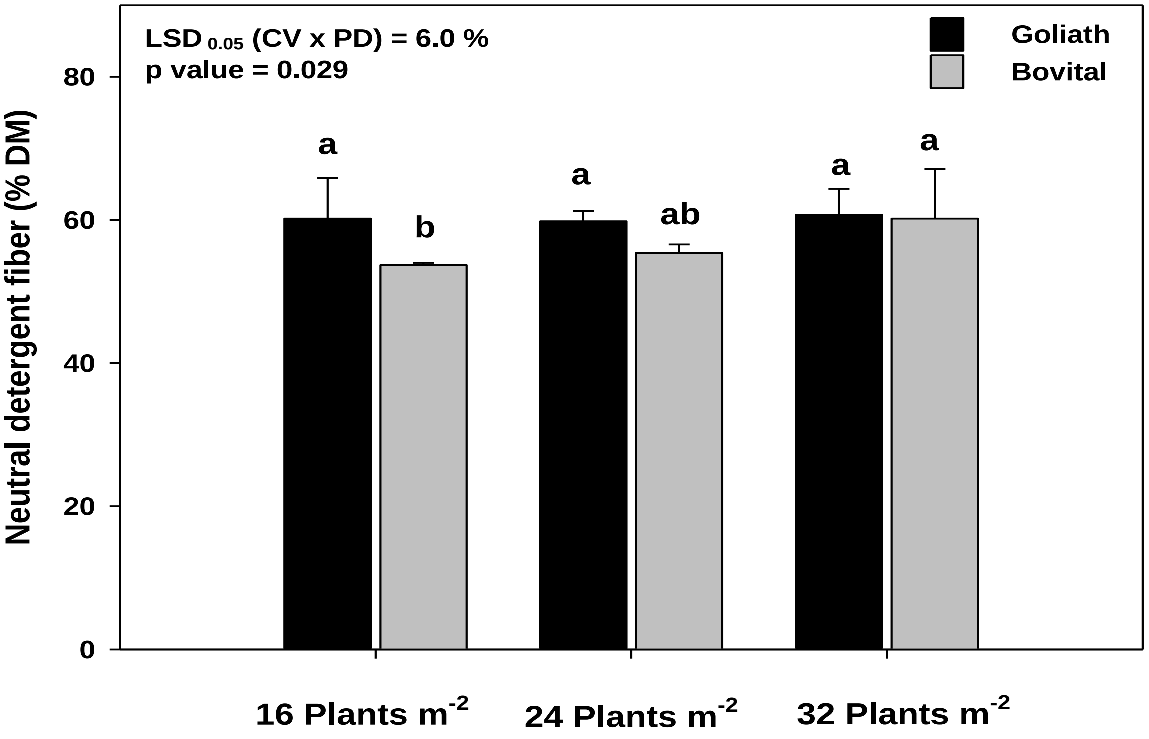

Fig. 4.10: Interaction between cultivars (CV) and plant density (PD) regarding neutral detergent fiber (NDF) of sorghum in 2nd sowing at experimental station Giessen 2008 (T = SD)

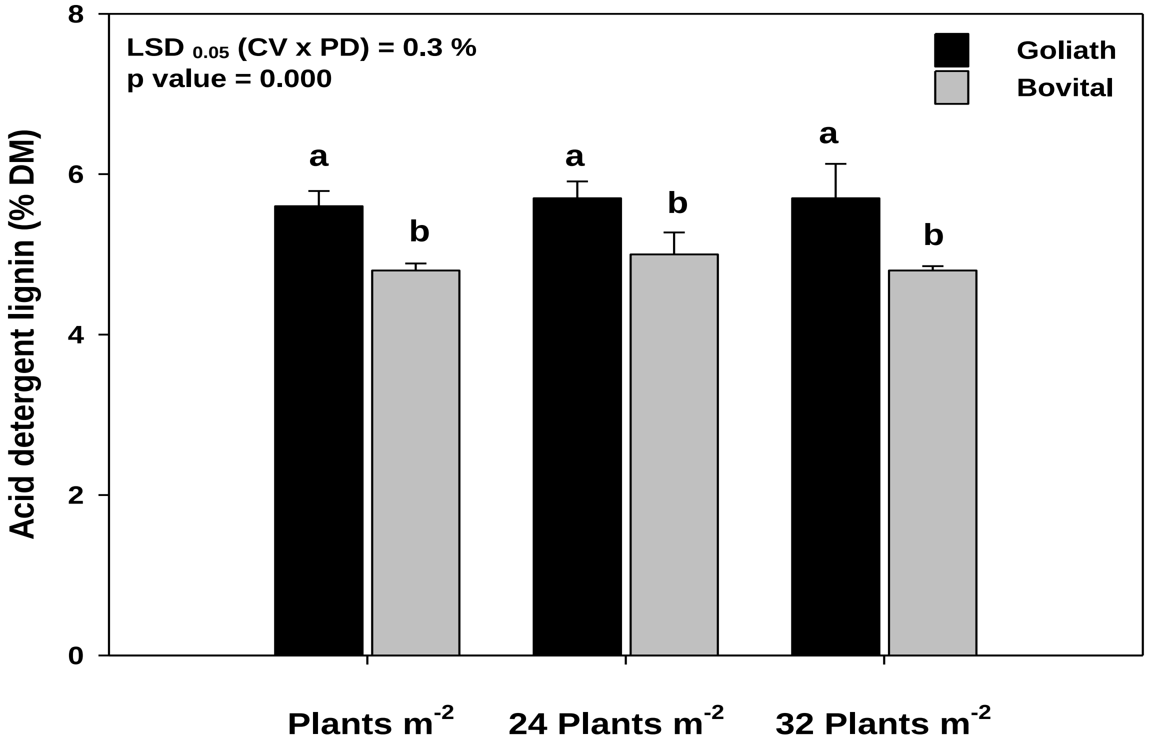

Fig. 4.11: Interaction between cultivars (CV) and plant density (PD) regarding acid detergent lignin (ADL) of sorghum in 1st sowing at experimental station Giessen 2008 (T = SD)

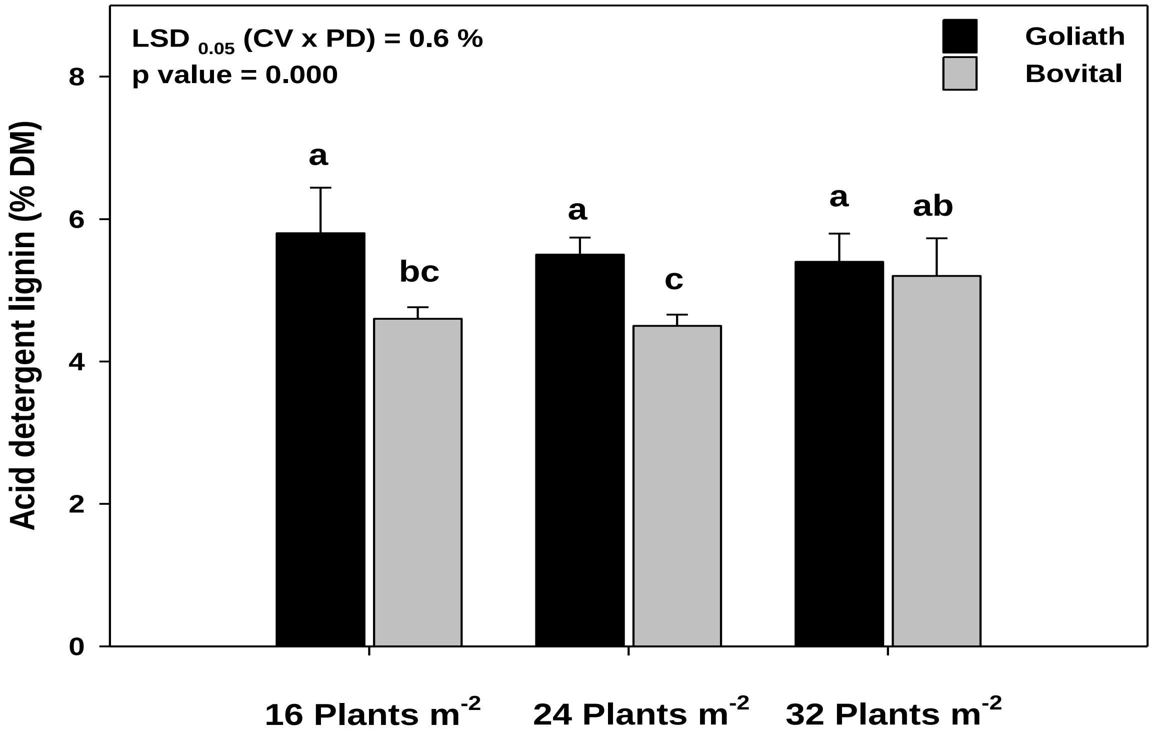

Fig. 4.12: Interaction between cultivars (CV) and plant density (PD) regarding acid detergent lignin (ADL) of sorghum in 2nd sowing at experimental station Giessen 2008 (T = SD)

4.2 Plant density and sowing time experiment Gross-Gerau 2008

4.2.1 Biomass yield and plant stand parameters

Tillers, dry matter concentration and dry matter yield

The number of tillers per m^2 ranged from 25 to 31 tillers m^{-2} in 2nd and 3rd sowing times respectively. In all three sowing times cultivar as well as plant density had significant impact on number of tillers m^{-2} (table 4.6). Higher plant density (32 plants m^{-2}) induced an increase in number of tillers m^{-2} followed by medium level of PD (24 plants m^{-2}) whereas considerably lower value was observed with 16 plants m^{-2} in all three sowings. There was no interaction of CV x PD with respect to number of tillers m^{-2} of sorghum. Cv. Bovital is characterized by pronouncedly higher number of tillers as compared to cv. Goliath in all three sowing times. DM concentration varied between 24.1 (2nd sowing) and 26.1 % (3rd sowing). Plant density did not influence the DM concentration of sorghum in 1st and 3rd sowing. Contrary to that in 2nd sowing DM concentration was clearly affected (p value = 0.033) by plant density. However significant interaction (CV x PD) was observed regarding DM concentration in 1st sowing (fig. 4.14). Similar DM concentration of 28.7 % was determined for cv. Bovital with lower (16 plants m^{-2}) and cv. Goliath with medium level of plant density (24 plants m^{-2}) followed by cv. Bovital in higher plant density of 32 plants m^{-2}. On the other hand markedly lower value was exhibited by cv. Goliath (16 plants m^{-2}) which was comparable to cv. Bovital in combination with medium level of plant density (fig. 4.13). In all three sowings early maturing cv. Bovital led to higher DM concentration than that of cv. Goliath.

Table 4.6: Effect of different cultivars (CV) and planting densities (PD) on number of tillers m^{-2}, dry matter concentration (DMC) and dry matter yield (DMY) of sorghum at different sowing times in Gross-Gerau 2008

CV	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		Till./m^2	DMC	DMY	Till./m^2	DMC	DMY	Till./m^2	DMC	DMY
		No.	%	t/ha	No.	%	t/ha	No.	%	t/ha
1		25b	24.7a	16.79a	21b	23.5b	17.63a	23b	25.6b	18.10a
2		32a	25.0a	10.78b	29a	24.8a	11.69b	40a	26.7a	12.32b
	1	22b	25.0a	13.02a	22b	24.2ab	13.50b	28b	25.8a	14.26b
	2	28ab	25.2a	14.56a	24ab	24.7a	14.45a	32ab	26.4a	15.73a
	3	34a	24.3a	13.77a	29a	23.5b	15.04a	35a	26.2a	15.66a
Mean		29	24.9	13.79	25	24.1	14.7	31	26.1	15.21
LSD$_{0.05}$										
PD		6	ns	ns	5	1.1	0.90	5	ns	0.70
CV		4	ns	1.47	4	0.9	0.75	4	0.8	0.57
PD x CV		ns	1.9	ns	ns	ns	ns	ns	ns	ns

1st sowing = 13.05.2008, 2nd sowing = 27.05.2008, 3rd sowing = 10.06.2008, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2

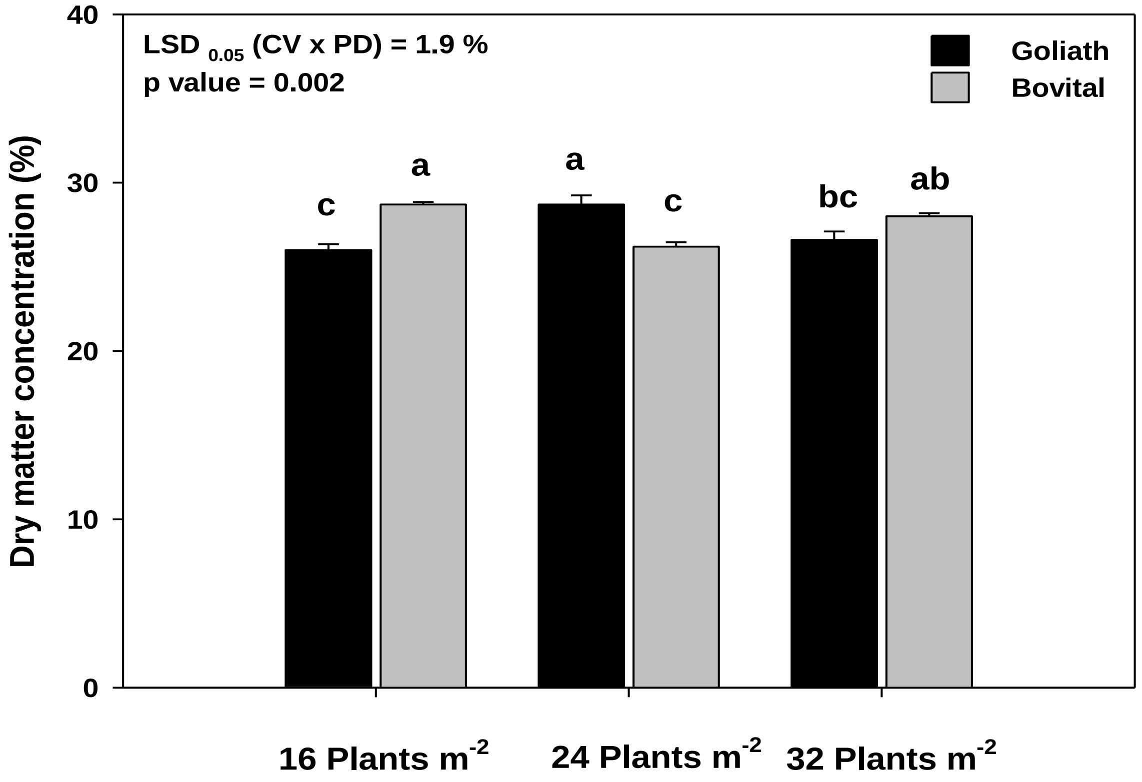

Fig. 4.13: Interaction between cultivars (CV) and plant density (PD) regarding dry matter concentration (DMC) of sorghum in 1st sowing at experimental station Gross Gerau 2008 (T = SD)

Dry matter yield (DMY) ranged from 13.79 (1st sowing) to 15.21 t ha^{-1} (3rd sowing) (table 4.6). In 1st sowing plant density had no clear effect on dry matter whereas it was significantly affected by PD in 2nd and 3rd sowing.

In 2nd and 3rd sowing comparable DM yield was produced by medium and higher plant density while lower level of plant density induced a decline in dry matter yield of sorghum. Cv. Goliath reached markedly higher dry matter yield as compared cv. Bovital in all three sowing times (table 4.6).

Organ partitioning (% DM)

Stem dry matter concentration which ranged from 63 (1st sowing) until 68 % (3rd sowing) had the highest proportion within the whole biomass of sorghum plants followed by the proportion of leaves 18 (2nd sowing) – 19% (3rd sowing) and panicle 13 (3rd sowing) – 18% (1st sowing) (tab. 4.7). Plant density did not clearly affect the leaf, stem and panicle proportion of sorghum plant in all three sowings. Opposite to that cultivar significantly affected the proportion of sorghum organs (leaf, stem and panicle) (table 4.7). In all three sowings cv. Goliath is characterized by higher stem as well leaves dry matter concentration as compared with cv. Bovital. However cv. Bovital led to higher panicle dry matter proportion than that of cv. Goliath in all three sowing times (table 4.7).

Table 4.7: Effect of different cultivars (CV) and planting densities (PD) on leaf, stem and panicle dry matter proportion of sorghum at different sowing times in Gross-Gerau 2008

CV	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		Organ partioning (% DM)								
		Leaf	Stem	Panicle	Leaf	Stem	Panicle	Leaf	Stem	Panicle
1		20.8a	73.1a	6.2b	20.5a	74.4a	5.5b	21.5a	74.2a	4.3a
2		16.7b	53.7b	29.2a	15.5b	60.6b	23.8a	17.2b	61.4b	21.4b
	1	19.9a	63.0a	17.2a	18.1a	66.5a	15.4a	18.5a	68.3	13.2a
	2	18.8a	61.6a	19.7a	17.3a	67.7a	15.0a	19.5a	67.0	13.4a
	3	17.6a	65.6a	16.6a	18.6a	67.9a	13.5a	20.0a	68.0	12.0a
Mean		18.8	63.4	17.7	18.0	67.5	17.4	19.3	67.9	12.9
$LSD_{0.05}$										
PD		ns	ns	ns	ns	ns	ns	ns	ns	ns
CV		ns	4.3	2.7	2.3	3.3	2.7	2.9	3.4	2.1
PD x CV		ns	ns	ns	ns	ns	ns	ns	ns	ns

1st sowing = 13.05.2008, 2nd sowing = 27.05.2008, 3rd sowing = 10.06.2008, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2

4.2.2 Data of NIRS analyses

Protein, sugar and ash concentration

In the executed trials protein concentration of sorghum ranged from minimum 7.2 (1st sowing) to maximum 8.4 % DM (3rd sowing) (table 4.8). Plant density did not cause a clear change of protein concentration in 1st and 2nd sowing. Contrary to that protein concentration was significantly (p value 0.003) influenced by plant density in 3rd sowing. It could be observed that in both sowing (1st and 2nd) cv. Bovital led to higher protein concentration as compared to cv. Goliath.

Sugar concentration varied between 13 (2nd sowing) and 17 % DM (3rd sowing). Plant density did not significantly affect the sugar as well as ash concentration of sorghum in 1st and 2nd sowing. Opposite trend was observed in case of 3rd sowing where higher level of plant density caused a decrease in sugar concentration while significantly higher sugar concentration was determined for medium and lower level of plant density. Sugar concentration was markedly influenced (p value = 0.000) by cultivar in 1st sowing but not in 2nd and 3rd sowing. Cv. Goliath reached sugar concentration of 16 % while considerably lower value (11 %) was determined for cv. Bovital.

All levels of plant density led to comparable ash concentration in 1st and 2nd sowing time while in 3rd sowing higher level of plant density induced an increase of ash concentration from 7.1 to 8.0 % DM (table 4.8). Ash concentration was affected by cultivar in 1st and 3rd sowing while similar average was observed in 2nd sowing. In 1st sowing cv. Goliath exhibited higher ash concentration as compared to cv. Bovital while opposite trend was found in 3rd sowing. No interaction was noticed between cultivar and plant density regarding protein, sugar and ash concentration in all three sowing times.

Table 4.8: Effect of different cultivars (CV) and planting densities (PD) on protein (XP), sugar (XZ) and ash concentration (XA) of sorghum at different sowing times in Gross-Gerau 2008

CV	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		XP	XZ	XA	XP	XZ	XA	XP	XZ	XA
		% DM	% DM	% DM	% DM	% DM	% DM	% DM	% DM	% DM
1		6.6b	16.4a	8.7a	7.3b	12.9a	8.8a	8.1a	17.8a	7.1b
2		7.8a	11.4b	8.3b	8.7a	12.9a	8.5a	8.7a	16.5a	7.9a
	1	7.0a	14.6a	8.5a	8.1a	13.0a	8.4a	8.2b	17.6a	7.1b
	2	7.4a	13.2a	8.4a	8.1a	13.4a	8.6a	7.7b	18.7a	7.4b
	3	7.1a	14.0a	8.5a	7.9a	12.3a	8.9a	9.2a	15.2b	8.0a
Mean		7.2	13.9	8.5	8.0	12.9	8.7	8.4	17.1	7.5
$LSD_{0.05}$										
PD		ns	ns	ns	ns	ns	ns	0.9	1.9	0.5
CV		0.8	1.8	0.4	2.3	ns	ns	ns	ns	0.4
PD x CV		ns	ns	ns	ns	ns	ns	ns	ns	ns

1st sowing = 13.05.2008, 2nd sowing = 27.05.2008, 3rd sowing = 10.06.2008, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2

Acid detergent fiber, neutral detergent fiber and acid detergent lignin

The variation of ADF concentration was between 35.8 (3rd sowing) and 37.8 % (2nd sowing) (table 4.9). Plant density had no clear impact on ADF concentration in all three sowing times. ADF concentration was affected by cultivar in 1st and 2nd sowing. Cv. Goliath produced higher ADF concentration than that of cv. Bovital in 1st and 2nd sowing whereas both of these led to similar average in 3rd sowing (table 4.9). The NDF concentration ranged from 51 to 54 % in 3rd and 2nd sowing respectively. In all three sowing times plant density showed similar average of NDF concentration. Cv. Goliath was characterized by markedly higher NDF concentration as compared to cv. Bovital in 1st and 2nd sowing time while comparable concentration was observed in 3rd sowing (table 4.9).

Table 4.9: Effect of different cultivars (CV) and planting densities (PD) on acid detergent fiber (ADF), neutral detergent fiber (NDF) and acid detergent lignin (ADL) concentration of sorghum at different sowing times in Gross-Gerau 2008

CV	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		ADF	NDF	ADL	ADF	NDF	ADL	ADF	NDF	ADL
		%DM	% DM	% DM	% DM	% DM	% DM	% DM	% DM	% DM
1		38.7a	53.6a	4.9a	40.4a	56.7a	5.0a	36.8a	51.8a	4.7a
2		35.7b	52.4b	4.2b	35.2b	50.8b	4.2b	34.8a	49.8a	4.4a
	1	37.2a	53.0a	4.7a	38.2a	54.1a	4.6a	36.1a	50.6a	4.7a
	2	36.7a	52.7a	4.4a	36.9a	52.9a	4.5a	36.0a	51.4a	4.6a
	3	37.7a	53.3a	4.6a	38.4a	54.2a	4.8a	35.3a	50.3a	4.3a
Mean		37.2	53	4.6	37.8	53.8	4.6	35.8	50.8	4.6
$LSD_{0.05}$										
PD		ns	ns	ns	ns	ns	ns	ns	ns	ns
CV		1.6	1.2	0.4	2.9	3.0	0.5	ns	ns	ns
PD x CV		ns	ns	ns	ns	ns	ns	ns	ns	0.5

1st sowing = 13.05.2008, 2nd sowing = 27.05.2008, 3rd sowing = 10.06.2008, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2

There was no interaction between cultivar and PD with respect to NDF concentration. Plant density did not affect while cultivar induced a clear change in ADL concentration of sorghum in 1st (p value = 0.001) and 2nd sowing (p value = 0.011). Cv. Bovital showed a decline in ADL concentration while pronouncedly higher value was exhibited by cv. Goliath.

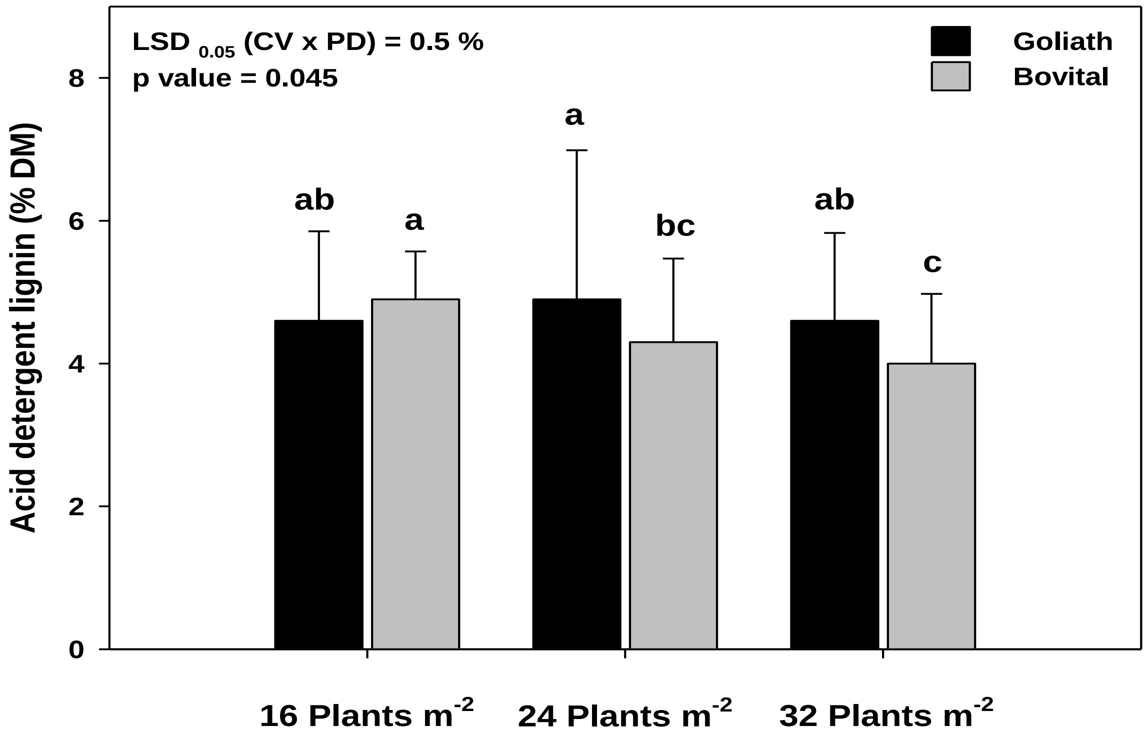

Fig. 4.14: Interaction between cultivars (CV) and plant density (PD) regarding lignin concentration (ADL) of sorghum in 3rd sowing at experimental station Gross-Gerau 2008 (T = SD)

On the other ADL concentration influenced neither by plant density nor by cultivar. However interaction (p value = 0.045) of CV x PD was observed in 3rd sowing regarding ADL concentration. Cv. Bovital with lower and cv. Goliath with medium level of plant density produced same ADL concentration whereas lowest was determined for cv. Bovital with higher plant density (fig. 4.14)

4.2.3 Anaerobic digestion

Biogas yield, methane concentration and methane yield

It could be observed that biogas yield of sorghum at different sowing times ranged from minimal 548 (2nd sowing) to maximal 578 nl kg VS^{-1} (1st sowing). Biogas yield was not significantly affected by plant density in all three sowing times (table 4.10). However a slight increase with higher plant density was found in 2nd and 3rd sowing in present study. Similar trend was observed regarding the methane yield within different plant densities evaluated in the experiment. In 1st and 3rd sowing cultivar did not induce change in biogas as well as methane yield of sorghum.

Table 4.10: Effect of different cultivars (CV) and planting densities (PD) on biogas yield (BGY), methane yield (MY) and methane concentration (XM) of sorghum at different sowing times in Gross-Gerau 2008

CV	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		BGY	XM	MY	BGY	XM	MY	BGY	XM	MY
		nl/kg VS	% vol.	nl/kg VS	nl/kg VS	% vol.	nl/kg VS	nl/kg VS	% vol.	nl/kg VS
1		595a	53b	311a	637a	53a	340a	569a	53b	300a
2		561a	54a	303a	458b	54a	245b	551a	54a	296a
	1	597a	53a	317a	546a	53a	287a	544a	53a	287a
	2	542a	54a	290a	544a	54a	293a	566a	54a	300a
	3	596a	53a	314a	552a	54a	297a	572a	54a	307a
Mean		578	54	307	548	54	292	555	54	298
$LSD_{0.05}$										
PD		ns	ns	ns	ns	ns	ns	ns	ns	ns
CV		ns	0.5	ns	78	ns	42	ns	0.6	ns
PD x CV		ns	ns	ns	ns	ns	ns	ns	ns	ns

1st sowing = 13.05.2008, 2nd sowing = 27.05.2008, 3rd sowing = 10.06.2008, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2, vol = volume

Contrary to that opposite results were observed in 2nd sowing where cv. Goliath is characterized by clearly higher biogas and methane yield than that of cv. Bovital (table 4.10). Plant density had no clear impact on methane concentration in all sowing times tested in present study. Methane concentration was significantly influenced by cultivar in 1st (p value = 0.000) and 3rd sowing (p value = 0.000). In both sowing times cv. Goliath led to considerably lower methane concentration as compared to cv. Bovital (table 4.10). No interaction (CV X PD) was observed regarding biogas, methane yield and methane concentration in all three sowing times.

4.3 Plant density and sowing time experiment Rauischholzhausen 2008

4.3.1 Biomass yield and plant stand parameters

Plant height, dry matter concentration and dry matter yield

With in different sowing times (mean of each sowing) plant height of sorghum varied between 291 (1st sowing) and 311 cm (3rd sowing). Plant density had no clear impact on plant height at all three sowing times (table 4.11). In all sowing times, plant height was significantly modified by cultivar. Cv. Bovital led to critically lower plant height as compared with cv. Goliath in present study. CV x PD interaction was not observed regarding plant height.

Dry matter concentration ranged from minimal 24 (2nd sowing) to 28.5 % (3rd sowing) (table 4.11). In 2nd and 3rd sowing all three plant densities showed same level of dry matter concentration. Contrary to that opposite trend was observed in 1st sowing where dry matter concentration was considerably (p value = 0.032) influenced by plant density. In 1st sowing higher plant density showed highest DM concentration followed by medium level of plant density while lower value was exhibited by 16 plant m^{-2} (table 4.11). Both tested cultivars led to comparable DM concentration in all three sowing times. There was no significant interaction between cultivar and PD with respect to DM concentration.

In present executed trial with in different sowing times, the variation of DM yield was between 14.7 (2nd sowing) and 16.38 t ha^{-1} (1st sowing). Plant density did not significantly affected DM yield of sorghum in 1st and 2nd sowing however with increasing PD caused a slight increase in DM yield. On the other hand a clear difference (p value = 0.005) was noticed in 3rd sowing among different level of PD evaluated in present study. In 3rd sowing medium and higher plant density led to similar DM yield while lower yield was observed with smaller PD (16 plants m^{-2}). In all three sowing times cv. Goliath produced higher DM yield than that of cv. Bovital (table 4.11).

Table 4.11: Effect of different cultivars (CV) and planting densities (PD) on plant height (Ph), dry matter concentration (DMC) and dry matter yield (DMY) of sorghum at different sowing times in Rauischholzhausen 2008

CV	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		Ph	DMC	DMY	Ph	DMC	DMY	Ph	DMC	DMY
		cm	%	t/ha	cm	%	t/ha	cm	%	t/ha
1		331a	26.2a	20.32a	349a	24.6a	19.50a	344a	28.6a	18.98a
2		250b	26.5a	12.44b	270b	23.6a	9.90b	277b	28.4a	10.85b
	1	286a	24.7b	14.02a	310a	23.8a	13.6a	312a	28.2a	13.88b
	2	303a	26.8ab	16.58a	310a	24.2a	14.67a	313a	29.4a	15.57a
	3	282a	27.6a	18.54a	308a	24.3a	15.83a	306a	27.9a	15.30a
Mean		291	26.4	16.38	310	24.1	14.7	311	28.5	14.92
$LSD_{0.05}$										
PD		ns	2.2	ns	ns	ns	ns	ns	ns	1.00
CV		19	ns	3.01	9.5	ns	1.67	13	ns	0.82
PD x CV		ns	ns	ns	ns	ns	ns	ns	ns	ns

1st sowing = 09.05.2008, 2nd sowing = 19.05.2008, 3rd sowing = 29.05.2008, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2

4.3.2 Data of NIRS analyses

Protein, sugar and ash concentration

In all three sowing times protein concentration was not affected by plant density. Cultivars significantly altered the protein concentration in all sowing times tested in this experiment. Cv. Bovital reached higher protein concentration whereas markedly lower was determined for cv. Goliath (table 4.12).

Between different sowing times small variation of sugar concentration from 10 to 11 % was observed. Sugar concentration difference between PD was smaller and not significant in all three sowing times. Cultivar induced a clear change in sugar concentration of sorghum in 1st (p value = 0.002) and 3rd sowing (p value = 0.000) but not in 2nd sowing time. In 1st and 3rd sowing cv. Goliath exhibited higher sugar concentration whereas lower value was determined for cv. Bovital. Interaction of CV x PD was not found regarding sugar concentration.

Same level of ash concentration was observed for all three PD in 1st and 3rd sowing while considerably ash concentration decreased with higher plant density in 2nd sowing. In 2nd and 3rd sowing cv. Goliath led to lower ash concentration as compared to cv. Bovital (4.12). Opposite findings were observed for 1st sowing where both cultivars showed similar averages of ash concentration. In the executed experiments there was no interaction between cultivars and plant density with respect to ash concentration.

Table 4.12: Effect of different cultivars (CV) and planting densities (PD) on protein (XP), sugar (XZ) and ash concentration (XA) of sorghum at different sowing times in Rauischholzhausen 2008

CV	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		XP	XZ	XA	XP	XZ	XA	XP	XZ	XA
		% DM	% DM	% DM	% DM	% DM	% DM	% DM	% DM	%DM
1		8.1b	12.0a	7.7a	7.9b	12.5a	7.7b	7.3b	12.2b	7.5b
2		9.5a	9.9b	8.1a	9.8a	8.1a	8.2a	9.2a	8.5a	8.1a
	1	8.8a	9.6a	7.9a	9.4a	8.0a	8.1a	8.7a	9.1a	7.8a
	2	8.9a	11.4a	8.0a	9.2a	9.6a	8.0a	8.1a	11.0a	7.6a
	3	8.5a	11.7a	7.7a	7.9a	13.3a	7.6b	7.9a	11.1a	7.9a
Mean		8.8	11.0	7.9	8.9	10.3	8.0	8.3	10.4	7.8
LSD$_{0.05}$										
PD		ns	ns	ns	ns	ns	0.3	ns	ns	ns
CV		0.7	2.6	ns	0.8	ns	0.2	0.5	2.1	0.3
PD x CV		ns	ns	ns	ns	ns	ns	ns	ns	ns

1st sowing = 09.05.2008, 2nd sowing = 19.05.2008, 3rd sowing = 29.05.2008, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2

Acid detergent fiber, neutral detergent fiber and acid detergent lignin

The range of ADF concentration among different sowing times was from 39 to 40 % (table 4.13). Comparable ADF concentration was observed for different PD evaluated in all three sowing times. Cv. Goliath characterized by higher ADF concentration as compared to cv. Bovital in 1st and 2nd sowing while same level was reached with both cultivars in 3rd sowing (table 4.13). PD had no significant effect on NDF concentration in all three sowing times. But cultivars induced a clear change in NDF concentration in 1st (p value = 0.029) and 2nd (p value = 0.000) sowing. In 1st and 2nd sowing cv. Bovital led to pronouncedly lower NDF concentration than that of cv. Goliath. NDF and ADF concentration affected neither by PD nor by cultivars in 3rd sowing. Interaction of cultivar and PD was not significant regarding ADF as well as NDF concentration of sorghum. ADL concentration was not influenced by PD in 1st and 3rd sowing but markedly higher ADL concentration was determined for 32 plants m^{-2} while 16 and 24 plants m^{-2} led to comparable value which was significantly lower. In 3rd sowing both cultivars showed same level of ADL concentration but considerably higher concentration was reached with cv. Goliath as compared to cv. Bovital in 1st and 2nd sowing. Interaction (CV x PD) was not observed for ADL concentration in all three sowing times.

Table 4.13: Effect of different cultivars (CV) and planting densities (PD) on acid detergent fiber (ADF), neutral detergent fiber (NDF) and acid detergent lignin (ADL) concentration of sorghum at different sowing times in Rauischholzhausen 2008

CV	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		ADF	NDF	ADL	ADF	NDF	ADL	ADF	NDF	ADL
		% DM	% DM	% DM	% DM	% DM	% DM	% DM	% DM	%DM
1		40.8a	56.2a	5.7a	40.3a	55.6a	5.7a	41.5a	56.7a	5.8a
2		38.2b	54.8b	5.3b	37.8b	54.8b	5.3b	37.8a	55.5a	5.4a
	1	39.0a	55.8a	5.4a	38.4a	55.4a	5.3b	38.1a	55.6a	5.3a
	2	39.9a	55.5a	5.3a	39.4a	56.1a	5.4b	40.5a	56.3a	5.6a
	3	39.6a	55.3a	5.8a	39.3a	54.2a	5.8a	40.3a	56.3a	5.8a
Mean		39.5	55.5	5.5	39.1	55.2	5.5	39.7	56.1	5.6
$LSD_{0.05}$										
PD		ns	ns	ns	ns	ns	0.2	ns	ns	ns
CV		2.8	2.1	0.3	1.0	1.1	0.2	ns	ns	ns
PD x CV		ns	ns	ns	ns	ns	ns	ns	ns	ns

1st sowing = 09.05.2008, 2nd sowing = 19.05.2008, 3rd sowing = 29.05.2008, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2

4.3.3 Anaerobic digestion

Biogas yield, methane concentration and methane yield

Among different sowing times biogas ranged from 519 (3rd sowing) to 563 nl kg VS^{-1}. Biogas yield was not clearly affected by plant density in all three sowing times. Cultivars had significant effect on biogas yield in 2nd (p value = 0.002) and 3rd sowing (p value = 0.002) but not in 1st sowing. In both sowing times cv. Goliath reached considerably higher biogas yield as compared with cv. Bovital (table 4.14). There was no interaction between cultivar and plant density in all three sowing times. Similar trend was observed regarding methane yield where plant density had no clear impact while cv. Goliath led to markedly higher methane yield than that of cv. Bovital in 2nd and 3rd sowing (table 4.14). However an interaction (CV x PD) was found with respect to methane yield in 2nd sowing. With lower plant density (16 plants m^{-2}) cv. Bovital produced lowest methane yield among the treatments (Fig. 4.15). In executed trials methane concentration varied between 52 (2nd sowing) to 54 % (1st sowing) with in different sowing times. Plant density as well as cultivar did not induce a change in methane concentration in all three sowing times.

Table 4.14: Effect of different cultivars (CV) and planting densities (PD) on biogas yield (BGY), methane yield (MY) and methane concentration (XM) of sorghum at different sowing times in Rauischholzhausen 2008

CV	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		BGY	XM	MY	BGY	XM	MY	BGY	XM	MY
		nl/kg VS	% vol.	nl/kg VS	nl/kg VS	% vol	nl/kg VS	nl/kg VS	% vol.	nl/kg VS
1		580a	54a	313a	598a	51a	255b	591a	53a	311a
2		546a	54a	295a	524b	52a	272a	446b	52a	233b
	1	593a	54a	321a	535a	52a	199a	567a	52a	297a
	2	590a	54a	319a	559a	52a	290a	542a	52a	286a
	3	506a	54a	273a	589a	51a	301a	445a	52a	232a
Mean		563	54	304	561	52	264	519	53	272
$LSD_{0.05}$										
PD		ns	ns	ns	ns	ns	ns	ns	ns	ns
CV		ns	ns	ns	45	ns	20	83	ns	44
PD x CV		ns	ns	ns	ns	2.6	34	ns	ns	ns

1st sowing = 09.05.2008, 2nd sowing = 19.05.2008, 3rd sowing = 29.05.2008, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m², PD 2 = 24 plants/m², PD 3 = 32 plants/m², vol. = volume

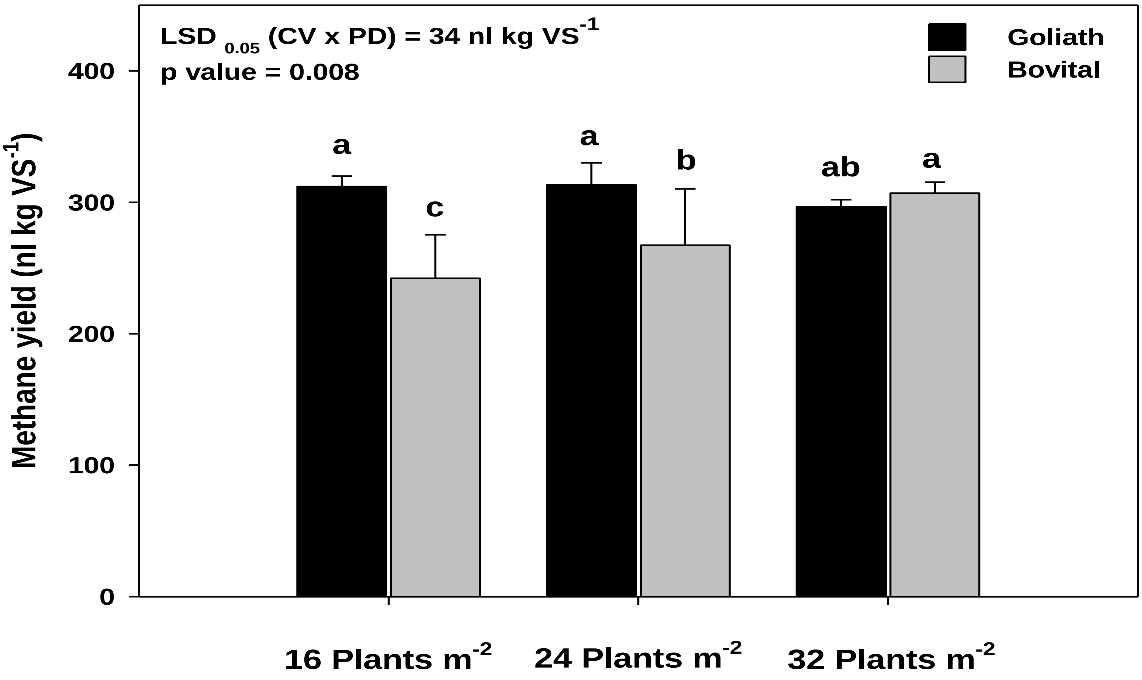

Fig. 4.15: Interaction between cultivars (CV) and plant density (PD) regarding methane yield (MY) of sorghum in 2nd sowing at experimental station Rauischholzhausen 2008 (T = SD)

However a significant interaction (p value = 0.019) was observed between cultivar and PD in 2nd sowing. Cv. Goliath with 16 plants m^{-2} and cv. Bovital with 24, 32 plants m^{-2} showed comparable methane concentration while significantly lower value was determined for cv. Goliath in combination with 24 and 32 plants m^{-2} (fig. 4.16).

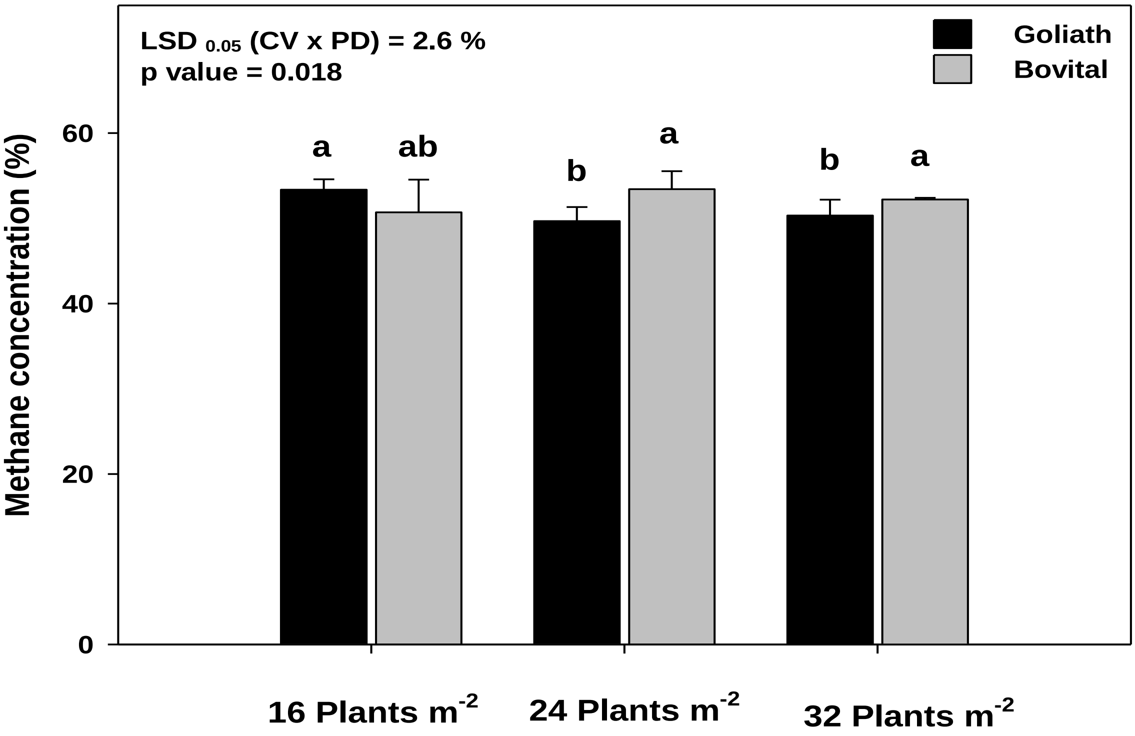

Fig. 4.16: Interaction between cultivars (CV) and plant density (PD) regarding methane concentration (XM) of sorghum in 2nd sowing at experimental station Rauischholzhausen 2008 (T = SD)

4.4 Plant density and sowing time experiment Giessen 2009

4.4.1 Biomass yield and plant stand parameters

Leaf area index (LAI)

Maximum level of LAI was reached at 90 days after germination (DAG) followed by 60 DAG and lowest value was showed by 30 DAG in all three sowing times (table 4.15). After 30 days of germination higher plant density of 32 plants m^{-2} led to similar LAI with 24 plants m^{-2} while predominantly lower was exhibited by 16 plants m^{-2} in 1st sowing. In later plant development after 60 and 90 days after germination there were no differences under the influence of plant densities. In 2nd sowing interaction of CV x PD (p value = 0.019) was observed regarding LAI at 30 DAG. Cv. Bovital with higher plant density and cv. Goliath with all levels of plant densities led to comparable averages of LAI. Same level of LAI was attained with cv. Bovital in combination with 16 and 24 plants m^{-2} which was significantly lower (fig. 4.17). In first sowing time the tested cultivars induced different LAI values after 30 and 90 days after germination whereas in all other cases same level of LAI was noticed. At 30 days after germination cv. Goliath was characterized by higher LAI than for cv. Bovital. Contrary to this at 90 DAG opposite trend was found where cv. Bovital led to higher LAI as compared with cv. Goliath (table 4.15).

Table 4.15: Effect of different cultivars (CV) and planting densities (PD) on leaf area indices (LAI) of sorghum at different sowing times in Giessen 2009

Cv	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		LAI 1	LAI 2	LAI 3	LAI 1	LAI 2	LAI 3	LAI 1	LAI 2	LAI 3
1		3.7a	4.6a	4.4b	2.4a	3.6a	4.1a	2.0a	3.5a	4.1a
2		3.1b	4.8a	4.9a	2.2a	3.8a	4.0a	1.7a	3.7a	3.9a
	1	2.7b	4.4a	4.5a	2.1b	3.4a	3.6a	1.4a	3.2a	3.6a
	2	3.6a	4.7a	4.5a	2.2b	3.7a	4.3a	2.0a	3.7a	4.2a
	3	3.8a	5.1a	5.0a	2.6a	4.0a	4.3a	2.1a	3.8a	4.1a
Mean		3.4	4.7	4.7	2.3	3.7	4.1	1.8	3.6	4.0
$LSD_{0.05}$										
PD		0.7	ns	ns	0.3	ns	ns	ns	ns	ns
CV		0.6	ns	0.4	ns	ns	ns	ns	ns	ns
PD x CV		ns	ns	ns	0.4	ns	ns	ns	ns	ns

1st sowing = 20.05.2009, 2nd sowing = 29.05.2009, 3rd sowing = 08.06.2009, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m², PD 2 = 24 plants/m², PD 3 = 32 plants/m², LAI 1 = 30 days after germination, LAI 2 = 60 days after germination, LAI 2 = 90 days after germination

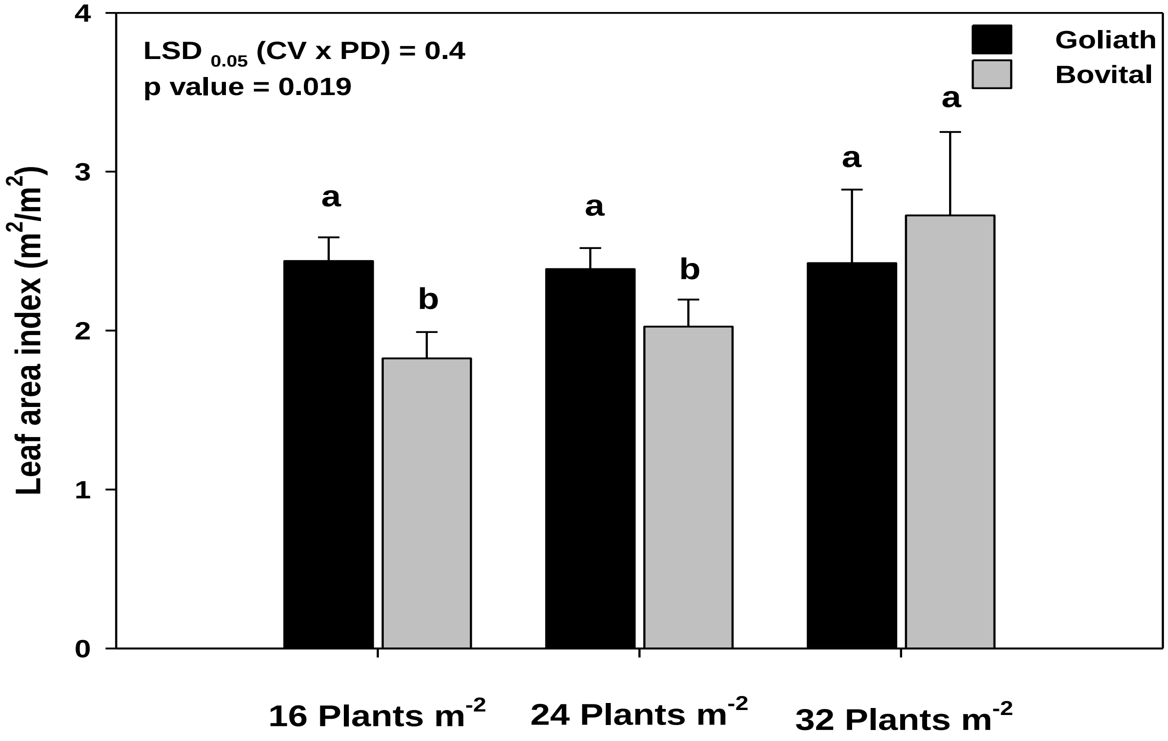

Fig. 4.17: Interaction between cultivars (CV) and plant density (PD) regarding leaf area index (LAI) of sorghum in 2nd sowing at experimental station Giessen 2009 (T = SD)

Plant height

With in different sowing times plant height ranged from minimal 227 to maximal 263 cm at 90 days after germination (last measuring stage) (table 4.16). Plant height was not affected by plant density at 60 and 90 DAG but clearly modified at 30 DAG in 1st and 2nd sowing. At this stage of measurement in 1st and 2nd sowing higher plant density caused an increase in plant height of sorghum (table 4.16).

Table 4.16: Effect of different cultivars (CV) and planting densities (PD) on plant height (Ph) of sorghum at different sowing times in Giessen 2009

Cv	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		Ph 1	Ph 2	Ph 3	Ph 1	Ph 2	Ph 3	Ph 1	Ph 2	Ph 3
		cm	cm	cm	cm	cm	cm	cm	cm	cm
1		109a	222a	270a	101a	171a	246a	89a	154a	234a
2		86b	190b	256b	95a	151b	228b	76b	136b	220b
	1	126b	193a	255a	90b	152a	233a	78a	141a	224a
	2	141a	211a	266a	101a	164a	235a	82a	145a	226a
	3	152a	215a	269a	103a	166a	242a	88a	149a	231a
Mean		97.5	206	263	98	161	237	83	145	227
LSD $_{0.05}$										
PD		14	ns	ns	10	ns	ns	ns	ns	ns
CV		11	21	11	ns	12	10	8	11	9
PD x CV		ns	ns	ns	ns	ns	ns	ns	ns	ns

1st sowing = 20.05.2009, 2nd sowing = 29.05.2009, 3rd sowing = 08.06.2009, Ph 3 = 90 days after germination, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2

Cultivar differed for plant height at all measuring stages as well as in all three sowing times except in 2nd sowing at 30 DAG. Cv. Goliath had a higher plant stand in comparison with cv. Bovital whereas at 30 DAG in 2nd sowing both cultivars were similar (table 4.16).

Tillers, dry matter concentration and dry matter yield

Number of tillers varied between 22 (2nd sowing) and 25 (3rd sowing) among different sowing times evaluated in present study (table 4.17). Cultivar as well as plant density induced a clear change in number of tillers m^{-2} of sorghum. Cv. Bovital produced higher number of tillers m^{-2} in all three sowing times. In present executed trials (in all three sowing times) lower plant densities caused a clear decline in number of tillers (table 4.17).

In 1st and 3rd sowing time plant density had no effect on dry matter concentration. But on the other hand in 2nd sowing time medium plant density led to significantly higher level of DM concentration followed by higher plant density while smaller plant density showed clearly lower value of DM concentration. Cv. Bovital showed higher DM concentration than cv. Goliath in 2nd and 3rd sowing times (table 4.17). Among different sowing times dry matter yield ranged from minimal 11.68 (2nd sowing) to maximal 12.70 t ha^{-1} (1st sowing). DM yield was not influenced by plant density in 1st and 3rd sowing time. On the contrary a significantly lower DM yield was recorded for smaller plant density while medium and higher plant densities showed similar level of DM yield in 2nd sowing (table 4.17). In 3rd sowing dry matter yield influenced neither by cultivar nor by plant density. No interaction was significant between cultivar and plant density with respect to DM concentration as well as dry matter yield in all three sowing times.

Table 4.17: Effect of different cultivars (CV) and planting densities (PD) on number of tillers (m^{-2}), dry matter concentration (DMC) and dry matter yield (DMY) of sorghum at different sowing times in Giessen 2009

CV	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		Til./m²	DMC	DMY	Til./m²	DMC	DMY	Til./m²	DM	DMY
		No.	%	t/ha	No.	%	t/ha	No.	%	t/ha
1		21b	24.1a	15.58a	17b	22.7b	13.76a	19b	23.0b	13.80a
2		26a	24.0a	9.73b	27a	23.4a	9.60b	30a	24.7a	11.27a
	1	21b	23.9a	11.69a	17c	22.4b	10.31b	22c	28.3a	11.57a
	2	22b	24.1a	12.36a	22b	23.6a	12.35a	24b	24.0a	13.24a
	3	28a	24.3a	13.90a	27a	23.1ab	12.38a	28a	24.7a	12.80a
Mean		24	24.1	12.70	22	23.1	11.68	25	35.4	12.53
$LSD_{0.05}$										
PD		3	ns	ns	3	0.8	1.10	2	ns	ns
CV		2	ns	1.72	2	0.7	0.90	2	1.1	ns
PD x CV		ns	ns	ns	ns	ns	ns	ns	ns	ns

1st sowing = 20.05.2009, 2nd sowing = 29.05.2009, 3rd sowing = 08.06.2009, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m², PD 2 = 24 plants/m², PD 3 = 32 plants/m²

4.4.2 Data of NIRS analyses

Protein, sugar and ash concentration

Protein concentration among different sowing times ranged from minimal 9 (1st sowing sowing) to maximal 10 % (2nd sowing) (table 4.18). In present study protein concentration was not affected by plant density in 1st and 3rd sowing. Opposite to that in 2nd sowing time plant density significantly altered (p value = 0.014) protein concentration of sorghum. Higher plant density induced a clear decline in protein concentration while comparable concentration was obtained with lower and medium plant densities (table 4.18). In all three sowing times cv. Bovital led to markedly higher protein concentration as compared with cv. Goliath. With in different sowing times sugar concentration varied between 11 to 13 % in 2nd and 1st sowing respectively. Plant density had no significant impact on sugar concentration in all three sowing times. However cv. Goliath led to higher sugar concentration than that of cv. Bovital in all tested sowing times evaluated in present experiments. A considerable interaction (p value = 0.018) of CV x PD was observed regarding sugar concentration in 2nd sowing time. Cv. Goliath in combination with lower plant density (16 plants m^{-2}) produced highest sugar concentration followed by cv. Goliath with medium PD while lowest was exhibited by cv. Bovital with medium and lower plant density (fig.4.18).

Table 4.18: Effect of different cultivars (CV) and planting densities (PD) on protein (XP), sugar (XZ) and ash concentration (XA) of sorghum at different sowing times in Giessen 2009

CV	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		XP	XZ	XA	XP	XZ	XA	XP	XZ	XA
		%DM	%DM	%DM	%DM	%DM	%DM	%DM	%DM	%DM
1		8.3b	15.5a	8.6b	9.2b	12.7a	8.6b	8.9b	12.1a	8.7b
2		10.3a	9.4b	9.2a	11.1a	10.1b	9.4a	10.1a	11.0b	9.2a
	1	9.4a	11.9a	8.7a	10.4a	11.3a	9.3a	9.5a	12.0a	8.9a
	2	9.5a	13.6a	8.9a	10.2a	11.1a	9.1a	9.6a	11.6a	8.9a
	3	9.1a	11.9a	8.9a	9.8b	11.8a	8.7b	9.3a	11.9a	8.8a
Mean		9.3	12.5	8.9	10.2	11.4	9.0	9.5	11.6	8.6
$LSD_{0.05}$										
PD		ns	ns	ns	0.4	ns	0.3	ns	ns	ns
CV		0.4	1.7	0.2	0.3	0.8	0.2	0.4	1.2	0.3
PD x CV		ns	ns	ns	ns	1.4	ns	ns	ns	ns

1st sowing = 20.05.2009, 2nd sowing = 29.05.2009, 3rd sowing = 08.06.2009, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2

Ash concentration was not influenced by plant density in all three sowing times. In the executed trials the tested cultivars differed in all three sowing times regarding ash concentration (table 4.18). Cv. Goliath showed clearly lower ash concentration in comparison with cv. Bovital. There was no interaction between cultivar and PD in any sowing time.

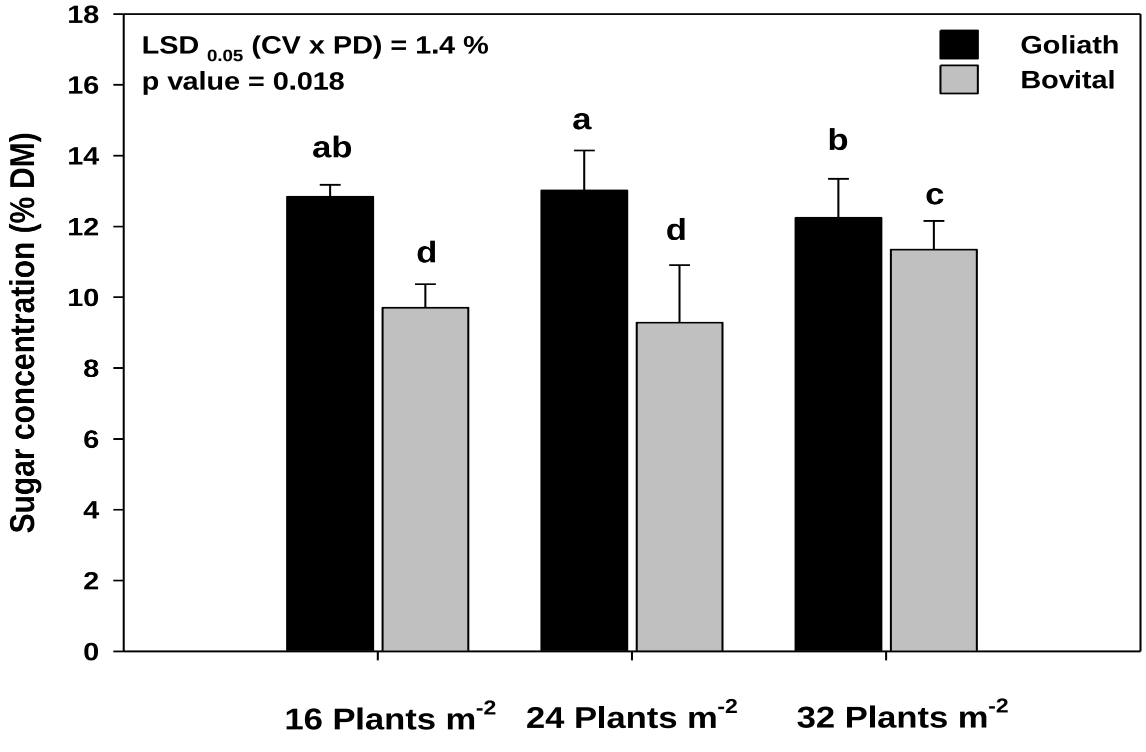

Fig. 4.18: Interaction between cultivars (CV) and plant density (PD) regarding sugar concentration (XZ) of sorghum in 2nd sowing at experimental station Giessen 2009 (T = SD)

Acid detergent fiber, neutral detergent fiber and acid detergent lignin

The average of ADF and NDF concentration was 36 and 52 % DM respectively within different sowing times. ADF as well as NDF concentration was not influenced by different plant densities test in present study. Cultivars pronouncedly affected both ADF and NDF concentration of sorghum in all three sowing times. Cv. Goliath led to higher ADF as well as NDF concentration than that of cv. Bovital (table 4.19). CV x PD interaction (p value = 0.005) was observed for NDF concentration in 2nd sowing time.

Table 4.19: Effect of different cultivars (CV) and planting densities (PD) on acid detergent fiber (ADF), neutral detergent fiber (NDF) and acid detergent lignin (ADL) concentration of sorghum at different sowing times in Giessen 2009

CV	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		ADF	NDF	ADL	ADF	NDF	ADL	ADF	NDF	ADL
		% DM	% DM	% DM	% DM	% DM	% DM	% DM	% DM	%DM
1		36.9a	53.8a	5.0a	37.1a	53.8a	4.9a	37.9a	53.1a	4.9a
2		35.1b	51.6b	4.6a	34.5b	51.5b	4.6b	35.0b	51.1b	4.8a
	1	36.6a	52.5a	4.7a	35.8a	52.5a	4.6b	36.6a	51.9a	4.9a
	2	34.9a	52.6a	4.7a	35.4a	52.6a	4.6b	36.6a	52.4a	4.8a
	3	36.4a	52.9a	4.9a	36.3a	52.9a	4.9a	36.1a	52.0a	4.8a
Mean		36.0	52.7	4.8	35.8	52.7	4.8	36.5	52.1	4.9
$LSD_{0.05}$										
PD		ns	ns	ns	ns	ns	0.2	ns	ns	ns
CV		1.8	0.6	ns	0.1	0.6	0.2	1.4	1.4	ns
PD x CV		ns	ns	ns	ns	1.0	ns	ns	ns	ns

1st sowing = 20.05.2009, 2nd sowing = 29.05.2009, 3rd sowing = 08.06.2009, CV 1 = Goliath, CV 2 = Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2

In higher plant density cv. Goliath exhibited highest NDF concentration followed by lower PD while in all three plant densities cv. Bovital showed comparable means which were significantly lower (fig. 4.19). ADL concentration was affected neither by cultivar nor by plant density in 1st and 3rd sowing. Opposite trend was observed in 2nd sowing where cultivar and plant density had a clear impact on ADL concentration. It could be found that cv. Goliath reached higher ADL concentration as compared with cv. Bovital. In addition higher plant density increased ADL concentration than lower plant densities (table 4.19).

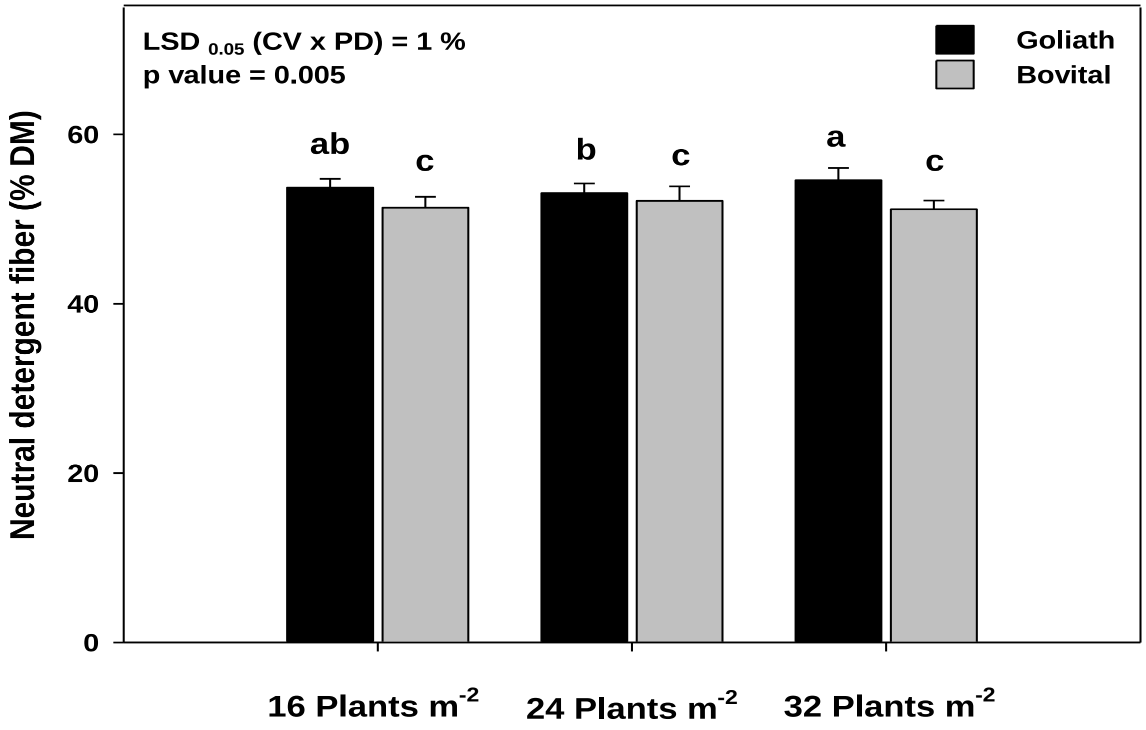

Fig. 4.19: Interaction between cultivars (CV) and plant density (PD) regarding neutral detergent fiber (NDF) of sorghum in 2nd sowing at experimental station Giessen 2009 (T = SD)

4.5 Plant density and sowing time experiment Gross-Gerau 2009

4.5.1 Biomass yield and plant stand parameters

Tillers, dry matter concentration and dry matter yield

The variation in number of tillers m^{-2} among different sowing times was from minimal 25 (2nd sowing) to maximal 32 (3rd sowing) (table 4.20). In all three sowing times plant density induced a clear change in number of tillers m^{-2}. Higher number of tillers m^{-2} were exhibited by 32 plants m^{-2} followed by 24 plant m^{-2} while plant density 16 plants m^{-2} showed significantly lower. Cv. Bovital was characterized by markedly higher number of tillers m^{-2} as compared with cv. Goliath in all three sowing times. There was a significant interaction (p value = 0.000) between the study factors cultivar and plant density regarding number of tillers m^{-2} in 3rd sowing. Cv. Bovital with medium and lower plant density led to higher number of tillers followed by same cultivar in combination with 32 plants m^{-2} while lowest value of 16 was attained with cv. Goliath with 16 plants m^{-2} (fig. 4.20).

DM concentration was influenced neither by cultivar nor by PD in all three sowing times. Furthermore no interaction (CV x PD) was observed with respect to DM concentration of sorghum. Dry matter yield ranged from 13.78 (3rd sowing) to 15.75 t/ha (1st sowing) in present study. Different plant densities produced similar DM yield in all three sowing times. On the other hand cultivar had clear impact on DM yield of sorghum where cv. Goliath led to considerably higher yield than that of cv. Bovital in all three sowing times (table 4.20).

Table 4.20: Effect of different cultivars (CV) and planting densities (PD) on number of tillers (m^{-2}), dry matter concentration (DMC) and dry matter yield (DMY) of sorghum at different sowing times in Gross-Gerau 2009

CV	PD	1^{st} sowing time			2^{nd} sowing time			3^{rd} Sowing time		
		Till./m^2	DMC	DMY	Till./m^2	DMC	DMY	Till./m^2	DMC	DMY
		No.	%	t/ha	No.	%	t/ha	No.	%	t/ha
1		25b	24.7	19.38a	21b	23.5a	17.33a	23b	25.6a	15.27a
2		32a	25.0	12.12b	29a	28.4a	13.83b	40a	26.7a	12.29b
	1	22c	25.1	15.30a	22b	24.2a	15.56a	28b	25.8a	13.39a
	2	28b	25.2	16.26a	24b	24.7a	16.16a	33a	26.4a	14.27a
	3	34a	24.3	15.69a	29a	23.5a	15.02a	35a	26.2a	13.68a
Mean		28	24.9	15.75	25	26.0	15.57	32	26.2	13.78
LSD$_{0.05}$										
PD		4	ns	ns	4	ns	ns	4	ns	ns
CV		3	ns	1.20	3	ns	2.35	3	ns	1.1
PD x CV		ns	ns	ns	ns	ns	ns	6	ns	ns

Till = tillers, DMC = dry matter concentration, DMY = dry matter yield, 1^{st} sowing = 14.05.2009, 2^{nd} sowing = 10.06.2009, 3^{rd} sowing = 23.06.2009, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2

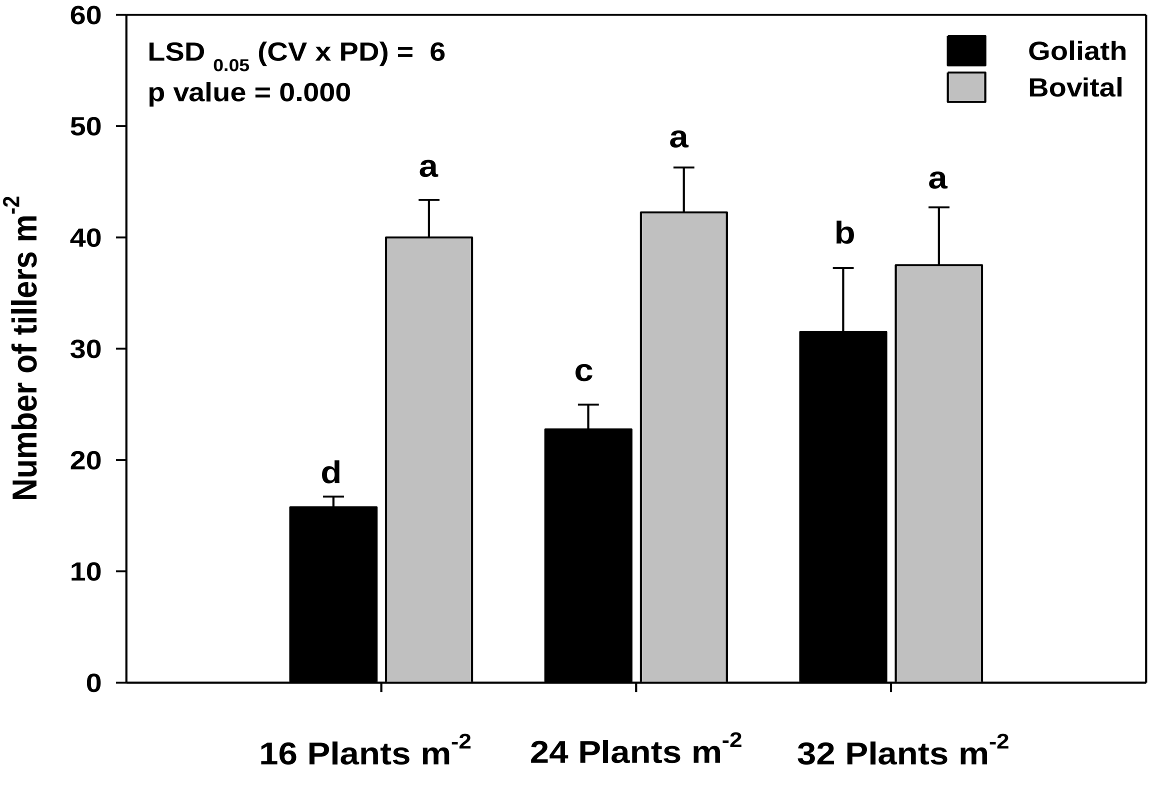

Fig. 4.20: Interaction between cultivars (CV) and plant density (PD) regarding number of tillers of sorghum in 3^{rd} sowing at experimental station Gross-Gerau 2009 (T = SD)

Organ partitioning (% DM)

Among different sowing times stem dry matter varied from 63.7 (3rd sowing) to 65 %. 1st and 2nd sowing time had the highest proportion within the whole biomass followed by comparable proportion of leaves 20 % and panicle 15 % (table 4.21). Plant density had no clear effect on dry matter percentage of leaf in 2nd and 3rd sowing. Contrary to that in 1st sowing leaf dry matter percentage was significantly (p value = 0.000) altered by plant density. Plant density of 16 and 24 plants m^{-2} led to same level of leaf dry matter % while pronouncedly higher was reached with 32 plants m^{-2}. Stem as well as panicle DM concentration was not affected by plant density in all three sowing times. In all three sowing times cultivar induced a clear change of stem dry matter concentration where cv. Goliath characterized by higher stem DM concentration as compared with cv. Bovital. The panicle DM concentration was 5 to 7 times greater in cv. Bovital than that of cv. Goliath (table 4.21). CV x PD interaction was not observed for leaf, stem as well as panicle dry matter concentration of sorghum.

Table 4.21: Effect of different cultivars (CV) and planting densities (PD) on leaf, stem and panicle dry matter proportion of sorghum at different sowing time in Gross-Gerau 2009

CV	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		Organ partioning (% DM)								
		Leaf	Stem	Panicle	Leaf	Stem	Panicle	Leaf	Stem	Panicle
1		22.7a	72.8a	4.5b	23.3a	73.6a	3.1b	23.8a	70.0a	6.2b
2		17.0b	57.4b	25.6a	16.5b	56.9b	26.6a	18.0b	57.3a	24.7a
	1	18.6b	66.8a	14.5a	19.0a	65.8a	15.1a	19.2a	64.8a	16.0a
	2	18.9b	64.3a	16.8a	20.3a	63.7a	16.0a	22.2a	63.1a	14.7a
	3	22.1a	64.1a	13.8a	20.4a	66.2a	13.4a	21.4a	63.1a	15.5a
Mean		19.9	65.1	15.1	19.9	65.3	14.9	20.9	63.7	15.5
$LSD_{0.05}$										
PD		2.6	ns	ns	ns	ns	ns	ns	ns	ns
CV		2.4	2.8	0.3	3.4	2.7	3.3	1.1	2.2	2.8
PD x CV		ns	ns	ns	ns	ns	ns	ns	ns	ns

1st sowing = 14.05.2009, 2nd sowing = 10.06.2009, 3rd sowing = 23.06.2009, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2

4.5.2 Data of NIRS analyes

Protein, sugar and ash concentration

With in different sowing times, protein concentration ranged from minimal 7.2 (2nd sowing) to maximal 7.7 % DM (3rd sowing) (table 4.22). Protein concentration was not influenced by plant density in all three sowing times. Cultivar induced a clear change in protein concentration where cv. Goliath showed lower protein concentration than that of cv. Bovital in all three sowing times (table 4.22). However in 1st sowing significant interaction (p value = 0.006) of CV x PD was observed regarding protein concentration. Cv. Bovital with all three levels of plant density led to comparable protein concentration while lowest was determined for cv. Goliath with lower PD in 1st sowing (fig. 4.21). Plant density did not affect sugar concentration of sorghum in all sowing times tested in present study.

Table 4.22: Effect of different cultivars (CV) and planting densities (PD) on protein (XP), sugar (XZ) and ash concentration (XA) of sorghum at different sowing times in Gross-Gerau 2009

CV	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		XP	XZ	XA	XP	XZ	XA	XP	XZ	XA
		% DM	% DM	% DM	% DM	% DM	% DM	% DM	% DM	%DM
1		6.8b	8.8a	8.7a	6.5b	11.3a	8.8a	7.3b	13.8a	8.6a
2		8.2a	5.6b	8.3a	7.9a	7.9b	8.5a	8.1a	10.9b	8.6a
	1	7.5a	7.8a	8.5a	7.0a	9.9a	8.4a	7.9a	12.5a	8.5a
	2	7.3a	7.6a	8.4a	7.3a	9.6a	8.6a	7.5a	12.5a	8.6a
	3	7.6a	6.3a	8.5a	7.3a	9.2a	8.9a	7.6a	12.0a	8.7a
Mean		7.5	7.2	8.5	7.2	9.6	8.7	7.7	12.3	8.6
$LSD_{0.05}$										
PD		ns	ns	ns	ns	ns	ns	ns	ns	ns
CV		0.3	1.2	ns	0.6	1.4	ns	0.6	1.2	ns
PD x CV		0.6	ns	ns	ns	ns	ns	ns	ns	0.5

1st sowing = 14.05.2009, 2nd sowing = 10.06.2009, 3rd sowing = 23.06.2009, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2

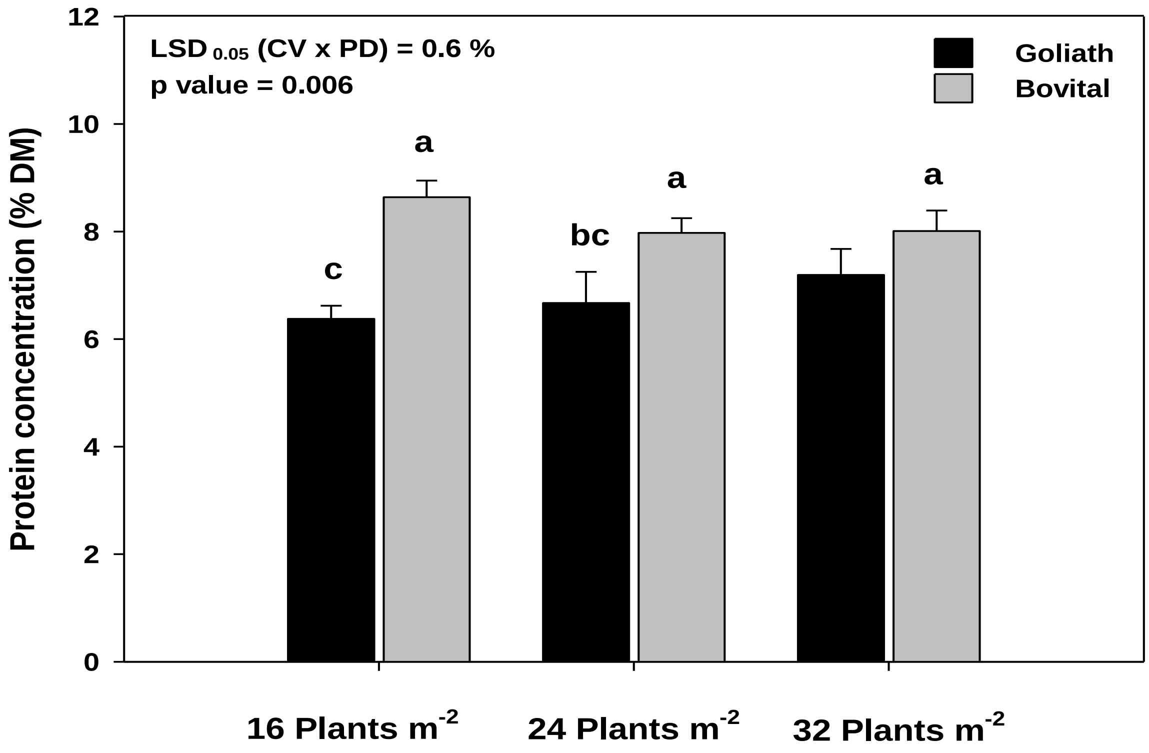

Fig. 4.21: Interaction between cultivars (CV) and plant density (PD) regarding protein concentration (XP) of sorghum in 1st sowing at experimental station Gross-Gerau 2009 (T = SD)

In all three sowing times cv. Goliath was characterized by significantly higher sugar concentration as compared with cv. Bovital. Ash concentration influenced neither by cultivar nor by plant density in all sowing times. However interaction between cultivar and PD was significant (p value = 0.004) in 3rd sowing. Cv. Bovital with 16 plants m^{-2}, cv. Goliath with 24 and 32 plants m^{-2} showed similar level of ash concentration while lowest was observed with cv. Goliath in combination with 16 plants m^{-2} (fig. 4.22).

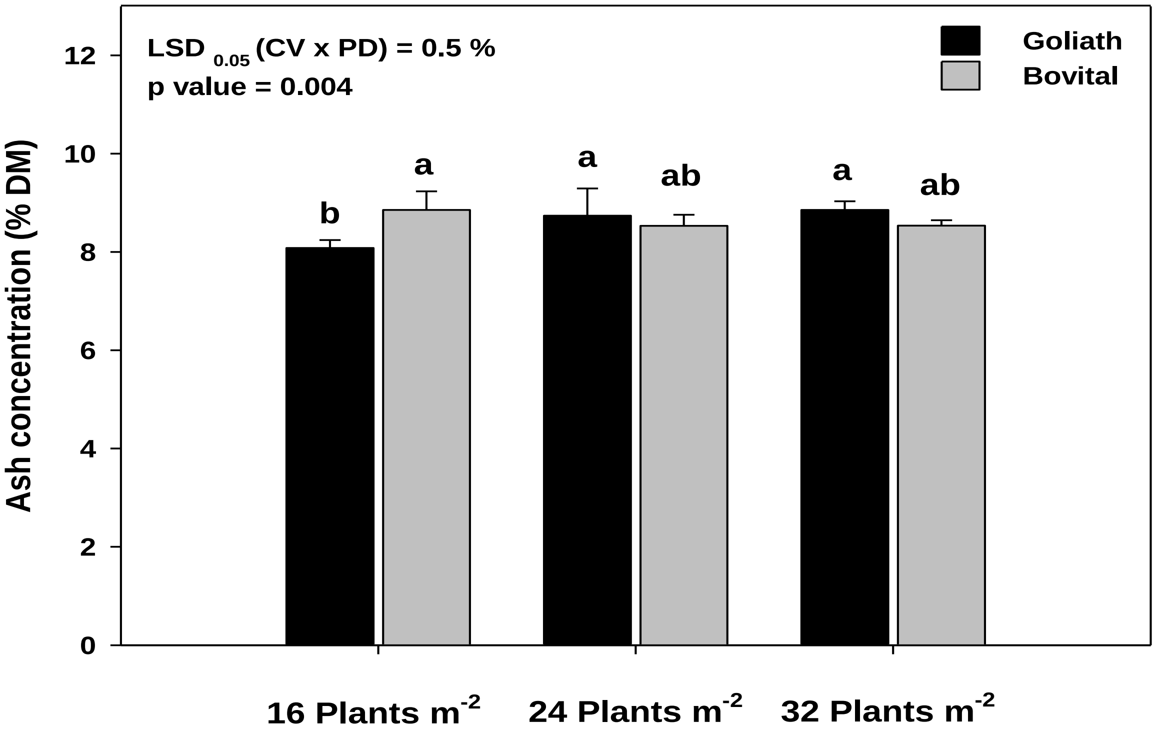

Fig. 4.22: Interaction between cultivars (CV) and plant density (PD) regarding ash concentration (XA) of sorghum in 3rd sowing at experimental station Gross-Gerau 2009 (T = SD)

Acid detergent fiber, neutral detergent fiber and acid detergent lignin

The ADF concentration among different sowing times ranged from 36.7 (2nd sowing) to 39.6 % (1st sowing). ADF concentration was not clearly modified by plant density in all three sowing times (table 4.23). Opposite to that both tested cultivars differed significantly with respect to ADF concentration. Higher ADF concentration was determined for cv. Goliath in comparison with cv. Bovital in all sowing times evaluated in present trials. In 2nd sowing CV x PD interaction was observed with respect to ADF concentration of sorghum. Cv. Goliath with medium and higher level of plant density led to similar ADF concentration while considerably lower value was showed by cv. Bovital with all three plant densities tested in present study (fig. 4.23). NDF concentration with in different sowing times ranged from minimal 56.6 (3rd sowing) to maximal 62.2 % (1st sowing) (table 4.23). All three plant densities led to similar level of NDF concentration in all sowing times. Cultivar induced a clear change in NDF concentration of sorghum except in 1st sowing. In 2nd and 3rd sowing lower NDF concentration was attained with cv. Bovital than that of cv. Goliath (table 4.23). ADL concentration was not modified by plant density in 1st and 2nd sowing whereas different trend was observed in 3rd sowing.

Table 4.23: Effect of different cultivars (CV) and planting densities (PD) on acid detergent fiber (ADF), neutral detergent fiber (NDF) and acid detergent lignin (ADL) concentration of sorghum at different sowing times in Gross-Gerau 2009

CV	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		ADF	NDF	ADL	ADF	NDF	ADL	ADF	NDF	ADL
		% DM	% DM	% DM	% DM	% DM	%DM	% DM	% DM	%DM
1		41.8a	63.0a	6.3a	38.8a	59.2b	6.0a	38.9a	57.1a	5.8a
2		37.4b	61.5a	5.2b	34.5b	57.4a	4.8b	36.2b	56.0a	5.2b
	1	39.6a	62.0a	5.8a	36.3a	58.2a	5.3a	37.0a	56.2a	5.4b
	2	39.5a	62.5a	5.8a	36.4a	57.8a	5.4a	37.7a	56.2a	5.6a
	3	39.6a	62.3a	5.7a	37.2a	58.9a	5.5a	38.0a	57.0a	5.5ab
Mean		39.6	62.2	5.8	36.7	58.3	5.4	37.6	56.6	5.5
$LSD_{0.05}$										
PD		ns	ns	ns	ns	ns	ns	ns	ns	0.2
CV		1.3	ns	0.3	1.0	1.2	0.3	1.0	ns	0.2
PD x CV		ns	ns	ns	1.9	ns	0.5	ns	ns	ns

1st sowing = 14.05.2009, 2nd sowing = 10.06.2009, 3rd sowing = 23.06.2009, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2

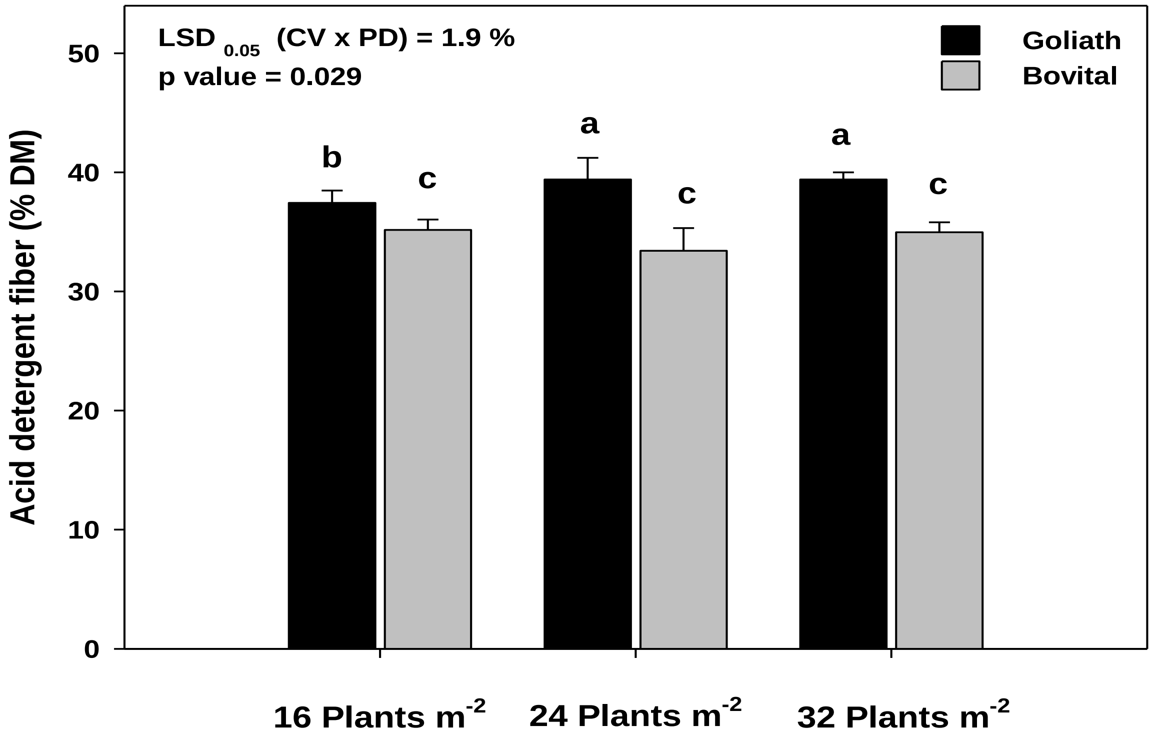

Fig. 4.23: Interaction between cultivars (CV) and plant density (PD) regarding acid detergent fiber (ADF) of sorghum in 2nd sowing at experimental station Gross-Gerau 2009 (T = SD)

In 3rd sowing time medium level of plant density (24 plants m^{-2}) led to higher ADL concentration followed by 32 plants m^{-2} while considerably lower value was obtained with smaller plant density (table 4.23). Cv. Goliath exhibited markedly higher ADL concentration in comparison with cv. Bovital in all three sowing times. There was no interaction between cultivar and PD regarding ADL concentration.

4.5.3 Anaerobic digestion

Biogas yield, methane concentration and methane yield

The biogas yield among different sowing times ranged from minimal 406 (2nd sowing) to maximal 566 nl kg VS^{-1} (3rd sowing) (table 4.24). Plant density had no clear impact on biogas yield of sorghum in all three sowing times. Cultivar altered biogas yield of sorghum in 2nd and 3rd sowing. Cv. Goliath reached significantly higher biogas yield than cv. Bovital in 2nd sowing time. Opposite trend was noticed in plots of 3rd sowing where cv. Bovital led to pronouncedly higher biogas yield in comparison with cv. Goliath. In first sowing time the study factor cultivar did not modify biogas yield but cv. Goliath produced 100 nl kg VS^{-1} of biogas more than cv. Bovital. Similarly methane yield was affected by PD in all sowing times.

Table 4.24: Effect of different cultivars (CV) and planting densities (PD) on biogas yield (BGY), methane yield (MY) and methane concentration (XM) of sorghum at different sowing times in Gross-Gerau 2009

CV	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		BGY	XM	MY	BGY	XM	MY	BGY	XM	MY
		nl/kg VS	% vol.	nl/kg VS	nl/kg VS	% vol.	nl/kg VS	nl/kg VS	% vol.	nl/kg VS
1		500a	54a	268a	456a	52a	240a	445b	53	236b
2		602a	53a	321a	356b	52a	187b	687a	53	368a
	1	608a	54a	326a	392a	53a	208a	619a	53	331a
	2	551a	53a	291a	397a	53a	209a	562a	54	302a
	3	495a	53a	265a	429a	52a	223a	517a	52	273a
Mean		551	53	294	406	53	213	566	53	302
$LSD_{0.05}$										
PD		ns	ns	ns	ns	ns	ns	ns	ns	ns
CV		ns	ns	ns	87	ns	48	112	ns	62
PD x CV		ns	ns	ns	ns	ns	84	ns	ns	ns

1st sowing = 14.05.2009, 2nd sowing = 10.06.2009, 3rd sowing = 23.06.2009, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2, vol. = volume

On the other hand cultivars had a clear effect on biogas yield in 2nd and 3rd sowing time. Cv. Goliath was characterized by higher methane yield as compared with cv. Bovital in 2nd sowing. Contrary to that in 3rd sowing cv. Bovital led to higher methane yield as compared with cv. Goliath (table 4.24). In 2nd sowing CV x PD interaction was observed regarding methane yield. Maximum methane yield was determined for cv. Goliath with higher plant density comparable to lower PD (same cultivar) followed by cv. Bovital in combination with medium PD. Cv. Bovital (higher and lower PD) and cv. Goliath with medium PD led to similar level of methane yield which was significantly lower (fig. 4.24). Methane concentration which was at a level of around 53 % was not influenced by cultivar as well as plant density in all three sowing times (table 4.24).

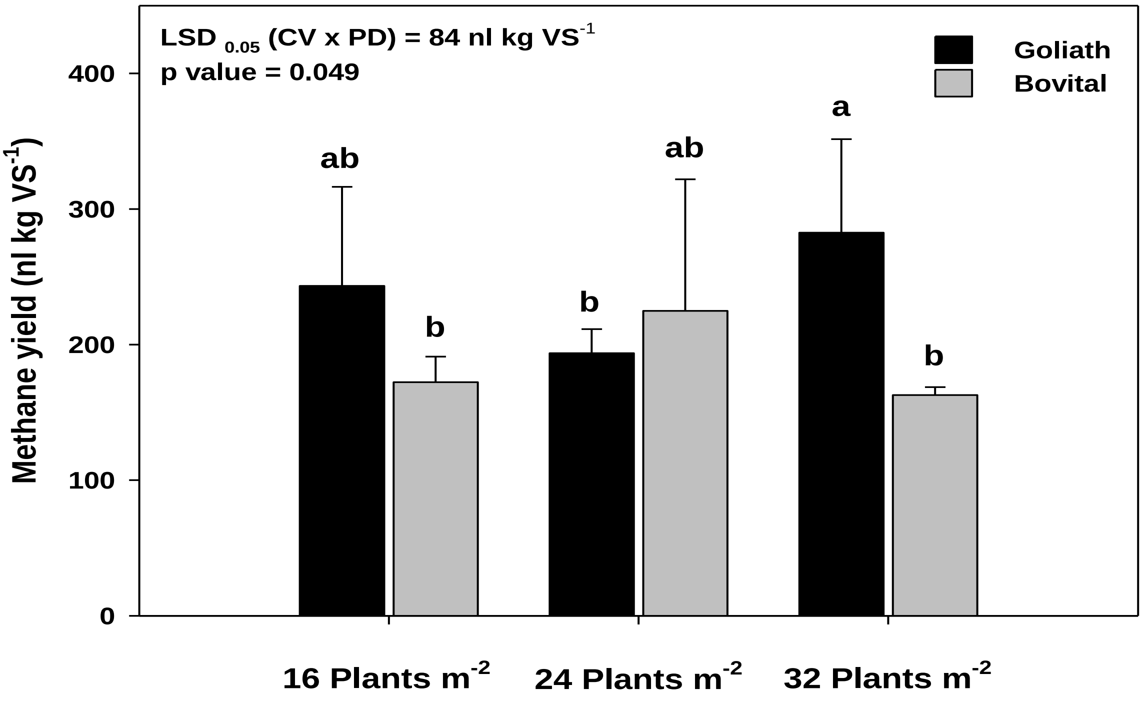

Fig. 4.24: Interaction between cultivars (CV) and plant density (PD) regarding methane yield (MY) of sorghum in 2nd sowing at experimental station Gross-Gerau 2009 (T = SD)

4.6 Plant density and sowing time experiment Rauischholzhausen 2009

4.6.1 Biomass yield and plant stand parameters

Tillers, dry matter concentration and dry matter yield

Within different sowing times the number of tillers plant^{-1} ranged from 2.1 (1st sowing) to 2.4 (3rd sowing). Plant density did not change the number of tillers per plant in all three sowing times. However lower plant density in all sowing times numerically increased number of tillers per plant (table 4.25). In addition the number of tillers per plant was significantly influenced by cultivar in all sowing times which are evaluated in the present study. Cv. Bovital reached higher number of tillers than cv. Goliath. All three plant densities showed same level of dry matter concentration in each sowing time. In first and 2nd sowing times dry matter concentration was not clearly affected by cultivar but higher DM concentration was observed with cv. Bovital as compared to cv. Goliath in 3rd sowing time (table 4.25). Dry matter yield within different sowing times varied between 10.06 (3rd sowing) and 14.91 t ha^{-1}. In first sowing higher and medium plant density led to similar dry matter yield while significantly lower yield was observed with smaller plant density. Both lower and medium plant densities reached the same level of dry matter yield whereas predominantly higher DM yield was exhibited by higher plant density in 2nd sowing time. Contrary to that in 3rd sowing time a comparable dry matter yield was determined for all three plant densities (table 4.25). In present executed trials cultivar affected dry matter yield in all sowing times. Cv. Goliath led to consistently higher dry matter yield in all three sowing times as compared to cv. Bovital (table 4.25).

Table 4.25: Effect of different cultivars (CV) and planting densities (PD) on tillers per plant, dry matter concentration (DMC) and dry matter yield (DMY) of sorghum at different sowing times in Rauischholzhausen 2009

CV	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		Tillers	DMC	DMY	Tillers	DMC	DMY	Tillers	DMC	DMY
		PL.$^{-1}$	%	t/ha	PL.$^{-1}$	%	t/ha	PL.$^{-1}$	%	t/ha
1		1.7b	21.6a	18.50a	1.8b	22.5a	16.25a	1.9b	23.1a	12.39a
2		2.4a	22.6a	11.33b	2.6a	23.0a	9.63b	2.8a	22.3a	7.73b
	1	2.3a	23.4a	13.06b	2.3a	23.6a	11.49b	2.5a	24.2a	9.02a
	2	2.0a	23.0a	15.46a	2.3a	22.5a	12.57b	2.3a	23.2a	11.15a
	3	1.9a	19.9a	16.23a	2.0a	22.2a	14.17a	2.3a	20.8b	10.01a
Mean		2.1	22.1	14.91	2.2	22.8	12.74	2.4	22.7	10.06
LSD$_{0.05}$										
PD		ns	ns	2.1	ns	ns	1.20	ns	1.6	ns
CV		0.4	ns	1.7	0.4	ns	0.98	0.5	ns	1.40
PD x CV		ns	ns	ns	ns	ns	ns	ns	ns	ns

1st sowing = 13.05.2009, 2nd sowing = 27.05.2009, 3rd sowing = 10.06.2009, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2, PL.$^{-1}$ = per plant

4.6.2 Data of NIRS analyses

Protein, sugar and ash concentration

It could be observed that the variation of protein, sugar and ash concentration within different sowing times was quite small (table 4.26). In first sowing plant density had a clear influence on protein concentration (p value = 0.007). Medium and lower plant densities showed similar protein concentration while significantly higher value was determined for higher plant density in 1st sowing.

Table 4.26: Effect of different cultivars (CV) and planting densities (PD) on protein (XP), sugar (XZ) and ash concentration (XA) of sorghum at different sowing times in Rauischholzhausen 2009

CV	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		XP	XZ	XA	XP	XZ	XA	XP	XZ	XA
		% DM	% DM	% DM	% DM	% DM	% DM	% DM	% DM	%DM
1		9.7b	15.4a	8.5b	9.4b	15.2a	8.4b	9.6b	14.7a	8.5a
2		11.8a	12.8b	9.1a	11.6a	13.4b	9.2a	11.8a	13.4a	9.4a
	1	10.0b	15.9a	8.4a	9.2a	17.0a	8.4a	9.3a	16.6a	8.4a
	2	10.4b	14.5a	8.7a	10.4a	15.3a	8.8a	10.7a	14.5a	8.9a
	3	11.8a	12.0a	9.3a	11.9a	10.5a	9.2a	12.0a	11.1a	9.6a
Mean		10.7	14.1	8.8	10.5	14.3	8.8	10.7	14.1	9.0
LSD$_{0.05}$										
PD		0.5	ns	ns	ns	ns	ns	ns	ns	ns
CV		0.4	1.3	0.5	0.4	1.3	0.2	0.6	ns	ns
PD x CV		ns	ns	ns	ns	ns	ns	ns	ns	ns

1st sowing = 13.05.2009, 2nd sowing = 27.05.2009, 3rd sowing = 10.06.2009, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2

Opposite to that in 2nd and 3rd sowing comparable averages of protein concentration were obtained with different plant densities evaluated in present experiments (table 4.26). On the other hand cultivar considerably modified the protein concentration where cv. Bovital reached higher protein concentration than cv. Goliath in all three sowing times. Data of present trials reveal that in each sowing time plant density did not affect the sugar concentration of sorghum. However cv. Goliath was characterized by higher sugar concentration in all three sowing times as compared with cv. Bovital (table 4.26). In all sowing times plant density had no impact on ash concentration. Cv. Goliath led to significantly lower ash concentration as compared to cv. Bovital in 1st and 2nd sowing while similar level of ash concentration was observed with both cultivars (table 4.26).

Acid detergent fiber, neutral detergent fiber and acid detergent lignin

Among different sowing times, averages of 36%, 51% and 4.8% DM were observed for ADF, NDF and ADL respectively (table 4.27). ADF concentration was not influenced by plant density in all three sowing times. Cultivar had no clear impact on ADF concentration in 1st sowing time. On the contrary in 2nd and 3rd sowing, cv. Goliath showed markedly higher ADF concentration than that of cv. Bovital (table 4.27). However a significant interaction (p value = 0.000) of CV x PD was observed regarding ADF concentration in 2nd sowing (fig. 4.27).

Table 4.27: Effect of different cultivars (CV) and planting densities (PD) on acid detergent fiber (ADF), neutral detergent fiber (NDF) and acid detergent lignin (ADL) concentration of sorghum at different sowing times in Rauischholzhausen 2009

CV	PD	1st sowing time			2nd sowing time			3rd Sowing time		
		ADF	NDF	ADL	ADF	NDF	ADL	ADF	NDF	ADL
		% DM	% DM	% DM	% DM	% DM	% DM	% DM	% DM	%DM
1		36.9a	52.1a	4.8a	37.3a	52.4a	5.0a	37.0a	52.6a	5.0a
2		35.3a	50.8a	4.7a	35.0b	50.5b	4.6b	34.7b	50.4a	4.6a
	1	35.6a	51.1a	4.7a	35.5a	51.1a	4.9a	36.0a	51.9a	4.9a
	2	36.0a	52.0a	4.8a	35.3a	51.1a	4.6b	35.2a	51.3a	4.8a
	3	36.8a	51.2a	4.6a	37.6a	52.1a	4.9a	36.3a	51.1a	4.7a
Mean		36.1	51.4	4.7	36.1	51.4	4.8	35.8	51.4	4.8
$LSD_{0.05}$										
PD		ns	ns	ns	ns	ns	ns	ns	ns	ns
CV		ns	ns	ns	0.6	0.6	0.2	1.4	ns	ns
PD x CV		ns	ns	ns	1.1	1.1	0.3	ns	ns	ns

1st sowing = 13.05.2009, 2nd sowing = 27.05.2009, 3rd sowing = 10.06.2009, CV 1 = cv. Goliath, CV 2 = cv. Bovital, PD 1 = 16 plants/m^2, PD 2 = 24 plants/m^2, PD 3 = 32 plants/m^2

With higher plant density cv. Goliath showed maximum ADF concentration whereas lowest value was exhibited by cv. Bovital in same level of plant density (fig. 4.25). Interestingly, interaction (p value = 0.000) of CV x PD with respect to NDF concentration showed similar trend where lowest NDF concentration was reached with cv. Bovital in higher plant density while highest value of NDF concentration was observed in cv. Goliath with same plant density (fig. 4.26). Maximal lignin concentration was observed with Cv. Goliath in higher plant density. Cv. Bovital with higher and medium plant and density led to same level of lignin concentration which was significantly lower (fig. 4.27).

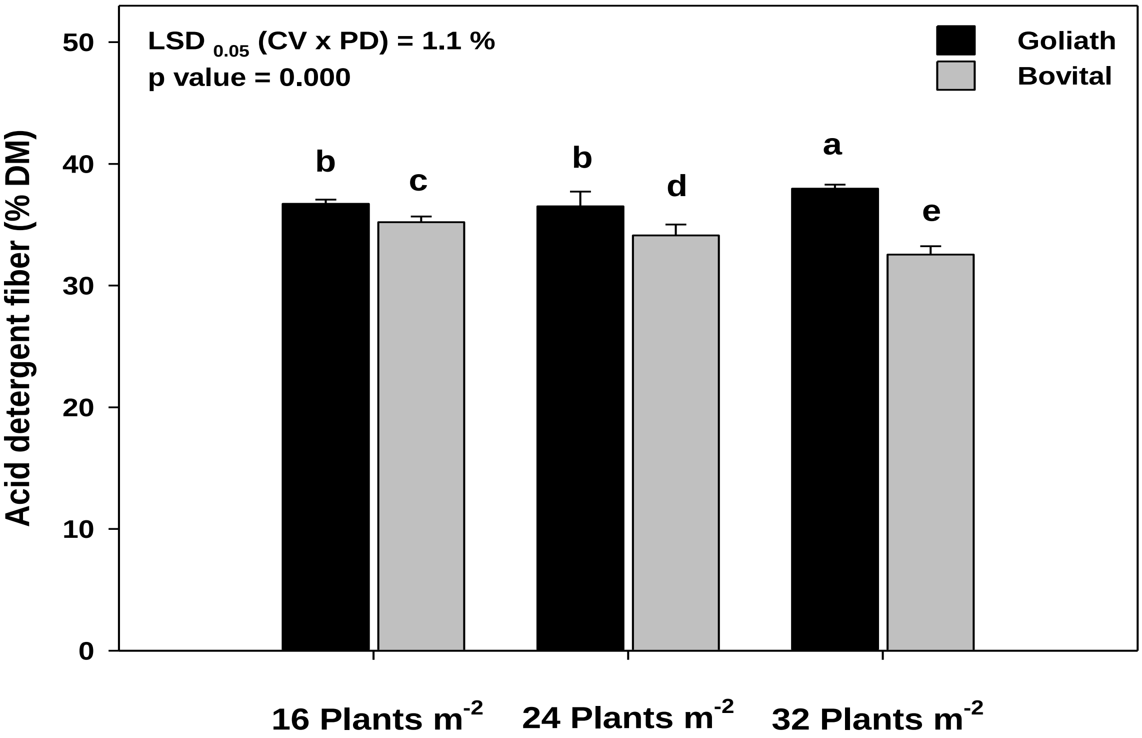

Fig. 4.25: Interaction between cultivars (CV) and plant density (PD) regarding acid detergent fiber concentration (ADF) of sorghum in 2nd sowing at experimental station Rauischholzhausen 2009 (T = SD)

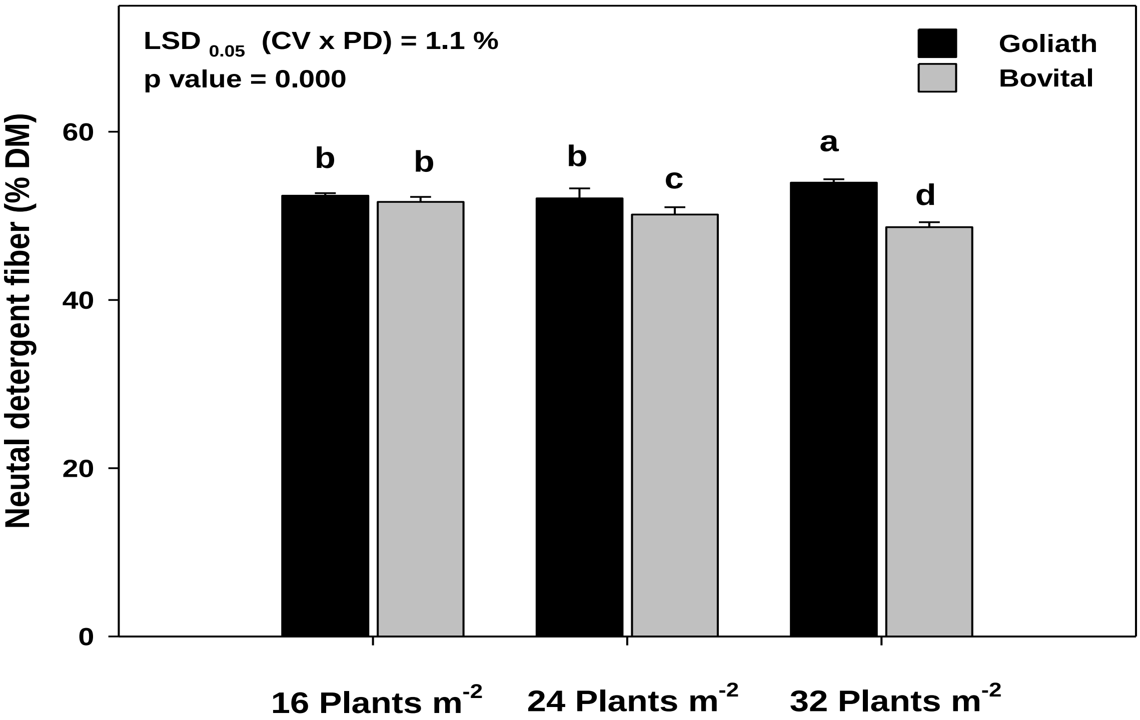

Fig. 4.26: Interaction between cultivars (CV) and plant density (PD) regarding neutral detergent fiber concentration (NDF) of sorghum in 2nd sowing at experimental station Rauischholzhausen 2009 (T = SD)

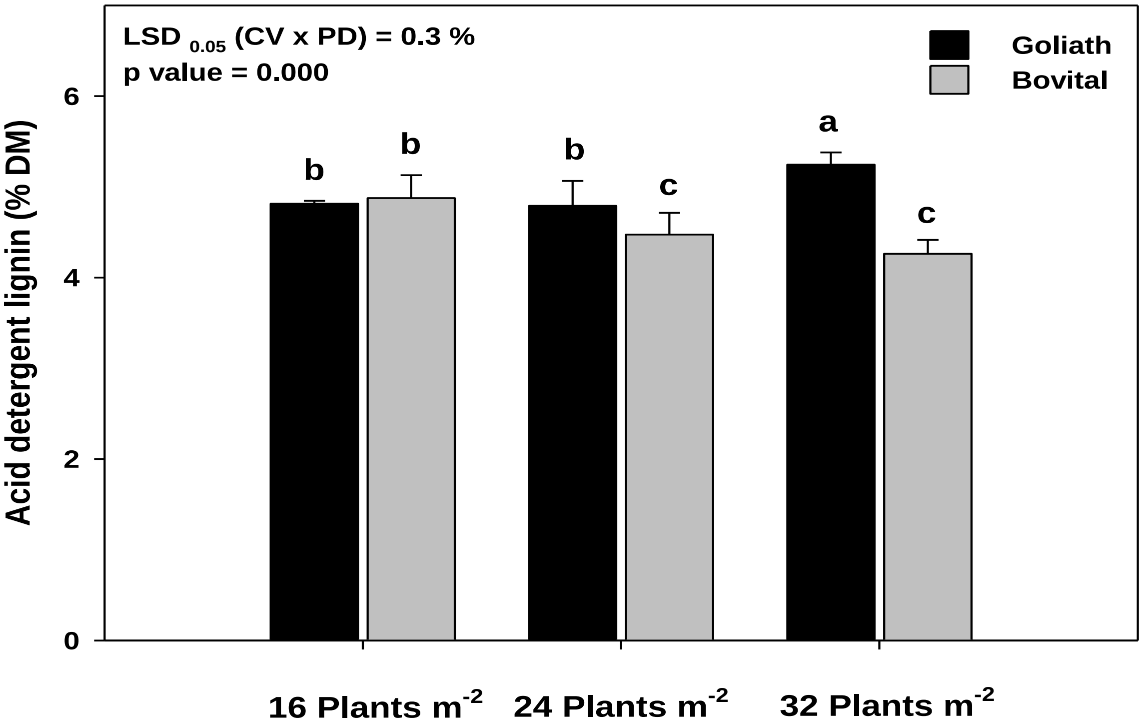

Fig. 4.27: Interaction between cultivars (CV) and plant density (PD) regarding acid detergent lignin concentration (ADL) of sorghum in 2nd sowing at experimental station Rauischholzhausen 2009 (T = SD)

4.7 Row spacing experiment Giessen 2008

4.7.1 Biomass and plant stand parameters

Leaf area index, plant height, number of tillers, dry matter concentration and dry matter yield

It could be observed that cv. Goliath reached a plant height of 364 cm while significantly lower value was observed with Bovital (284 cm) (table 4.28). The factor row spacing had a significantly effect on the plant height (p value = 0.035) of sorghum. There was a tendency toward higher plant height with narrow row spacing. Double row spacing (DR) and 37.5 cm led to comparable plant heights of 324 and 321 cm whereas significantly lower plant height of 311 cm was determined for 75 cm. Regarding plant height no interaction between cultivars and row spacing was observed.

The leaf area index (LAI) of sorghum plant stand ranged from 2.9 to 4.1 (30 days after germination) until 4.0 to 5.5 (60 days after germination) and 4.5 to 5.2 (90 days after germination) (table 4.28). The LAI difference between the tested cultivars was significantly only at 90 days after germination when Bovital reached higher LAI (5.0) than Goliath (4.7). The smallest row space of 37.5 cm led to increase of LAI in comparison with the other row spacing. This effect was observed at two measuring dates (30 and 60 days after germination). Cultivars and row spacing clearly influenced the numbers of tillers/m^2. Cv. Bovital produced significantly higher number of tillers/m^2 as compared to the cv. Goliath. It was observed that wider row space caused a significant decrease of the number of tillers/m^2.

Table 4.28: Effect of different row spacing (RS) and cultivars (CV) on leaf area index (LAI), plant height (Ph), tillers/m^2, dry matter concentration (DMC) and dry matter yield (DMY) of sorghum in Giessen 2008

RS	CV	LAI 1	LAI 2	LAI 3	Ph	Tillers/m^2	DMC	DMY
		m^2/m^2	m^2/m^2	m^2/m^2	cm	No.	%	t/ha
1		3.0b	4.4b	4.9ab	311b	28.5b	25.9a	15.04a
2		4.1a	5.5a	5.2a	322ab	45.7a	25.9a	16.50a
3		2.9b	4.0b	4.5b	324a	40.7ab	26.0a	17.00a
	1	3.6a	4.3a	4.7b	363a	31.3b	26.4a	19.72a
	2	3.1a	4.9a	5.0a	274b	45.4a	25.4a	12.64b
LSD $_{0.05}$								
RS		0.6	0.9	0.5	10	9	ns	ns
CV		ns	ns	0.4	8	12	ns	1.5
RS x CV		ns	ns	ns	ns	ns	2.0	ns

RS 1 = 75 cm, RS 2 = 37.5 cm, RS 3 = 75 cm (DR); double row 75 cm apart and 10-15 cm with in row, CV 1 = Goliath, CV 2 = Bovital, LAI 1 = 30 days after germination, LAI 2 = 60 days after germination, LAI 2 = 90 days after germination

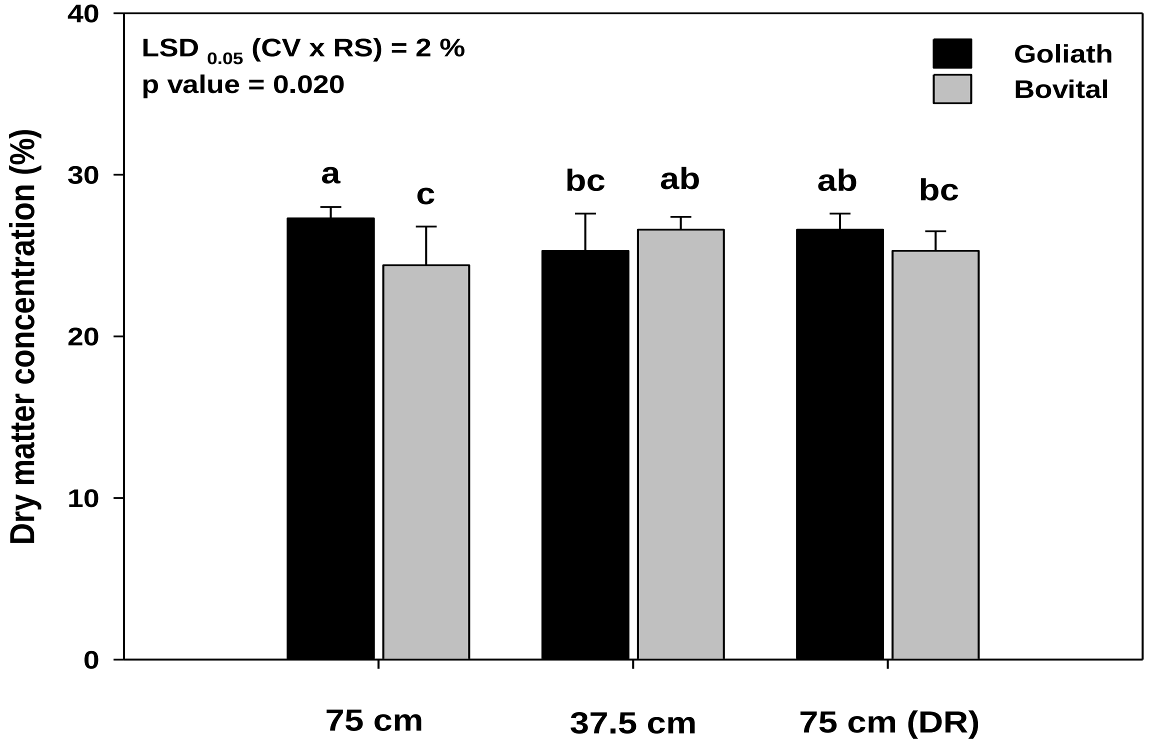

Fig. 4.28: Interaction between cultivars (CV) and row spacing (RS) regarding dry matter concentration (DMC) of sorghum at experimental station Giessen 2008 (T = SD)

The biomass yield of sorghum varied in the executed experiment from minimal 12.64 t DM/ha (cv. Bovital) until maximal 19.72 t DM/ha (cv. Goliath). Cv. Goliath reached significantly higher biomass yield than that of cv. Bovital. Row spacing had no clear effect on the dry matter yield. However, maximal dry matter yield was observed in narrow row spacing of 75 cm (DR) followed by 37.5 cm and minimum was obtained with wider row spacing of 75 cm. However regarding dry matter yield no significant interaction was noticed between cultivars and row spacing. DM percentage of the harvested biomass was about 25 to 26 % which was influenced neither by the cultivar nor by the row spacing. An interaction of cultivar x row spacing was observed with respect to dry matter concentration. Cv. Goliath reached highest DM concentration in wider row spacing while lowest was observed with cv. Bovital in same row spacing (fig. 4.28).

4.7.2 Data of NIRS analyses

Protein, sugar, acid detergent fiber, neutral detergent fiber, lignin, ash and lipid concentration

Protein concentration ranged from 8 to 9 % DM within row spacing and cultivars (table 4.29). It could be observed that row spacing had a clear effect on protein concentration (p value = 0.013). Row spacing of 37.5 cm and 75 cm (DR) led to comparable protein concentration while clearly lower value was determined for 75 cm. The tested cultivars altered the protein concentration in their biomass. Cv. Bovital exhibited higher protein concentration as compared to Goliath. Sugar concentration was not influenced by row spacing. Cv. Bovital was characterized by lower sugar concentration (4.6 %) while considerably higher value (7.4 %) was found with cv. Goliath. The ash concentration of sorghum varied between around 7.8 to 8.3% (table 4.29). There was an effect of the tested cultivars on ash concentration with maximal ash concentration in cv. Bovital as compared to cv. Goliath. No interactions of cultivar x row spacing were found for sugar, protein and ash concentration. It was observed that ADF concentration was similar in all three row spacing. Higher ADF concentration was determined for cv. Goliath as compared with cv. Bovital. However row spacing did not influence NDF concentration. In present executed trial row spacing had no clear effect on NDF concentration.

Table 4.29: Effect of different row spacing (RS) and cultivars (CV) on protein (XP), sugar (XZ) acid detergent fiber (ADF), neutral detergent fiber (NDF), acid detergent lignin (ADL), Ash (XA) and lipid (XL) concentration of sorghum in Giessen 2008

RS	CV	XP	XZ	ADF	NDF	ADL	XA	XL
		% DM	% DM	% DM	% DM	% DM	% DM	% DM
1		7.5b	5.9a	39.0a	61.8a	5.6a	8.1a	1.3a
2		8.1a	6.3a	39.7a	61.3a	5.8a	8.1a	1.4a
3		8.3a	5.9a	38.7a	60.7a	5.6a	8.1a	1.4a
	1	6.9b	7.4a	42.5a	63.6a	6.3a	7.9b	1.2b
	2	9.0a	4.6b	35.8b	58.9b	5.0b	8.3a	1.6a
LSD $_{0.05}$								
RS		0.6	ns	ns	ns	ns	ns	ns
CV		0.4	1.0	1.1	1.2	0.2	0.3	0.2
RS x CV		ns	ns	ns	ns	ns	ns	ns

RS 1 = 75 cm, RS 2 = 37.5 cm, RS 3 = 75 (DR); double row 75 cm apart and 10-15 cm with in row, CV 1 = Goliath, CV 2 = Bovital

All three row spacing led to comparable values of NDF concentration ranged from 60.7 to 61.8 % (table 4.29). Cultivars induced a change of NDF concentration. Cv. Bovital showed lower value of NDF concentration (58.9 %) as compared with Goliath (63.6 %). Row spacing had no clear impact on lignin concentration. Cv. Bovital was characterized by a lignin concentration of 5.0 % while considerably higher value (6.3 %) was determined with cv. Goliath.

4.8 Row spacing experiment Gross-Gerau 2008

4.8.1 Biomass and plant stand parameters

Dry matter concentration and dry matter yield and organ portioning (% DM)

Within cultivars biomass yield ranged from 9.9 (cv. Bovital) to 15.04 t/ha (cv. Goliath). Cultivars significantly affected dry matter yield of sorghum. Cv. Goliath reached considerably higher dry matter yield of as compared with cv. Bovital. However, row spacing did not affect DM yield. Cultivars had clear impact on DM concentration of biomass, ranging from 22 to 25 % (table 4.30). Cv. Bovital produced considerably higher concentration of dry matter in comparison with cv. Goliath. There was no interaction with respect to DM concentration as well as for DM yield. Stem dry matter proportion which ranged from 57 to 70 % had greater proportion within the whole biomass followed by the leaf 22 to 24 % and panicles proportion from 7 to 21 % (table 4.30).

Table 4.30: Effect of different row spacing (RS) and cultivars (CV) on dry matter concentration (DMC), dry matter yield (DMY) and organ portioning (% DM) of sorghum in Gross-Gerau 2008

RS	CV	DMC	DMY	Leaves	Stems	Panicles
		%	t/ha	Organ partioning (% DM)		
1		23.3a	12.02a	23.1a	63.2a	13.8a
2		23.9a	12.56a	22.6a	63.8a	13.6a
3		23.9a	12.89a	21.8a	63.4a	14.8a
	1	22.3b	15.04a	23.5a	69.9a	6.6b
	2	25.1a	9.94b	21.5a	57.0b	21.5a
LSD $_{0.05}$						
RS		ns	ns	ns	ns	ns
CV		0.9	1.64	ns	2.0	3.8
RS x CV		ns	ns	ns	ns	ns

RS 1 = 75 cm, RS 2 = 37.5 cm, RS 3 = 75 (DR); double row 75 cm apart and 10-15 cm with in row, CV 1 = Goliath, CV 2 = Bovital

It could be found that cv. Goliath had considerably higher dry matter proportion of stem than that of cv. Bovital. Row spacing of 37.5 cm induced a greater stem dry matter proportion while considerably lower value was reached by 75 cm (DR). Early maturing cv. Bovital had higher proportion of panicles as compared to cv. Goliath (late maturing). Row spacing had no significant effect on dry matter proportion of leaf. Leaf dry matter proportion was affected neither by cultivars nor the row spacing (table 4.30).

4.8.2 Data of NIRS analyses

Protein, sugar, acid detergent fiber, neutral detergent fiber, lignin, ash concentration

Protein concentration within different row spacing and cultivar ranged from 7 to 8% of DM (table 4.31). It was observed that cultivars affected the protein concentration of sorghum. Protein concentration was significantly higher in cv. Bovital than that of cv. Goliath. However, protein concentration was not affected by row spacing. Interaction was not observed between cultivar and row spacing regarding protein concentration. It could be found that cultivars showed significant variation with respect to sugar concentration. Cv. Bovital produced a higher sugar concentration as compared to cv. Goliath. However row spacing showed comparable averages ranged from 8.6 to 9.6 % (table 4.31). Cultivars had a clear impact on ADF concentration (p value = 0.000). Higher ADF concentration was determined with cv. Goliath as compared to cv. Bovital. All three tested row spacing led to similar means regarding ADF concentration. There was no row spacing x cultivars interaction for ADF concentration. Interaction (row spacing x cultivars) was observed with respect to NDF concentration of sorghum. Cv. Goliath induced a significantly higher concentration of 64 % NDF in wider row spacing. Cv. Bovital shows considerably lower levels of NDF concentration ranged from 52 to 54 % which were significantly lower (Fig. 4.29).

Table 4.31: Effect of different row spacing (RS) and cultivars (CV) on protein (XP), sugar (XZ), acid detergent fiber (ADF), neutral detergent fiber (NDF), acid detergent lignin (ADL) and ash (XA) of sorghum in Gross-Gerau 2008

RS	CV	XP	XZ	ADF	NDF	ADL	XA
		% DM	% DM	% DM	% DM	% DM	% DM
1		7.8a	8.6a	38.5a	58.7a	5.1a	8.2a
2		7.8a	9.6a	37.3a	56.4a	4.6b	8.4a
3		7.9a	9.1a	37.8a	58.2a	5.0a	7.8b
	1	7.3b	7.2b	41.6a	61.5b	5.3a	8.3a
	2	8.4a	11.1a	34.1b	54.0a	4.5b	8.0b
LSD $_{0.05}$							
RS		ns	ns	ns	ns	0.3	0.3
CV		0.9	1.7	1.5	1.8	0.3	0.3
RS x CV		ns	ns	ns	3.1	ns	ns

RS 1 = 75 cm, RS 2 = 37.5 cm, RS 3 = 75 (DR); double row 75 cm apart and 10-15 cm with in row, CV 1 = Goliath, CV 2 = Bovital

The lignin concentration ranged from 4.5 to 5.3 % DM (table 4.31). Cultivars significantly modified the lignin concentration (p value = 0.000) of sorghum. Cv. Goliath led to higher value of 5.3 % lignin concentration while considerably lower value of 4.5 % was determined with Bovital.

Row spacing of 75 cm and 75 cm (DR) led to increase the lignin concentration as compared to 37.5 cm. There was no interaction (row spacing x cultivar) regarding lignin concentration of sorghum. Cultivars had no clear effect on ash concentration. On the other hand row spacing had significant effect on ash concentration. It could be observed that row spacing of 37.5 cm and 75 cm exhibited comparable concentration of ash while considerably lower value was determined with 75 cm (DR).

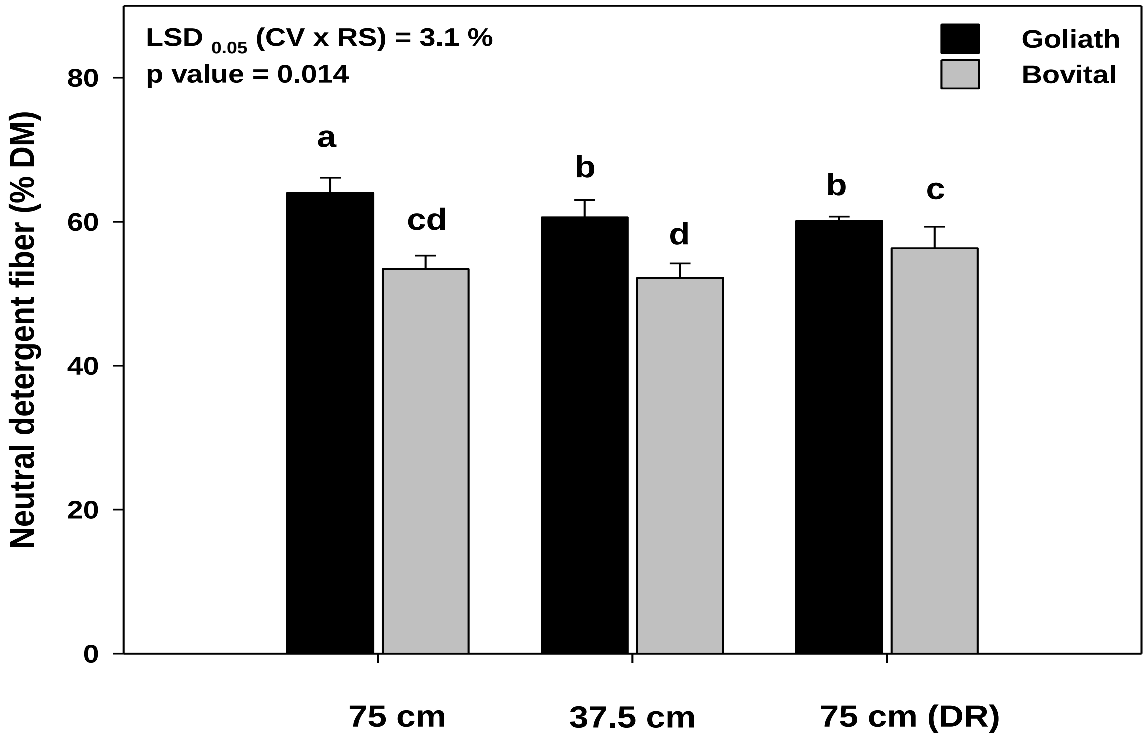

Fig. 4.29: Interaction between cultivars (CV) and row spacing (RS) regarding neutral detergent fiber concentration (NDF) of sorghum at experimental station Gross-Gerau 2008 (T = SD)

4.8.3 Anaerobic digestion

Biogas yield, methane concentration and methane yield

Within row spacing and cultivars specific biogas yields ranged from 553 to 600 l_N kg Vs^{-1} (table 4.32). In present trial specific biogas yield was affected neither by cultivars nor the row spacing. However cv. Goliath (586 l_N kg Vs^{-1}) led to slightly higher specific biogas yield as compared to cv. Bovital. It was observed that there were no significant differences within the study factor row spacing. However, row spacing of 37.5 cm produced lower biogas yield as compared with other row spacing. It was found that specific methane yield was not affected by cultivars. Methane concentration of the samples varied between 54 to 55 % (table 4.32). Cultivar had a clear effect on methane concentration (p value = 0.017). Cv. Goliath produced significantly higher methane concentration than that of cv. Bovital. However row spacing did not modified methane concentration. No interaction was found between row spacing and cultivars. Analyses of variance reveal that biogas and methane yield ha^{-1} was modified by cultivars. The biogas yield varied between 5358 (cv. Bovital) and 8260 m^3_N ha^{-1} (table 4.32). Higher yields of biogas and methane ha^{-1} were determined with Goliath as compared to cv. Bovital (tab. 4.32). Row spacing had no significant effect on biogas and methane yield.

Table 4.32: Effect of row spacing (RS) and cultivars (CV) on biogas, specific methane yield, and methane concentration of sorghum in Gross-Gerau 2008

RS	CV	Biogas	Methane	Biogas	Methane	Methane
		l_N/kg VS	l_N/kg VS	m^3_N/ha	m^3_N/ha	%
1		600a	326a	6884a	3741a	54a
2		553a	299a	6504a	3522a	54a
3		570a	307a	7038a	3782a	54a
	1	586a	320a	8260a	4493a	55a
	2	563a	302a	5358b	2870b	54b
LSD $_{0.05}$						
RS		ns	ns	ns	ns	ns
CV		ns	ns	1070	575	0.8
RS x CV		ns	ns	ns	ns	ns

RS 1 = 75 cm, RS 2 = 37.5 cm, RS 3 = 75 (DR); double row 75 cm apart and 10-15 cm with in row, CV 1 = Goliath, CV 2 = Bovital

4.9 Row spacing experiment Giessen 2009

4.9.1 Biomass yield and plant stand parameters

Leaf area index, number of tillers and plant height

The leaf area index (LAI) of sorghum plant stand ranged from 2.1 to 3.2 (30 days after germination) until 3.9 to 4.7 (60 days after germination) and 4.3 to 5.1 (90 days after germination) (table 4.33). The LAI difference between cv. Goliath and Bovital was small and not significant. Among five tested cultivars the lowest LAI was observed in Akklimat at all three measuring dates. The LAI of this cultivar reached only the level of 2.1 (30 DAG), 3.9 (60 DAG) and 4.3 (90 DAG), which was significantly lower in comparison with the LAI of the other cultivars.

Table 4.33: Effect of different row spacing (RS) and cultivars (CV) on leaf area index (LAI), tillers/m^2, and plant height (Ph) of sorghum in Giessen 2009

RS	CV	LAI 1	LAI 2	LAI 3	Tillers/m^2	Ph
		m^2/m^2	m^2/m^2	m^2/m^2	No.	cm
1		2.9a	4.4a	4.3b	43b	238a
2		2.8a	4.7a	5.1a	55a	243a
3		3.0a	4.5a	4.8a	55a	241a
	1	3.2a	4.6a	4.7ab	31c	262a
	2	3.2a	4.7a	4.9a	43b	248b
	3	2.9a	4.7a	4.9a	34bc	225c
	4	3.2a	4.7a	4.8a	36bc	235c
	5	2.1b	3.9b	4.3b	111a	232c
LSD $_{0.05}$						
RS		ns	ns	0.3	8	ns
CV		0.4	0.5	0.4	10	11
RS x CV		ns	ns	ns	ns	ns

RS 1 = 75 cm, RS 2 = 37.5 cm, RS 3 = 75 (DR); double row 75 cm apart and 10-15 cm with in row, CV 1 = Goliath, CV 2 = Bovital, CV 3 = Aron, CV 4 = Rona-1, CV 5 = Akklimat, LAI 1 = 30 days after germination, LAI 2 = 60 days after germination, LAI 2 = 90 days after germination

The smallest row space of 37.5 cm led to increase the LAI in comparison with the other row spacing. This effect was observed at one measuring date (90 days after germination) (table 4.33).
Maximal plant heights were observed with Goliath (262 cm) followed by Bovital (248 cm) and the other three cultivars Aron, Rona 1 and Akklimat (225, 235 and 231 cm) respectively (table 4.33). Row spacing had no clear effect on the plant height of sorghum. Regarding plant height no interaction between cultivars and row spacing was observed. Cultivars and row spacing clearly influenced the numbers of tillers/m^2. Cv. Akklimat led to higher number of tillers/m^2 followed by cv. Bovital as compared to the other tested cultivars in present experiment. It was observed that wider row spacing caused a significant decrease of the number of tillers/m^2 (table 4.33).

Dry matter concentration and dry matter yield and organ portioning (% DM)

The biomass yield of sorghum varied from minimal 10.10 to maximal 15.81 t DM/ha (table 4.34). Cv. Goliath reached significantly higher biomass yield than the compared cultivars (table 4.34). Cv. Bovital and Rona 1 had the same level of biomass yields followed by cv. Aron and Akklimat, which yields were significantly lower. Row spacing had clear impact on the dry matter yield (p value = 0.000). Narrow row spacing of 75 cm (DR) and 37.5 cm led to significantly higher biomass yield than wider row spacing of 75 cm (table 4.34). However regarding dry matter yield no significant interaction was noticed between cultivars and row spacing. Cv. Goliath and Bovital had nearly the same DM percentage but significantly lower dry matter concentration was observed with Aron and Rona 1 whereas cv. Akklimat reached nearly the same DM percentage like cv. Goliath and Bovital. Row spacing did not affect the DM concentration of sorghum biomass and no interaction of cultivar x row spacing was observed. Stem dry matter percentage which ranged from 54 until 66 % had the highest proportion within the whole biomass followed by the proportion of panicles (13 – 29%) and leaves (16 – 21%) (table 4.34).

Table 4.34: Effect of different row spacing (RS) and cultivars (CV) on dry matter concentration (DMC), dry matter yield (DMY) and organ portioning (% DM) of sorghum in Giessen 2009

RS	CV	DMC	DMY	Leaves	Stems	Panicles
		%	t/ha	Organ partioning (% DM)		
1		24.3a	10.24b	17.6b	58.9b	23.5a
2		24.9a	12.72a	18.8a	60.3a	20.9a
3		25.6a	13.47a	17.4b	61.2b	21.4a
	Goliath	26.3a	15.81a	21.3a	66.0a	12.7d
	Bovital	26.9a	12.26b	16.5cd	54.1c	29.4a
	Aron	22.0b	10.19c	18.6b	61.3a	20.1c
	Rona-1	23.8b	12.36b	16.0d	60.7a	23.3c
	Akklimat	25.7a	10.10c	17.4c	58.5b	24.1b
LSD $_{0.05}$						
RS		ns	1.47	0.9	ns	ns
CV		1.8	1.90	1.2	2.8	3.1
RS x CV		ns	ns	ns	ns	ns

RS 1 = 75 cm, RS 2 = 37.5 cm, RS 3 = 75 (DR) ; double row 75 cm apart and 10-15 cm with in row

The biomass of cv. Goliath had the highest proportion of stems (66 %) while lowest was observed with Bovital (54.1%). The different row spacing evaluated in this study had no significant effect on relative proportion of stem as well as panicle DM. However it could be observed that cultivars altered the relative proportion of the panicle. Early maturing cv. Bovital induced higher relative proportion of panicle whereas late maturing cv. Goliath had lowest among the cultivars. There were main effects of different row spacing and cultivars on the relative proportion of leaf dry matter. Cv. Goliath produced considerably higher relative leaf proportion whereas Rona 1 exhibited the minimum value (table 4.34). Row spacing of 37.5 cm caused an increase of leaf relative proportion in comparison with 75 cm and double row 75 cm apart and 10-15 cm with in row.

4.9.2 Data of NIRS analyses

Protein, sugar, acid detergent fiber, neutral detergent fiber, lignin and ash concentration

The protein concentration ranged from 9 to 11 % (table 4.35). A similar concentration of protein was determined for both 75 cm and 75 cm (DR), while significantly higher concentration was observed with 37.5 cm spacing. The tested cultivars had clear impact on protein concentration (p value = 0.000) in their biomass. Cv. Akklimat produced a protein concentration of 10.6% which was considerably highest among the cultivars. It could be observed that an average sugar concentration of 12.8, 10.7 and 12.3 g/100 g of DM were determined for 75 cm, 37.5 cm and 75 (D.R) respectively (table 4.35). Cv. Rona 1 reached maximum value of sugar concentration (18.7 %) comparable to cv. Aron which were clearly higher in comparison with other tested cultivars. Comparable ADF concentration of 33.3 and 33.5 was observed with 75 cm and 37.5 respectively, while significantly lower ADF concentration of 32.4 g/100 g DM was exhibited by 75 cm (D.R). Row spacing of 75 cm row spacing caused an increase of lignin concentration as compared to other row spacing. Cv. Goliath showed higher value of ADF concentration, comparable to Akklimat, whereas minimum ADF content was observed with Rona 1.

Table 4.35: Effect of different row spacing (RS) and cultivars (CV) on protein (XP), sugar (XZ), acid detergent fiber (ADF), neutral detergent fiber (NDF), acid detergent lignin (ADL) and ash (XA) of sorghum in Giessen 2009

RS	CV	XP	XZ	ADF	NDF	ADL	XA
		% DM	% DM	% DM	% DM	% DM	% DM
1		9.6b	12.8a	33.3a	53.2b	5.0b	8.8a
2		10.2a	10.7b	33.5a	56.4a	5.4a	9.0a
3		9.6b	12.3a	32.4b	56.7a	5.3ab	9.0a
	Goliath	8.9c	10.9b	37.8a	58.4ab	5.6b	8.8c
	Bovital	10.0b	6.4c	34.9b	56.7b	5.3c	9.3b
	Aron	10.0b	17.9a	28.3c	51.5c	4.9d	8.3d
	Rona-1	9.5b	18.7a	27.6c	50.8c	4.3e	7.8e
	Akklimat	10.6a	5.8c	36.8a	59.9a	6.2a	10.6a
LSD $_{0.05}$							
RS		0.3	1.3	0.9	1.6	0.2	ns
CV		0.5	1.7	1.2	2.1	0.3	0.4
RS x CV		ns	ns	ns	ns	ns	ns

RS 1 = 75 cm, RS 2 = 37.5 cm, RS 3 = 75 (DR); double row 75 cm apart and 10-15 cm with in row

It could be found that row spacing of 75 cm (D.R) led to comparable NDF concentration with 37.5 cm row spacing but considerably higher than 75 cm. Cv. Rona 1 and Aron showed similar NDF concentration while markedly higher value was determined for cv. Akklimat followed by Goliath. Cultivars had significant effect on lignin concentration (table 4.35). Cv. Akklimat produced maximum lignin concentration in comparison with the other tested cultivars. The ash concentration of sorghum varied between around 8 and 11%. There was an effect of the tested cultivars on ash concentration with maximal ash concentration in cv. Akklimat.

4.10 Row spacing experiment Gross-Gerau 2009

4.10.1 Biomass yield and plant stand parameters

Dry matter concentration and dry matter yield and organ portioning (% DM)

Dry matter yield ranged between 12 and 21 t/ha (table 4.36). In executed trial cultivar caused a clear change in dry matter yield (p value = 0.000). Cv. Aron and Rona 1 produced similar dry matter yields followed by cv. Bovital whereas minimum value was exhibited by cv. Akklimat (table 4.36). However, DM yield was not affected by row spacing. Cv. Bovital had the higher level of dry matter concentrations followed by cv. Goliath, Akklimat, Rona 1 and Aron, which concentrations were significantly lower than cv. Bovital. It could be observed that row spacing had no effect on dry matter concentration of sorghum. Interaction (row spacing x cultivar) was not observed regarding DM concentration as well as DM yield. Stem dry matter proportion which ranged from 69 to 77 % had greater proportion within the whole biomass followed by the leaf 16 to 19 % and panicles proportion from 4 to 15 % (table 4.36). It was found that cv. Goliath had highest dry matter proportion of stem while significantly lowest was observed with cv. Bovital among the tested cultivars.

Table 4.36: Effect of different row spacing (RS) and cultivars (CV) on dry matter concentration (DMC), dry matter yield (DMY) and organ portioning (% DM) of sorghum in Gross-Gerau 2009

RS	CV	DMC	DMY	Leaf	Stem	Panicle
		%	t/ha	Organ partioning (% DM)		
1		27.3a	16.03a	17.4ab	70.2a	12.4a
2		26.1b	16.40a	18.0a	71.1a	10.8b
3		27.4a	16.35a	16.9b	70.7a	12.4a
	Goliath	28.3b	20.84a	19.0a	77.0a	4.0e
	Bovital	30.2a	14.81c	17.5b	63.6d	18.9a
	Aron	22.8d	16.67b	18.0ab	72.4b	9.6d
	Rona-1	24.8c	16.91b	16.6bc	71.6b	11.8c
	Akklimat	28.5b	12.07d	16.0c	68.9c	15.1b
LSD $_{0.05}$						
RS		1.1	ns	0.9	ns	0.9
CV		14	0.93	1.1	1.3	1.2
RS x CV		ns	ns	ns	ns	ns

RS 1 = 75 cm, RS 2 = 37.5 cm, RS 3 = 75 (DR); double row 75 cm apart and 10-15 cm with in row

Early maturing cv. Bovital caused an increase of dry matter proportion of panicles while markedly lowest value was exhibited by cv. Goliath (late maturing) among the tested cultivars. Row spacing influenced the dry matter proportion of panicle. Cultivars and row spacing had clear effect on dry matter proportion of the leaves. Cv.

Goliath produced markedly greater leaf dry matter proportion among the tested cultivars followed by Aron. Cv. Bovital, Rona 1 and Akklimat had similar level of leaf dry matter proportions, which were significantly lower than cv. Goliath (table 4.36).

4.10.2 Data of NIRS analyses

Protein, sugar, acid detergent fiber, neutral detergent fiber, lignin and ash concentration

In present study protein concentration within tested cultivars varied from 6 to 8% (table 4.37). Cv. Akklimat had highest protein concentration followed by cv. Bovital whereas lowest was observed with Goliath among the tested cultivars. Row spacing significantly altered protein concentration (p value = 0.023). Row spacing of 37.5 cm and 75 cm led to similar protein concentration whereas significantly lower value was found in 75 cm (DR) row spacing. There was no cultivar x row spacing interaction for protein concentration. The concentration of sugar was ranged from 6 to 13 % of DM (table 4.37). Interaction was found between row spacing and the tested cultivars regarding sugar concentration. Cv. Aron with row spacing of 37.5 cm showed markedly higher sugar concentration followed by 75 cm (DR) with same cultivar (Aron). Cv. Akklimat in combination with 37.5 cm caused a decline of sugar concentration (Fig. 4.30). Ash concentration (p value = 0.000) was significantly affected by cultivar. It was found that cv. Rona 1 induced a lower ash concentration while cv. Goliath, Akklimat, Aron and cv. Bovital led to comparable values. However, row spacing did not cause change in ash concentration of sorghum.

Table 4.37: Effect of different row spacing (RS) and cultivars (CV) on protein (XP), sugar (XZ), acid detergent fiber (ADF), neutral detergent fiber (NDF), acid detergent lignin (ADL) and ash (XA) of sorghum in Gross-Gerau 2009

RS	CV	XP	XZ	ADF	NDF	ADL	XA
		% DM	% DM	% DM	% DM	% DM	% DM
1		7.5a	9.8a	33.0b	54.7a	4.6a	7.5a
2		7.3ab	9.8a	34.4a	55.5a	4.6a	7.7a
3		7.2b	9.0b	34.0a	55.6a	4.5a	7.2a
	Goliath	6.3d	11.2b	38.7a	58.0b	5.3a	7.9a
	Bovital	7.6b	6.5c	33.7c	56.0c	4.5b	7.7a
	Aron	7.2c	13.4a	31.8d	52.3d	4.4b	7.6a
	Rona-1	7.5bc	10.7b	28.4e	50.3e	3.1c	6.2b
	Akklimat	8.0a	6.0c	36.4b	59.6a	5.5a	8.1a
LSD $_{0.05}$							
RS		0.2	0.5	0.9	ns	ns	ns
CV		0.3	0.7	1.1	1.1	0.4	0.6
RS x CV		ns	1.2	ns	2.0	ns	ns

RS 1 = 75 cm, RS 2 = 37.5 cm, RS 3 = 75 (DR); double row 75 cm apart and 10-15 cm with in row

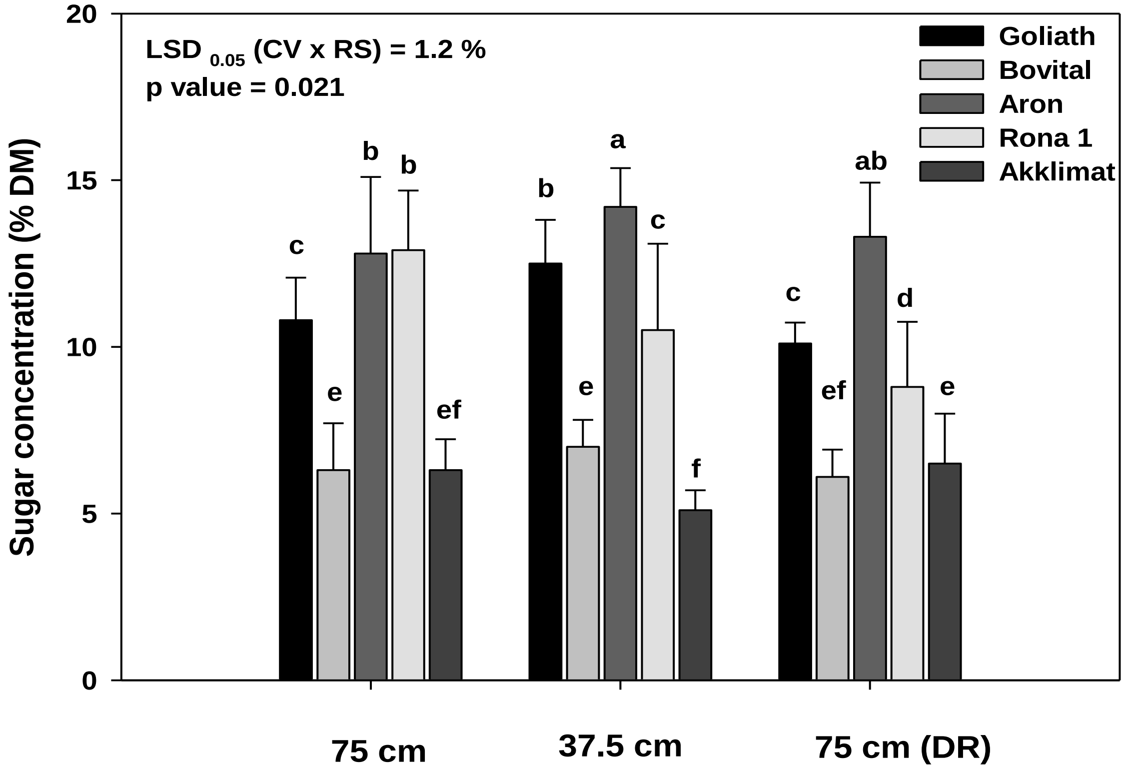

Fig. 4.30: Interaction between cultivars (CV) and row spacing (RS) regarding sugar concentration (XZ) of sorghum at experimental station Gross-Gerau 2009 (T = SD)

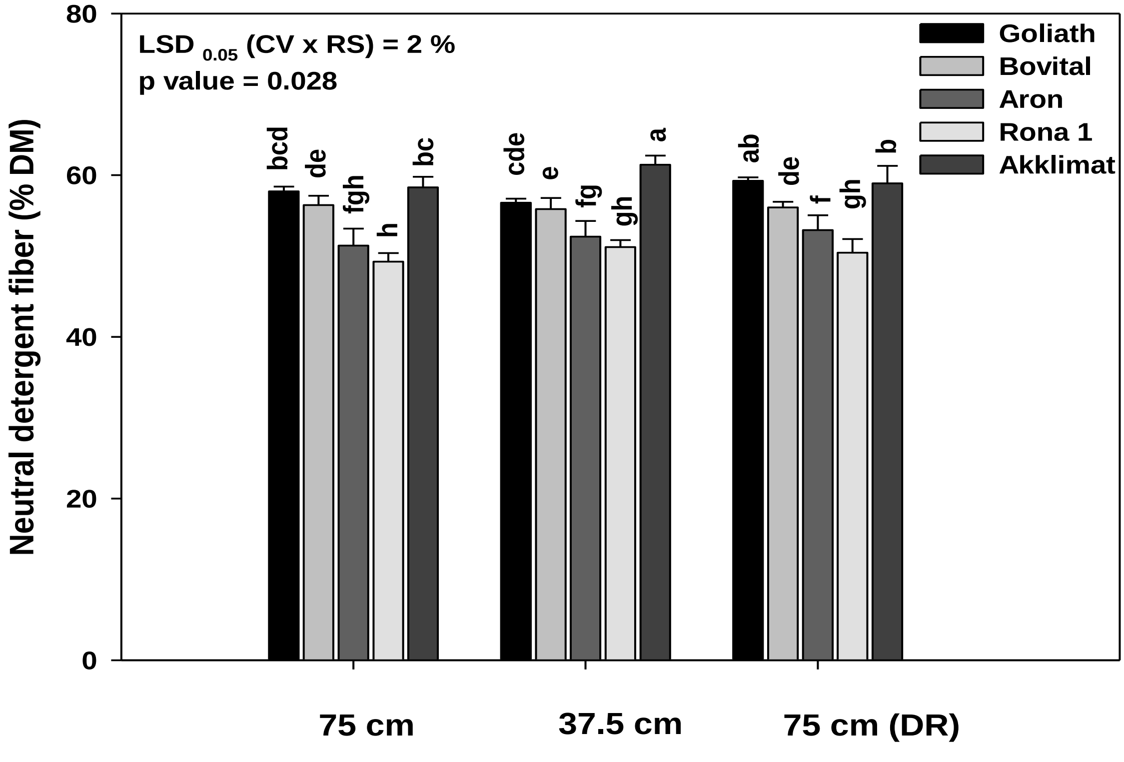

Fig. 4.31: Interaction between cultivars (CV) and row spacing (RS) regarding neutral detergent fiber concentration (NDF) of sorghum at experimental station Gross-Gerau 2009 (T = SD)

Maximal ADF concentration was determined with cv. Goliath while considerably lower values were exhibited by cv. Rona 1. ADF concentration (p value = 0.014) was markedly affected by row spacing. There was a tendency of higher ADF concentration with narrow row spacing. Row spacing of 37.5 cm and 75 cm (DR) led to clearly higher ADF concentration in comparison with 75 cm row spacing. There was no row spacing x cultivar interaction with respect to ADF concentration. Interaction (row spacing x cultivars) was observed regarding NDF concentration. Cv. Akklimat caused an increase of NDF concentration in 37.5 cm row spacing followed by Goliath with 75 cm (DR) whereas minimum value of 49 % was determined by Rona 1 in combination with 75 cm (fig. 4.31). Lignin concentration was clearly affected by cultivars which were evaluated in the experiment. Cv. Goliath caused an increase of lignin concentration at same level with cv. Akklimat in comparison with cultivars tested in the experiment. Cv. Bovital and Aron had same level of lignin concentration followed by cv. Rona 1, which concentration was significantly lower than other cultivars. Comparable averages of 4.6 % were determined for all row spacing evaluated in experiments (tab. 4.37). No interaction was noticed between row spacing and cultivars.

4.10.3 Anaerobic digestion

Biogas yield, methane concentration and methane yield

A range of 415 to 721 l_N per kg VS of specific biogas concentration have been observed in present experiment (4.38). Cultivars predominantly influenced the specific biogas yield (p value = 0.000) of sorghum. Cv. Rona 1 induced a higher specific biogas yield (720 l_N kg Vs^{-1}) as compared to the other tested cultivars. Cv. Aron and Bovital had same level of specific biogas yield followed by cv. Goliath and Akklimat, which yields were significantly lower (table 4.38). It could be observed that cultivars had clear impact on the specific methane yield of sorghum. Data shows that specific methane yields varied from minimal 232 to maximal 387 l_N kg Vs^{-1}. Cv. Rona 1 produced a markedly higher specific methane yield followed by cv. Aron while minimum was observed with cv. Akklimat among the used cultivars. Row spacing did not affect the specific methane concentration. There was no interaction between cultivars and row spacing.

Table 4.38: Effect of row spacing (RS) and cultivars (CV) on biogas, specific methane yield, and methane concentration of sorghum in Gross-Gerau 2009

RS	CV	Biogas	Methane	Methane
		l_N/kg VS	l_N/kg VS	% volume
75 cm		567a	311a	53a
37.5 cm		524a	280a	53a
75 cm (DR)		574a	306a	53a
	Goliath	519bc	280bc	54a
	Bovital	526b	282bc	53b
	Aron	594b	316b	53b
	Rona-1	721a	387a	53b
	Akklimat	415c	232c	52c
RS		ns	ns	ns
CV		109	63	0.9
RS x CV		ns	ns	ns

5. Discussion

5.1 Effect of sowing time, plant density and cultivar

5.1.1 Plant stand parameters and biomass

Leaf area index (LAI) is an important structural property of crop canopy which predicts photosynthesis and which can be characterized as a reference tool for crop growth measurements (Lan et al. 2009). In current experiments, it was observed that LAI values of the tested sorghum cultivars which varied from 4.0 to 5.2 were higher than those of grain sorghum (LAI 2.5 to 4.0) carried out in field experiments under semi-arid climate in lower Rio Grande Valley of Texas (23°C mean daily air temperature) (Weidenfeld and Matocha 2009). They measured the LAI of sorghum at harvesting stage (grain ripening stage) of the plants, when the leaves started to dry and showed first symptoms of senescence. Contrary to that in present study, the LAI was measured at flowering stage when leaves were green and did not show any senescence. It can be concluded that this earlier stage of plant development of sorghum resulted in higher LAI values in the own experiment. In addition cultivars used in present study contained higher number of tillers which contributed more number of leaves. All these factors led to higher LAI in current trials in comparison with previous study carried out by Wiedenfeld and Matocha (2009).

In several investigations with sorghum and maize it was found that plant density can modify the plant morphology (Lafarge and Hammer 2002) and can promote larger changes in shoot organs (leaf dimensions and plant height), individual leaf area as well as total leaf area index (Maddonni et al. 2001). In our experiments with sorghum higher plant densities (24 and 32 plant m^{-2}) resulted in an increase of LAI. The increase in LAI with higher plant densities may be due to greater number of plants and leaves which resulted in more leaf cover than lower plant density. These findings are in conformity with previous work that showed a clear increase in LAI of grain sorghum as plant density increased from 5 to 26 plants m^{-2} (Rosenthal et al. 1993).
The highest LAI was achieved 90 days after germination in all sowing times evaluated in current trials. The continuous increase in leaf area index of sorghum from 30 to 90 d after germination might be due to increase in plant height, number of leaves per plant and single leaf area of sorghum. The results indicate that the LAI increased throughout the growth period. However this increase was less rapid 60-70 days after germination. It can be supposed that the rate of increase in specific leaf area and the number of leaves was higher between 30 to 60 days after germination but slower after 65-75 days after germination. Additionally it can be supposed that the position of the leaves (angles of leaves) may be altered with the stage of crop growth. For these reasons the increase in LAI was higher at earlier stage (30-60 days after germination) but gradually slow down after 65-75 days after germination.

Tillering is an important agronomical trait as it has a major impact on leaf area development of *Sorghum bicolor* (Hammer et al. 1987, Lafarge et al. 2002) and on crop water use pattern (van Oosterom et al. 2008). In sorghum the number of tillers per plant can vary from zero to around four fertile tillers depending on growing conditions and variety (Hammer et al. 1993). In our study the number of tillers varied between one and three tillers per plant which were predominantly influenced by the tested cultivar. Cv. Bovital was characterized by higher number of tillers than cv. Goliath. It can be suggested that higher potential for tiller formation of cv. Bovital can be due to the genetically background of this cultivar as a hybrid of *S. bicolor* x *S. sudanense*. An earlier study also showed significant differences between cultivars of sorghum regarding number of tillers (Dolciotti et al. 1998). The authors conducted experiments with sweet type sorghum ‘Wray’ (*Sorghum bicolor* L.; Moench ssp. *bicolor*) and the non sweet type, ‘H173’ (hybrid; *Sorghum bicolor* L.; Moench x *Sorghum docna;* var. *technicum*) in a field trial under well-watered conditions in northern Italy. They found that H173 was characterized by a greater tillering ability than that of cv. Wray. Therefore it can be suggested that cultivars (Bovital and H173) which belong to the sub-species of *Sorghum sudanense* and ssp. *docna* possess higher capability for tiller production than *Sorghum bicolor* like Goliath and Wray.

Beside the effect of cultivar there was also an effect of plant density on the number of tillers m^{-2} in the executed trials. Higher plant density caused markedly higher number of tillers m^{-2} but reduced numbers of tillers per plant. It is a known fact that tillers per plant is negatively correlated with plant density. The higher number of tillers per plant at lower plant density was due to lower competition among plants for light, water and nutrients. These findings are in good agreement with previous work with sorghum (Lafarge and Hammer 2002, Buah and Mwinkaara 2009) as well as with sward grass (Casal et al. 1986) where higher numbers of tillers per plant at lower plant densities were recorded. According to Lafarge and Hammer (2002), tiller emergence ceased when canopy leaf area index reached 0.64. This relationship was connected with hormonal effects in the plants in response to changes to light quality (red : far red ratio). Casal et al. (1986) also found a relationship between light quality and tiller emergence and they concluded that an artificial increase in red light enhanced tiller emergence in sward plants.

In the own experiments in 2009, an interaction between cultivar and plant density was observed regarding tillers m^{-2} at experimental station Gross Gerau at 3rd sowing time (end of June). The reason of this interaction can be explained by different responses of the cultivars on changed plant density. Cv. Goliath showed higher sensitivity regarding number of tillers as plant density decreased, whereas cv. Bovital reached similar number of tillers on each level of plant density.

Plant height was significantly correlated with dry matter yield in present study ($r = 0.86$ in 2008, $r = 0.69$ in 2009). These findings support the previous work that also reported a significant correlation between plant height and DM yield of sorghum by a correlation coefficient of $r = 0.50$ (Habyarimmana et al. 2004) and $r = 0.63$ (Venuto and Kindiger 2008). Therefore it can be suggested that plant length can be used as an indicator for biomass yield as well as for growing conditions of the crop. This relation could be found in Giessen 2008 where sowing times had clear impact on plant height of sorghum. Late sowing resulted in smaller growth cycle of sorghum which reduces the duration of photosynthesis as well as water and nutrient uptake of sorghum plants which results in smaller plant height.

Present study showed that cv. Goliath was characterized by consistently higher dry matter yield as compared with cv. Bovital in all sowing times as well as at all experimental stations. It can be supposed that genetic potential and longer growth cycle (late maturing characteristics) enable cv. Goliath to produce higher biomass yield per hectare in comparison with Bovital.
Changes in dry matter yields among forage cultivars of sorghum have also been previously recorded by other researchers (Habyyarimana et al. 2004, Carmi et al.

2005). From six hybrids and three commercial strains of sorghum, the hybrids ABF-25 and H-132 produced higher biomass yields in experiments conducted in Italy (Habyyarimana et al. 2004). Carmi et al. (2005) recorded similar dry matter yield in forage sorghum cv. Pnina and cv. FS-5 whereas significantly lower DM yield was obtained with cv. Nutriplus.

Differences between sorghum cultivars regarding biomass yield can also be caused by improved water use efficiency. This hypothesis was supported by Unger (1988) who found significant differences in water use efficiency and dry matter production between various grain and forage cultivars of sorghum. He concluded that forage cultivars of sorghum use water more efficiently for the production of dry matter than grain sorghum. It was found that there are also differences in water use efficiency between sweet and grain sorghum, with an advantage for sweet sorghum (8.6-6.5 kg m^{-3} Saeed and El-Nadi 1988; 6.0-4.1 kg m^{-3} Mastrorilli et al. 1995) in comparison with grain sorghum (4.4-5.5 kg m^{-3} by Steduto and Albrizio 2005).

Plant density (PD) had no clear impact on dry matter yield in present study. The lower plant densities caused a slight decline in dry matter yield of sorghum. This similarity in dry matter yields might be due to the compensation of smaller number of plants m^{-2} by other yield parameters like higher number of tillers per plant and plant height. But this conclusion can´t be generalized for all cultivars. So at Giessen 2008 a remarkable interaction of CV x PD was observed regarding dry matter yield in 3rd sowing time (first week of June). Under 3rd sowing time (first week of June; Giessen 2008), lowest rainfall (150 mm) was received among different sowing times ranging from 180 to 280 mm. Hence it can be assumed that lower precipitation during plant development might cause different reaction of cultivars with different plant densities. Cv. Goliath showed an increase in dry matter yield with higher plant density while Bovital exhibited clear decline in dry matter yield as plant density increased. Therefore, it can be assumed that under water stress conditions, cv. Goliath can use available resources (water and nutrients) more efficiently as plant density increases. On the other hand, cv. Bovital showed an inverse response to higher plant density for biomass yield under diverse conditions like water stress.

Cultivar adapted sowing times and plant densities are needed to maximize the benefits of dry matter yield as well as grain yield. Adjustment of planting dates was helpful to increase the biomass yield by taking the maximum radiation (Hipp et al. 1970). Acceptable dry matter yields were obtained from seventeen experiments realized in different sowing times (ranged from 10 to 16 t/ha; tab. 5.1). However, an extremely lower dry matter yield in delayed sowing (first week of June) was observed at Giessen 2008. In fact, early harvesting (90 days after sowing, at 18% of DM) led to critically lower dry matter yield. Shorter growth period reduced the duration of photosynthesis as well as water and nutrient uptake of sorghum plants which resulted in lower dry matter yield. In addition, during whole plant development at Giessen 2008, sorghum received markedly lower precipitation of 150 mm in delayed sowing (first week of June). These drought conditions might be another reason which caused a clear decline in dry matter yield by reducing the photosynthesis activity. This relationship was found in several crops like, sorghum, millet and sunflower where the gross and net photosynthesis declined linearly induced by low or moderate water stress (Krampitz et al. 1984, Kreig and Hutmacher 1986, Singh and Singh 1995, Ludlow and Ng 1976). Other effects of water stress given in literature are a reduction in intercellular CO_2 concentration with a consequent reduction in the net photosynthesis observed in sorghum (Kreig and Hutmacher 1986). Mastrorilli et al. (1999) carried out a study to investigate the effect of soil water deficit at different phenological stages of sweet sorghum under semi-arid conditions in the Mediterranean environment of southern Italy. The authors concluded that in comparison with well watered crop, sweet sorghum biomass production was reduced in case of early water stress.

Table 5.1: Mean dry matter yields of sorghum in different sowing times in 2008 and 2009

Sowing time	2008			2009		
	GI	**GG**	**RH**	**GI**	**GG**	**RH**
	DM t/ha	DM t/ha	DM t/ha	DM t/ha	DM t/ha	DM t/ha
1st sowing	10.29	13.79	16.38	12.70	15.75	14.91
2nd sowing	10.19	14.70	14.70	11.68	15.57	12.74
3rd sowing	5.50	15.21	14.92	12.53	13.78	10.06

GI = Giessen, GG = Gross Gerau, RH = Rauischholzhausen

Ercoli et al. (2004) carried out experiments to investigate the effects of chilling temperature and various durations of its exposure on growth of sorghum. Chilling exposure including both the duration and severity of the temperature considerably influenced the sorghum growth, showing that photosynthetic rate was more affected than respiratory rate. The nature and severity of chilling damage was a function of the severity and duration of the exposure. When the duration of chilling was prolonged, plants were able to adapt chilling probably by restoring photosynthesis, but this ability was decreased with a decrease in temperature. Plants succeeded to produce positive growth rates only at 8°C, while at lower temperatures growth was ceased. In present study, 7-8 days after emergence (the plants of first sowing were at seedling stage), plants suffered a low night temperature for two days (< 5°C; end of May) which resulted in yellow stripes on leaves of sorghum at Gross Gerau 2009. However, it did not cause any damage of sorghum plants, because the duration of exposure was short and this problem was abolished in 10-15 days. Thus, the well known phenomenon of cold-sensitivity in sorghum at early stage has also been proved in present study.

5.1.2 Chemical composition

The various components of organic material produce different amounts of biogas and variable contents of methane gas. Microorganisms, active in anaerobic fermentation use only small amounts of energy for their growth and the major portion of available energy from the substrate is converted to methane. Berglund and Börjesson (2003) calculated quantity and composition of biogas from primary compounds like carbohydrates, fat and protein which are synthesized in plants. The theoretical amounts of biogas and its composition estimated from major compounds are given in table 5.2.

Table 5.2: Theoretical quantity and composition of biogas formed from carbohydrates, fat and protein (Berglund and Börjesson 2003)

Component	Biogas volume (m^3/ kg Vs)	Biogas composition: CH_4: CO_2
Carbohydrates	0.38	50:50
Fat	1.0	70:30
Protein	0.53	60:40

From Berglund and Börjesson (2003) can be concluded that fat compounds induce higher volume of biogas with higher proportion of methane followed by protein and lower values were estimated for carbohydrates. However these major compounds differ in their theoretical specific methane yield from anaerobic digestion. For instance, the individual components like protein which in theory produces a high volume of biogas, can give considerably lower biogas due to ammonia inhibition of methane producing microorganisms (Gerardi 2003). Amon et al. (2006) reported substantially higher specific methane yield with maize in comparison to sunflower during the course of vegetation period at four to six different times.

In present study, protein concentrations of tested sorghum cultivars ranged from 6 to 9% which was similar to maize and forage sorghum as recorded by Iptas and Acar (2006), Miron et al. (2006) and Marsalis et al. (2010) who found protein contents in a range from 6 to 8% DM. Data demonstrate that sorghum cultivars exhibited differences in protein concentration. The reason of higher protein concentration in present trials for cv. Bovital may be due to higher number of tillers per plant which are formatted by this cultivar. It can be stated that in comparison with main stems and leaves from main stems, tillers can be characterized as physiological younger plant organs with higher activity of protein synthesis. Furthermore, the accumulation of carbohydrates like sucrose and the synthesis of fiber compounds like cellulose were increased in main stems. These processes may explain the higher protein concentration of cv. Bovital. Previous work also showed clear differences in protein concentration among the tested forage cultivars of sorghum (Miron et al. 2006, Miron et al. 2005). According to Miron et al. (2005) and Miron et al. (2006), who conducted studies in Israel, cv. BMR-101 contained considerably higher protein concentration in comparison with FS-5, Silobuster and Supersile 20 cultivars of forage sorghum. The authors argued that higher protein concentration in cv. BMR-101 is associated with leafy appearance because leaves are main contributor of protein in sorghum plants.

Contrary to the effect of cultivar the study factor plant density had no influence on protein concentration of sorghum in own experiments. These findings coincide with the recent work showing that planting rate had no clear impact on crude protein content of sorghum as well as of maize (Marsalis et al. 2010). On the other hand, these results are in contrast from previous study of Caravetta et al. (1990), who reported that a decrease in plant density leads to improved protein contents in forage sorghum. They concluded that the reason of higher protein concentration in plants grown at low populations was due to luxury consumption of nitrogen.

Significant interactions of cultivar x plant density in 1st and 2nd sowing time (GI 2008) and 1st sowing (GG 2009) were due to differential response of both cultivars regarding protein concentration. Cv. Goliath showed a reduction in protein concentration at lower plant density while similar averages were attained for cv. Bovital. It can be

assumed that both cultivars have different plant morphology (especially tillering and number of leaves) which caused different reaction on protein concentration as plant density decreased.
Similarly, sorghum cultivars also showed variations in sugar concentration. Similar results were reported for sweet sorghum (Dolciotti et al. 1998, Almodares et al. 2008). Almodares et al. (2008) showed that sweet sorghum cultivar Rio showed significantly higher sugar contents than that of other four cultivars and four lines used in that experiment. In current study, higher sugar concentration of cv. Goliath may be due to higher proportion of stem as compared to cv. Bovital. This effect can be explained by a large accumulation of sugar in main stems as compared with side stems (tillers). The main stem can be characterized as a sink organ for soluble sugars (Zhao et al. 2009). For that reason, cultivars with a higher proportion of main stems like Goliath may accumulate larger amounts of soluble sugars.

The acid detergent fiber concentration (ADF) was significantly affected by the cultivars in present trials. It is possible that higher ADF and NDF concentration in cv. Goliath may be due to its greater stem and leaves proportion, which may contain higher fiber content than panicle. Variations in acid detergent fiber (ADF) concentrations among different cultivars have been previously reported for sorghum (Beck et al. 2007) as well as for maize (Cusicangui and Lauer 1999, Iptas and Acar 2006). Among three sorghum × Sudan grass hybrids, Beck et al. (2007) recorded significantly higher ADF concentration with cv. Sweet Sunny Sue (non BMR) than cv. Nutriplus (BMR) and cv. Dry Stalk BMR (DS-BMR). The BMR (brown midrib) trait in sorghum is characterized by a reduced lignin concentration, which can considerably enhance the level of digestibility (Oliver et al. 2004, Bean and McCollum 2006).

Plant density in present executed trials had no clear impact on ADF concentration of sorghum. However in some treatments, interactions of CV x PD were observed with respect to ADF concentration. These interactions can be explained by different reactions of both tested cultivars. Cv. Goliath showed either an increase or a comparable ADF concentrations as plant density increased. On the other hand, the trend of cv. Bovital with increasing plant density was not consistent and it needs further explanation.

The neutral detergent fiber (NDF) concentrations in present experiments varied from 50 to 56% of DM which is similar with the findings of other investigations with forage sorghum like Marsalis et al. (2010) who found 50% NDF. Cv. Goliath was characterized by higher NDF concentration as compared with cv. Bovital in current trials. The higher NDF concentration in cv. Goliath might be a result of greater fraction of leaves in this variety which contain more NDF than stems (Carmi et al. 2005). In present study plant density had no effect on NDF concentration of sorghum. These findings are in accordance with Carmi et al. (2006) and Marsalis et al. (2010) who reported that an increase in plant density did not affect NDF contents of sorghum, but are in contrast with observations in corn (Widdicombe and Thelen 2002). Thus, it appears that responses to plant density (PD) of sorghum and corn are different concerning NDF concentration. Significant interactions of CV x PD were found regarding NDF concentration in some treatments. These interactions can be explained by different reactions of the cultivars on different plant densities. Same level of NDF concentration with cv. Goliath but a clear decline in cv. Bovital was observed with increasing plant density. It can be suggested that cv. Goliath has lower tillering capacity and tillers remain almost similar with all three levels of plant density.

Opposite to that cv. Bovital showed higher number of tillers per plant in lower plant density which contributed higher number of leaves per plant. For that reason with higher number of leaves per plant cv. Bovital led to higher NDF concentration in lower plant density because leaves contain higher NDF concentration as compared to stems (Carmi et al. 2005).

Lignin is a polymer formed from monolignols derived from the phenylpropanoid pathway in vascular plants. This compound is considered as an anti-quality component because it interferes with the digestion of cell-wall polysaccharides by acting as a physical barrier to microbial enzymes. Plant organs containing high concentrations of these tissues, such as stems, are less digestible (Moore and Jung 2001). The concentration of lignin in biomass of sorghum varied among the cultivars evaluated in present experiments. The higher panicle proportion in cv. Bovital reduced lignin concentration of this cultivar in present study. This finding supports the conclusion that stems and leaves fractions contained higher lignin concentration than panicles (Miron et al. 2005). For that reason NDF digestibility of cv. Bovital is expected to be higher than cv. Goliath in current trials. Other researchers also found that cultivar of forage sorghum showed significant differences regarding lignin concentration (Carmi et al. 2005, Miron et al. 2006, Beck et al. 2007). Miron et al. (2006) carried out trials with three sorghum cultivars (named as FS-5, BMR-101 and Silobuster) and recorded markedly lower lignin concentration in cv. BMR-101 than in cv. FS-5 and cv. Silobuster. The BMR trait in sorghum, characterized by reduced lignin concentration, has considerably enhanced the level of digestibility (Oliver et al. 2004, Bean and McCollum, 2006). Brown midrib (BMR) mutants have been identified in maize and sorghum arising by either spontaneous or chemical mutagenesis. The characteristic of BMR (brown coloration of the leaf mid veins) is linked with reduced lignin content and altered lignin composition that is useful to improve forage digestibility. Additionally it has been reported that brown midrib mutants significantly enhanced conversion rate in the lignocellulosic bioenergy process (Sattler 2010).

Sorghum biomass consists of minerals like potassium (K), calcium (Ca), magnesium (Mg), manganese (Mn), iron (Fe), copper (Cu) and zinc (Zn) etc. (Gorz et al. 1987). These light metals may be released by the breakdown of organic matter (such as biomass), or added as pH adjustment chemicals (Grady et al. 1999). Some of them are required for microbial growth and moderate concentrations of these metals can stimulate microbial growth. But excessive amounts of these minerals can slow down the growth of microbes and can cause severe inhibition or toxicity (Soto et al. 1993).

Little information is available about the toxicity influences of potassium in the literature. Lower concentrations of potassium (less than 400 mg/L) can induce an enhancement in performance in both the thermophilic and mesophilic ranges, whereas an inhibitory effect was observed at higher concentrations that was more sever in the thermophilic temperature range (Chen et al. 2008).

Calcium is considered to be vital element for the growth of certain strains of methanogens (Murray and Zinder 1985). Excessive amounts of calcium lead to precipitation of carbonate and phosphate, which may lead to (i) scaling of reactors and pipes, (ii) scaling of biomass and reduced specific methanogenic activity, (iii) loss of buffer capacity and essential nutrients for anaerobic degradation (Keenan et al. 1993, El-Mamouni et al. 1995, van Langerak et al. 1998).

Cultures could be adapted to 300 mM Mg^{2+} without a change in growth rate, but growth ceased at 400 mg/L Mg^{2+} (Schmidt and Ahring 1993). The production of single cells has been stimulated by higher concentration of magnesium ions (Harris

1987, Xun et al. 1988, Schmidt and Ahring 1993). The high sensitivity of single cells to lysis is an important factor in the loss of aceticlastic activity in anaerobic reactors.

At low concentrations, sodium is vital for methanogens, perhaps because of its role in the formation of adenosine triphosphate or in the oxidation of NADH (Dimroth and Thomer 1989). However at high concentrations, it can readily influence the activity of microorganisms and impede with their metabolism (Rinzema et al. 1988, Gourdon et al. 1989, Balsleve-Olsen et al. 1990, Mendez et al. 1995). The intensity of inhibition depends on the concentration of sodium ions. An early study showed that sodium concentrations ranging from 3500 to 5500 mg/L to be moderately and 8000 mg/L to be strongly inhibitory to methanogens at mesophilic temperatures (McCarty 1964).

The ash concentration in cv. Bovital was significantly but slightly higher as compared to cv. Goliath in this study. It can be assumed that the minerals uptake capacity of cv. Bovital from soil is slightly higher than cv. Goliath. Another possibility of higher ash concentration is that cv. Bovital showed greater number of leaves per plant than cv. Goliath which might contain higher ash concentration. These results supports the findings that leaf blades of maize contain highest ash concentration as compared with any of the other tissues like stem epidermis and pith (Lanning 1980). In addition, the Author argued that the guard cells of stomata are highly mineralized. However, such a minor difference between both cultivars is not important for biogas production. Previous study also reported differences in ash concentrations among forage cultivars (Miron et al. 2005).

5.1.3 Biogas and methane yield

Biogas production from agricultural biomass is gaining importance as it offers environmental benefits (Chynoweth 2004). Suitable substrates for the anaerobic digestion are energy crops like maize, sorghum, sunflower, sudan grass, fodder beet, poor oat grass meadows, small-sedge poor-fen, meadow, and montane hay meadow (Jerger and Chynoweth 1987, Chynoweth et al. 1993, Weiland 2003, Amon et al. 2007, Richter et al. 2009). Methane production from organic substrates mainly depends on their contents of substances that can be degraded to methane and CO_2 (Amon et al. 2007). Composition and biodegradability of biomass are key factors for methane yield. Compounds like crude protein, crude fat, crude fiber, cellulose, hemi-cellulose, starch, and sugars clearly affect methane production (Balsari et al. 1983, Amonet al. 2002, Amon et al. 2007).

In present trials, cv. Goliath produced significantly higher biogas as well as methane yields at both experimental stations Gross Gerau and Rauischholzhausen. Despite having higher lignin and fiber concentration, late maturing cv. Goliath produced higher biogas as well as methane yield in comparison with early maturing cv. Bovital. These results are in good agreement with studies of Schittenhelm (2008), who showed that maize cv. Doge and Mikado, despite having significantly higher cellulose and lignin concentrations, did not produce lower specific methane yields than cultivars having lower fiber and lignin concentrations. The author argued that this may be due to the fact that complexity of bonding within the cell wall carbohydrates increases toward physiological maturity. Therefore it can be concluded that in present study early ripeness in cv. Bovital (early maturing) resulted in more complexity of bonding within the cell wall carbohydrates than late maturing cv. Goliath. Hence, the digestibility of early maturing cv. Bovital was decreased due to the complexity of bonding within the cell wall carbohydrates. For that reason cv. Bovital produced lower specific biogas as well as methane yield compared with cv. Goliath in present study.

In current study methane yields of the whole sorghum plant ranged from minimal 187 to maximal 340 NL kg^{-1} VS. This level was in the same magnitude as recorded by Richter et al. (2009) who found methane yields of around 158 to 268 NL kg^{-1} VS with poor oat grass meadows (*Arrhenaterion*), small-sedge poor-fen (*Caricion fuscae*) meadow, tall herb (*Filipendulion ulmariae*) meadow and with montane hay meadow (*Polygono-Trisetion*). Nearly similar methane yield was obtained by Baserga (1998) who got 280 NL kg^{-1} VS from extensive grassland, as well as by Lemmer and Oechsner (2001) who received 240 NL kg^{-1} VS from silage originating from extensive grassland. The corresponding proportions of methane in the biogas of 58% (Baserga 1998), 54–57% (Lemmer and Oechsner 2001) and 52% (Prochnow et al. 2005) are consistent with those found in the current study (51-53%). In executed trials sorghum cv. Bovital had slightly but significantly higher methane concentration in comparison with cv. Goliath. That is likely the result of higher protein concentration in cv. Bovital as it contains higher percentage of methane as compared to carbohydrates.
Generally it can be concluded from this study that cv. Goliath has advantage over cv. Bovital due to its higher biomass production. Under the specific experimental conditions, it can be concluded that sorghum can be cultivated by delayed sowing until mid of June without compromising the dry matter yield. Owing to the possibility of delayed sowing, it provides a chance for some pre-crops like winter wheat, winter barley, winter rye, and winter rapeseed for silage purpose. Another advantage of sorghum cultivation in Germany is that there is presently no infection by the European corn borer (*Ostrinia nubilalis*; Hübner) which causes severe damages in maize. Hence, it is rational to introduce sorghum in cropping system in Germany.

5.2 Effect of row spacing and cultivar

5.2.1 Biomass and plant stand parameters

In this experiment five cultivars were tested in combination with different row spacing. The cultivars could be characterized by different LAI and tiller formation. The earlier plant development and specific leaf formation (leaf expansion, individual leaf area, position and angle of leaves) in present study might be the reason of higher LAI of cv. Goliath, cv. Bovital, cv. Aron and cv. Rona 1 as compared to cv. Akklimat. Although cv. Akklimat had 3-4 times higher number of tillers per plant which contributed to higher number of leaves as compared with other cultivars. In spite of higher number of leaves (very narrow), cv. Akklimat could not compensate LAI due to lower individual leaf area. Ferraris and Charles-Edward (1986) carried out experiments with sweet sorghum cv. Wray and forage sorhum cv. Silk in Southern Queensland. The authors found that both cultivars had similar number of leaves per tiller, but cv. Silk had five times higher number of tillers, yet light interception and LAI was greater for cv. Wray because of greater leaf expansion.

In present study, it could be observed that highest LAI was reached with 37.5 cm row spacing in comparison with other row spacings, suggesting that more symmetrical distances and homogenous distribution of plants per area led to higher LAI with row spacing of 37.5 cm. These findings are consistent with results reported by Weidenfeld and Matocha (2009) who found that more symmetrical spacing led to greater LAI in grain sorghum.

In executed trials, it was found that plant height declined as the row spacing increased and vice versa. The reason of this effect can be explained by plant competition for light. As row spacing increased by keeping plant competition constant, intra row competition for light is increased. For that reason plants in wider row spacing gained more height in search of light. These results are in agreement with the findings of Caravetta and Cherney (1990) who reported that plant height declined with wider row spacing at constant plant population in *Sorghum bicolor*.

Data showed that cultivar significantly influenced plant height which is in accordance with the findings of Carmi et al. (2005) evidencing that the factor cultivar had a clear impact on plant height of forage sorghum. In own experiments plant height was significantly correlated ($r = 0.86$ in 2008, $r = 0.29$ in 2009) with dry matter yield of sorghum plants. In 2009 this relationship of plant height and dry matter yield was not strong which can be explained by different treatment used in these trials. In 2008, only two cultivars were used while five cultivars were included in current study in 2009.

Among the tested cultivars, cv. Akklimat showed maximum number of tillers/m^2 followed by cv. Bovital. Both cultivars are sorghum hybrids of the combination *S. bicolor* x *S. sudanense* which have higher potential for tiller formation than that of *S. bicolor* cultivars like cv. Goliath, Aron and Rona 1. Dolciotti et al. (1998) also showed significant differences between cultivars of sorghum regarding number of tillers. They found that non sweet type ‘H173’ (hybrid; *Sorghum bicolor* (L.) Moench x *Sorghum docna* var. *technicum*) was characterized by greater tillering ability than sweet type sorghum ‘Wray’ (Moench ssp. *bicolor*). Previous studies also reported that a forage cultivar Silk produced five times higher number of tillers as compared to sweet sorghum cv. Wray (Ferraris and Charles-Edward 1986).

Experimental data demonstrated that keeping plant density constant, the narrow row spacing exhibited more tillers/m^2 as compared to wider row spacing. This result might be due to reduced plant to plant competition (intra row competition) for light, water and nutrients in narrow row spacing.

Dry matter yield was markedly different among the cultivars tested in this study. Cv. Goliath is characterized by higher dry matter production than other cultivars in two consecutive years as well as at different experimental stations. It can be supposed that cv. Goliath possesses higher water use efficiency, higher genetic potential and longer growth cycle (late maturing ability) which resulted in higher biomass yield in comparison with other investigated cultivars. Significant differences in water use efficiency in terms of dry matter production between different sorghum cultivars (one grain and five forage cultivars) have been previously reported (Unger 1988). The authors concluded that forage sorghum use water more efficiently than grain sorghum for the production of dry matter. For water use efficiency, differences are also recorded between sweet and grain sorghum, with an advantage for sweet sorghum (8.6-6.5 kg m^{-3}, Saeed and El-Nadi 1988, 6.0-4.1 kg m^{-3}, Mastrorilli et al. 1995), in comparison with grain sorghum (4.4-5.5 kg m^{-3} by Steduto and Albrizio 2005). Changes in dry matter yields among different cultivars have been shown by other researchers (Habyyarimana 2004, Amaducci et al. 2004, Zhao et al. 2009). Habyarimmana et al. (2004) conducted experiments with nine sorghum hybrids in four different environmental conditions of Italy for biomass evaluation. They found that hybrid ABF 25 led to significantly higher DM yield followed by H 132 and Abetone.

Although in most treatments, there was no significant effect of row spacing on dry matter yield. However, the narrow row spacing slightly increased the dry matter yield than wider row spacing. Keeping the number of plant m^{-2} constant, higher dry matter yield with narrow rows pacing in present study might be caused by a reduced intra row competition (plant to plant competition) as compared to wider row spacing.

5.2.2 Chemical composition

Whole plant biomass of sorghum mainly contains water soluble carbohydrates (6-15%), proteins (6-9%), hemicelluloses (22-26%), cellulose (21-28%) and lignin (3-7%) (Miron et al. 2006, Carmi et al. 2006).

Proteins are made up of amino acids that are different in their structure. Amino acids are joined together by peptide bonds to synthesize protein. Each protein has a unique composition and sequence of amino acids in its chain. The complex proteins cannot be transported into bacterial cells. The bacteria use exoenzymes namely proteases or peptidases to hydrolyze peptide bonds that permits the release of amino acid units and their transport to bacterial cells (Gerardi 2003). During the process of degradation of amino acids, different types of organic acids are generated including acetate and butyrate. Ammonia is released during the degradation of amino acids. Acetate and butyrate are used by methane-forming bacteria for methane production while ammonia increases the alkalinity of digester and sometimes (depending on the concentration) it can cause toxicity (Gerardi 2003).

Small variation in protein concentration from 6.3 to 8.5% DM was obtained in present study which was nearly similar reported for hybrids of forage sorghum (6-8%; Miron et al. 2006 and 6-7%, Marsalis et al. 2010). Experimental data indicated that the protein concentration was different among cultivars. Cv. Akklimat exhibited considerably higher protein concentration than other cultivars. It is suggested that this effect in cv. Akklimat is might be due to its higher capability of tiller formation. Tillers are comparatively physiological younger plant organs with higher activity of protein synthesis than physiological older leaves and main stems. Additionally, the accumulation of carbohydrates (sucrose) and the synthesis of fiber compounds like cellulose are higher in main stems. These processes might explain the higher protein concentration in cv. Bovital and cv. Akklimat in the current study. Early studies also showed that protein concentration significantly varied among forage cultivars of sorghum (Miron et al. 2006, Beck et al. 2007). According to Miron et al. (2006) forage cultivar BMR-101 showed significantly higher protein concentration in comparison to FS-5 and Silobuster cultivars of forage sorghum. They argued that higher protein concentration in cv. BMR-101 is associated with the leafy appearance because leaves are main contributor of protein in sorghum plants.

Cv. Aron and Rona 1 produced higher sugar concentrations in comparison to other tested cultivars. Being hybrids of *S. bicolor*, both cultivars have superior tendency towards higher sugar concentration than *S. bicolor* x *S. sudanense* hybrids like cv. Bovital and *S. sudanense* and cv. Akklimat. Earlier studies have also shown remarkable differences among the sorghum cultivars regarding sugar concentration (Dolciotti et al. 1998, Almodares et al. 2008). Almodares et al. (2008) showed that sweet cultivar Rio exhibited considerably higher sugar contents than that of other four cultivars and four lines used in that experiment.

In present study, NDF concentrations in sorghum which varied from 50 to 56% which were nearly in the same range as reported by Miron et al. (2005) and Miron et al. (2006) who obtained 48 to 55% NDF as well as by Carmi et al. (2005) who found 52 to 64% of NDF. Experimental data demonstrated that cultivars showed pronouncedly different NDF as well ADF concentration. These results coincide with findings that hybrids had significant differences in NDF and ADF concentrations (Carmi et al. 2005, Miron et al. 2006; Beck et al. 2007). The lower ADF, NDF and ADL concentrations determined for cv. Rona 1 and Aron might be because of higher sugar concentration in stems which have reduced the fiber concentration in these cultivars. Significant interactions between cultivars and row spacings in Gross Gerau 2009 were found in cv. Rona 1 which showed critically lower NDF concentration in wider row spacing of 75 cm.

Beck et al. (2007) found clear differences in ADF concentration among the hybrids of sorghum. These authors carried out experiments with three sorghum x sudan grass hybrids and concluded that cv. Sweet Sunny Sue (non BMR) had higher ADF concentration as compared with cv. Nutriplus BMR and cv. DS BMR. ADF concentration in our experiment was not affected by row spacing. This observation coincides with the previous observation that row spacing had no clear impact on ADF concentration of forage sorghum (Rollins et al. 1970).

Lignin is highly resistant to chemical cleavage and protects cellulose fibers from cellulose hydrolysis to glucose (Chang and Holtzapple 2000). Differences in lignin concentration between sorghum cultivars have been previously reported (Carmi et al. 2005, Miron et al. 2006). Also in the current experiments executed during this study the used cultivars had a significant effect on lignin concentration. The higher lignin concentration in cv. Goliath and Akklimat may explain part of NDF digestibility among these five cultivars. Cv. Rona 1 and cv. Aron showed lower lignin concentration which may result in higher digestibility of both cultivars as compared with other tested cultivars of this study. Miron et al. (2006) carried out trials with three sorghum cultivars (named as FS-5, BMR-101 and Silobuster) and recorded markedly lower lignin concentration in cv. BMR-101 than in cv. FS-5 and cv. Silobuster. It was found that the BMR (brown midrib) trait in sorghum, characterized by a reduced lignin concentration, has considerably enhanced the level of digestibility (Oliver et al. 2004, Bean and McCollum 2006). It has been shown that the brown midrib (BMR) varieties usually contain low lignin contents and are more prone to lodging than the non BMR cultivars (Miron et al. 2005, Hanna et al. 1981).

Ash concentration in cv. Akklimat was highest among the tested cultivars in this study. In fact cv. Akklimat exhibited greater number of tillers per plant which contributed higher number of leaves per plant in comparison with other investigated cultivars. These number of leaves enable it to reach highest ash concentration among the cultivars. Present findings are in support of the conclusion that leaf blades of maize plants contain highest ash concentration than any of the other tissues like stem epidermis and pith (Lanning 1980). In addition, authors also found that the guard cells of stomata are highly mineralized. Another possibility is that the minerals uptake capacity of cv. Akklimat from soil is higher than other cultivar evaluated in present study.

5.2.3 Biogas and methane yield

The specific methane yield of sorghum ranged from 280 to 387 NL kg^{-1} of VS in present study as comparable to previous observations of Richter et al. (2009) with poor oat grass meadows (*Arrhenaterion*), small-sedge poor-fen (*Caricion fuscae*) meadow, tall herb (*Filipendulion ulmariae*) meadow and montane hay meadow (*Polygono-Trisetion*) (158–268 NL kg^{-1} VS) and of Baserga (1998) who obtained 280 NL kg^{-1} VS from extensive grassland, as well as by Lemmer and Oechsner (2001) who showed 240 NL kg^{-1} VS from a silage originating from extensive grassland. The corresponding proportions of methane in biogas of 58 % (Baserga 1998), 54–57% (Lemmer and Oechsner 2001) and 52% (Prochnow et al. 2005) are consistent with those found in the current study (51-53%).

In this study, cv. Rona 1 was characterized by a higher specific methane yield among the tested cultivars. The higher specific methane yield in Rona 1 might be due to the reduced lignin concentration that probably enhanced the digestibility of the plant material during the digestion process. A clear difference among sorghum cultivars regarding methane yield has also been reported in a previous study (Jerger and Chynoweth 1987). The methane yield per hectare was predominantly influenced by sorghum cultivars but not by row spacing in present trials. Cv. Goliath is characterized by a significantly higher biogas and methane yield per hectare as compared with other cultivars. In addition, interaction was also found between cultivars and row spacing with respect to biogas as well as methane yield per hectare in 2009. This interaction was caused by cv. Goliath which showed higher biogas as well as methane yield per ha in 75cm (DR). These results suggest that the impact of cultivars on methane and biogas yield can be expected to be different with different row spacings. Although cv. Rona 1 reached higher specific methane yield per kg VS but it was overcompensated by cv. Goliath due to higher dry matter yield ha^{-1}. Thus, cv. Goliath may have an advantage over other cultivars, due to its higher dry matter potential for the maximization of methane yield ha^{-1}. In present study, satisfactory methane yields were achieved, suggesting that sorghum can be used for methane production. However, further breeding research is needed to find appropriate cultivars for methane production.

Generally, it can be suggested that some of the above mentioned differences in chemical composition among the sorghum cultivars can be explained by different tillering capabilities and biomass distribution of the cultivars. It can be concluded that this morphological trait is more important in sorghum than in maize due to differences in tillering capability. Cv. Goliath has an advantage over other tested cultivars in this study, due to higher potential for the biomass production among the tested cultivars.

Regarding phenotype and morphology, there is a high diversity within the species of sorghum. For that reason, more cultivars should be included in future experiments. In future investigations on this subject, plants should be separated into main stems and side stems (tillers) which may provide better information about the chemical composition of sorghum.

6. Summary

Sorghum (*Sorghum bicolor* (L.) Moench) belonging to the Tribe *Andropogonae* of the family *Poaceae* is cultivated in tropical and subtropical regions and variously used for the production of animal feed as well as for energy and syrup. Presently sorghum is a new crop in Germany and still not well adapted to the local climate. So there is a dire need to produce adapted cultivars and to optimize husbandry practices of sorghum for its cultivation in Germany. One of the most important demands on sorghum cultivation is the establishment of plant stand. For that reason field experiments were conducted to clarify the effect of different sowing times, row spacing and plant densities on dry matter production, chemical composition, and biogas production of sorghum.

Two field experiments were carried out at three experimental stations in Giessen, Gross-Gerau and Rauischholzhausen in 2008 and 2009. First experiment was conducted to study the impact of different plant densities (16, 24 and 32 plants m^{-2}), sowing times (mid of May, end of May and first week of June) and cultivars (Goliath and Bovital). On the other hand the second experiment was conducted to clarify the effect of different row spacing (75 cm, 37.5 cm and 75 cm double row apart with strip rows of 10-15 cm) and cultivars (Goliath, Bovital, Aron, Rona 1 and Akklimat) on biomass yield, chemical composition and methane productivity of *Sorghum bicolor*. The field trials were designed in RCBD under split plot arrangement with four replications and statistically analyzed by using PIAF software.

It was observed that higher plant density and wider row spacing decreased the number of tillers per plant. On the other hand, higher plant density and narrow row spacing led to higher leaf area index (LAI). The biomass yield of sorghum varied from minimal 5.0 to maximal 17.0 t DM/ha in present trials. In most cases dry matter yield was not significantly affected by plant density as well as by row spacing evaluated in present trials. However in one experiment, narrow row spacing (37.5 cm and 75 cm double row apart with strip rows of 10-15 cm) led to significantly higher dry matter yield compared with wider row spacing of 75 cm.

In twelve from total eighteen sowing times, different plant densities led to comparable averages of dry matter yield. However in six sowing times, higher plant densities (24 and 32 plants m^{-2}) exhibited significantly greater dry matter yield than lower plant density (16 plants m^{-2}). Under the specific experimental conditions, it was found that sorghum can be cultivated by delayed sowing until mid of June without compromising the dry matter yield. Among five tested cultivars, Goliath was characterized by consistently higher dry matter yield than other tested cultivars in all experiments conducted at different experimental stations. Despite of higher number of tillers per plant, cv. Akklimat showed lowest LAI while comparable values were observed for cv. Goliath, Bovital, Aron and Rona 1.

Row spacing and plant density had no clear impact on most quality parameters (protein, neutral detergent fiber, acid detergent fiber and lignin concentration) of sorghum plants. However significant interactions of cultivar x plant density in 1st and 2nd sowing time (Giessen 2008) and 1st sowing (Gross-Gerau 2009) were observed. Cv. Goliath showed a reduction in protein concentration at lower plant density while similar averages were attained for cv. Bovital. The neutral detergent fiber (NDF) concentrations varied from 50 to 56% of DM. In some treatments, significant

interactions of cultivar x plant density were found regarding NDF and ADF concentration. Cultivars clearly influenced the chemical composition of sorghum. Protein concentrations of tested cultivars ranged from 6 to 9%. Higher protein concentrations were achieved by *Sorghum sudanense* like cv. Akklimat and cv. Bovital than *Sorghum bicolor* species tested in present experiments. Contrary to that *Sorghum bicolor* (cv. Aron and cv. Rona 1) accumulated markedly higher sugar concentration compared with *Sorghum sudanense* species such as cv. Bovital and cv. Akklimat. Lowest acid detergent fiber, neutral detergent fiber and ash concentrations were exhibited by cv. Rona 1 followed by cv. Aron among cultivars.

In present study, specific methane yield of sorghum ranged from 280 to 387 nL kg^{-1} of volatile solid. Cv. Rona 1 reached higher specific methane yield (Norm litter CH_4 per kg of volatile solids) than other tested cultivars. Although cv. Rona 1 produced higher specific methane yield per kg volatile solid but it was overcompensated by cv. Goliath due to higher dry matter yield ha^{-1}. Thus the cv. Goliath may have advantage over the cultivars of this study, due to its higher dry matter potential for the maximization of methane yield ha^{-1}.

7. Zusammenfassung

Sorghum (*Sorghum bicolor* (L.) Moench, Tribus *Antropogonae*, Familie *Poaceae*) ist eine in den subtropischen und tropischen Regionen angebaute Kulturpflanze, die vor allem zur Produktion von Tierfutter, Bioenergie und Sirup genutzt wird. In Deutschland ist Sorghum gegenwärtig eine relativ neue Kulturpflanze, die noch nicht ausreichend an die hiesigen klimatischen Bedingungen adaptiert ist. Aus diesem Grund ist es erforderlich, neue angepasste Sorten zu schaffen und die Methoden für einen Anbau von Sorghum in Deutschland zu optimieren. Eine wichtige Voraussetzung für die erfolgreiche Kultivierung von Sorghum ist die Etablierung des Pflanzenbestandes. Aus diesem Grund wurden Feldversuche durchgeführt, in denen der Einfluss verschiedener Saatzeiten, Reihenweiten und Pflanzendichten auf die Trockenmasseproduktion, die chemische Zusammensetzung und die Biogasausbeute geklärt werden sollte.

In den Jahren 2008 und 2009 wurden zwei Feldversuche an insgesamt drei Standorten in Gießen, Groß-Gerau und Rauischholzhausen durchgeführt. Im ersten Versuch wurden unterschiedliche Bestandesdichten (16, 24 und 32 Pflanzen/m^2) und verschiedene Saatzeiten (Mitte Mai, Ende Mai, erste Juniwoche) in Kombination mit zwei Sorten („Goliath“ und „Bovital“) geprüft. Im zweiten Versuch wurde der Einfluss unterschiedlicher Reihenentfernungen (75 cm, 37,5 cm und 75 cm Doppelreihen mit Streifenreihen von 10 - 15 cm) in Kombination mit fünf Sorten (Goliath, Bovital, Aron, Rona 1 und Akklimat) auf den Biomasseertrag, die chemische Zusammensetzung und die Methanausbeute untersucht. Die Feldversuche wurden in Form von zweifaktoriellen Spaltanlagen mit vier Wiederholungen durchgeführt und mit Hilfe des PIAF-Programms statistisch ausgewertet.

Aus den Ergebnissen ist zu erkennen, dass höhere Pflanzendichten und größere Reihenabstände zu einer geringeren Triebzahl pro Pflanze und gleichzeitig zu einem höheren Blattflächenindex führten. Der Biomasseertrag von Sorghum variierte in den durchgeführten Versuchen von 5 bis 17 t TM/ha. In den meisten Versuchen hatten die Pflanzendichten und Reihenabstände keinen signifikanten Einfluss auf die Biomasseerträge von Sorghum. In einem Versuch dagegen führten engere Reihenweiten von 37,5 cm und Doppelreihen (Streifen von 10 – 15 cm) zu signifikant höheren Trockenmasseerträgen im Vergleich mit großen Reihenweiten von 75 cm.

In zwölf von insgesamt achtzehn durchgeführten Saatzeiten hatte die Veränderung der Pflanzendichte keinen Einfluss auf den TM-Ertrag. In sechs weiteren Saatzeiten bewirkten höhere Pflanzendichten (32 und 24 Pflanzen/m^2) dagegen signifikant höhere Trockenmasseerträge im Vergleich mit geringeren Pflanzendichten von 16 Pflanzen/m^2. Unter den spezifischen Versuchsbedingungen zeigte sich, dass die Aussaat von Sorghum bis Mitte Juni zu keiner Beeinträchtigung der Trockenmasseerträge führte. Unter den fünf getesteten Sorten erreichte die Sorte „Goliath“ an allen Versuchsstandorten die höchsten Trockenmasseerträge. Trotz höherer Triebzahl/Pflanze wurden bei der Sorte „Akklimat“ die geringsten LAI-Werte gemessen, während die LAI-Werte bei den übrigen getesteten Sorten vergleichbar waren.

Die Prüffaktoren Reihenweite und Pflanzendichte hatten keinen gesicherten Einfluss auf die meisten Qualitätsparameter (Gehalte an Eiweiß, NDF, ADF und Lignin). Dagegen zeigten sich signifikante Interaktionen zwischen Sorte und Pflanzendichte in der 1. und 2. Saatzeit in Gießen 2008 und in der 1. Saatzeit in Groß-Gerau 2009. Es wurde festgestellt, dass die Sorte „Goliath“ im Gegensatz zu den Vergleichssorten auf die Verringerung der Pflanzendichte mit einer Reduktion der Eiweißkonzentration reagierte. Die NDF-Werte variierten von 50 bis 56% der TM. In einigen Versuchen wurden hinsichtlich der NDF- und ADF-Konzentration signifikante Interaktionen zwischen den Prüffaktoren Sorte und Pflanzendichte beobachtet.

Die chemische Zusammensetzung der Biomasse von Sorghum wurde deutlich durch die jeweilige Sorte bestimmt. Die Proteinkonzentration der geprüften Sorten variierte von 6 bis 9%. Sorten der Spezies *Sorghum sudanense* (cv. Akklimat und cv. Bovital) wiesen höhere Proteinkonzentrationen auf als Sorten von Sorghum bicolor. Im Gegensatz dazu lagen die Zuckerkonzentrationen bei den *Sorghum bicolor*-Sorten „Rona 1“ bzw. „Aron“ deutlich höher als bei *Sorghum sudanense*. Die geringsten ADF-, NDF- und Aschegehalte wies die Sorte „Rona 1“ auf, gefolgt von der Sorte „Aron“.

Die spezifischen Methanerträge variierten in den durchgeführten Versuchen von 280 bis 387 nL kg^{-1}. Die Sorte „Rona 1“ erreichte die höchsten spezifischen Methanerträge (Normliter CH_4/kg oTS) im Vergleich zu die übrigen Sorten. Dennoch erreichte unter dem Aspekt des Methanertrags/Flächeneinheit die Sorte „Goliath“ die höchsten Erträge, da sie die höchsten Trockenmasseerträge bei gleichzeitig ausreichenden Methangehalten aufwies.

8. References

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9. Appendices

Table A1: ANOVA p values for main effect and interaction between row spacing and cultivars of morphological parameters (Giessen 2008, 2009)

parameter	**2008**			**2009**		
	CV	**RS**	**CV X RS**	**CV**	**RS**	**CV X RS**
Ph 1 (cm)	0.000	0.650	0.905	0.000	0.000	0.920
Ph 2 (cm)	0.000	0.006	0.882	0.000	0.039	0.526
Ph 3 (cm)	0.000	0.035	0.138	0.000	0.560	0.514
LAI 1 m^2/m^2	0.093	0.004	0.768	0.000	0.693	0.760
LAI 2 m^2/m^2	0.112	0.008	0.358	0.027	0.324	0.499
LAI 3 m^2/m^2	0.041	0.002	0.070	0.018	0.000	0.590
DM (t/ha)	0.000	0.841	0.403	0.000	0.000	0.123
DM %	0.083	0.987	0.020	0.000	0.179	0.942
Tillers/m^2	0.006	0.017	0.447	0.000	0.009	0.143

CV = cultivars, RS = row spacing, Cv X RS = interaction between row spacing and cultivars, PL. = plant height, DM = dry matter yield, LAI = leaf area index

Table A2: ANOVA p values for main effect and interaction between row spacing and cultivars of quality parameters (Giessen 2008, 2009)

Parameter	**2008**			**2009**		
	CV	**RS**	**CV X RS**	**CV**	**RS**	**CV X RS**
XP %	0.000	0.013	0.389	0.000	0.000	0.718
XZ %	0.000	0.779	0.229	0.000	0.006	0.851
ADF %	0.000	0.335	0.061	0.000	0.040	0.922
NDF %	0.000	0.284	0.226	0.000	0.000	0.714
ADL %	0.000	0.213	0.429	0.000	0.001	0.118
XL %	0.000	0.168	0.595	0.000	0.000	0.196
XA %	0.023	0.930	0.423	0.000	0.399	0.717

XP = protein, XZ = sugar, ADF = acid detergent fiber, NDF = neutral detergent fiber, ADL= lignin, XL= lipids, XA = ash

Table A3: ANOVA p values for main effect and interaction between row spacing and cultivars of morphological and quality parameters of *Sorghum bicolor* (Gross Gerau 2008, 2009)

Parameter	**2008**			**2009**		
	CV	**RS**	**CV X RS**	**CV**	**RS**	**CV X RS**
DM(t/ha)	0.000	0.652	0.997	0.000	0.522	0.066
Til/m^2	0.000	0.999	0.640	0.000	0.280	0.733
Til/Pl.	0.000	0.999	0.640	0.000	0.280	0.733
DM %	0.000	0.353	0.999	0.000	0.035	0.202
XP %	0.022	0.986	0.502	0.000	0.023	0.381
XZ %	0.000	0.588	0.154	0.000	0.000	0.021
ADF %	0.000	0.354	0.252	0.000	0.014	0.219
NDF %	0.000	0.096	0.014	0.000	0.091	0.028
ADL %	0.000	0.018	0.081	0.000	0.805	0.512
Mt l_N/kg VS	0.411	0.574	0.703	0.000	0.373	0.123
BG l_N/kg VS	0.562	0.639	0.656	0.000	0.434	0.089

XP = protein content, XZ = sugar content, ADF = acid detergent fiber, NDF = neutral detergent fiber, ADL = acid detergent lignin content, DM = dry matter yield, Mt = methane, BG = biogas, VS = volatile solid, lN = norm litter, CV = cultivars, RW = row spacing, m^3N = norm cubic meter, Til = tillers, Pl. = plant

Table A4: ANOVA p values for main effect and interaction between plant density and cultivars of morphological parameters (Giessen 2008)

parameter	1st sowing time			2nd sowing time			3rd Sowing time		
	CV	PD	CV x PD	CV	PD	CV x PD	CV	PD	CV x PD
Ph 1	0.983	0.545	0.436	0.000	0.039	0.250	0.000	0.339	0.674
Ph 2	0.000	0.332	0.112	0.000	0.062	0.525	0.518	0.124	0.127
Ph 3	0.020	0.636	0.298	0.000	0.298	0.760	0.767	0.419	0.462
Ph 4	0.000	0.049	0.386	0.000	0.370	0.320	0.000	0.000	0.066
LAI 1	0.129	0.913	0.815	0.000	0.001	0.031	0.133	0.007	0.730
LAI 2	0.625	0.565	0.623	0.004	0.376	0.255	0.542	0.079	0.471
LAI 3	0.916	0.383	0.127	0.135	0.049	0.260	0.000	0.008	0.125
LAI 4	0.092	0.043	0.130	0.106	0.006	0.306	0.198	0.689	0.299
Tiller m^2	0.002	0.693	0.495	0.002	0.427	0.990	0.000	0.000	0.124
DM%	0.004	0.335	0.708	0.279	0.771	0.867	0.000	0.841	0.013
DMY	0.189	0.452	0.05	0.004	0.703	0.692	0.000	0.821	0.008

CV = cultivars, Ph = plant height, LAI = leaf area index, DM% = dry matter percentage, DMY = dry matter yield, PD = plant density

Table A5: ANOVA p values for main effect and interaction between plant density and cultivars of quality parameters (Giessen 2008)

parameter	1st sowing time			2nd sowing time			3rd Sowing time		
	CV	PD	CV x PD	CV	PD	CV x PD	CV	PD	CV x PD
XP%	0.013	0.125	0.000	0.000	0.001	0.001	0.930	0.005	0.210
XZ%	0.259	0.560	0.349	0.067	0.524	0.585	0.164	0.495	0.164
XA%	0.393	0.006	0.000	0.374	0.912	0.036	0.028	0.567	0.001
ADF%	0.009	0.672	0.000	0.431	0.595	0.000	0.064	0.582	0.175
NDF%	0.004	0.465	0.000	0.632	0.393	0.029	0.386	0.688	0.115
ADL%	0.049	0.976	0.000	0.142	0.288	0.000	0.166	0.487	0.191
XL%	0.014	0.096	0.003	0.000	0.000	0.000	0.517	0.003	0.093

XP = protein, XZ = sugar, ADF = acid detergent fiber, NDF = neutral detergent fiber, ADL= lignin, XL= lipids, XA = ash

Table A6: ANOVA p values for main effect and interaction between plant density and cultivars of morphological parameters (Gross Gerau 2008)

parameter	**1st sowing time**			**2nd sowing time**			**3rd Sowing time**		
	CV	**PD**	**CV x PD**	**CV**	**PD**	**CV x PD**	**CV**	**PD**	**CV x PD**
LDMP	0.908	0.361	0.828	0.000	0.620	0.813	0.006	0.654	0.884
SDMP	0.000	0.271	0.657	0.000	0.739	0.836	0.000	0.786	0.845
PDMP	0.000	0.161	0.259	0.000	0.456	0.570	0.000	0.480	0.311
Tiller m^{-2}	0.819	0.000	0.131	0.039	0.001	0.085	0.001	0.559	0.114
DMY	0.000	0.213	0.770	0.000	0.000	0.106	0.000	0.000	0.308
DM%	0.338	0.948	0.002	0.048	0.033	0.670	0.806	0.821	0.366

LDMP = leaf dry matter proportion, SDMP = stem dry matter proportion, PDMP = panicle dry matter proportion

Table A7: ANOVA p values for main effect and interaction between plant density and cultivars of quality parameters (Gross Gerau 2008)

parameter	**1st sowing time**			**2nd sowing time**			**3rd Sowing time**		
	CV	**PD**	**CV x PD**	**CV**	**PD**	**CV x PD**	**CV**	**PD**	**CV x PD**
XP%	0.004	0.579	0.933	0.048	0.666	0.750	0.102	0.008	0.675
XZ%	0.000	0.419	0.574	0.966	0.653	0.461	0.106	0.005	0.649
XA%	0.013	0.302	0.593	0.293	0.422	0.846	0.002	0.005	0.505
ADF%	0.000	0.452	0.264	0.002	0.660	0.433	0.051	0.697	0.247
NDF%	0.032	0.717	0.121	0.000	0.705	0.738	0.080	0.941	0.071
ADL%	0.002	0.549	0.195	0.011	0.694	0.973	0.64	0.108	0.045
XL%	0.000	0.134	0.743	0.003	0.971	0.429	0.031	0.008	0.087
BGY	0.441	0.510	0.769	0.000	0.978	0.910	0.623	0.811	0.418
MY	0.643	0.553	0.711	0.000	0.952	0.785	0.945	0.701	0.411
Meth%	0.000	0.325	0.077	0.850	0.199	0.150	0.000	0.081	0.087

XP = protein, XZ = sugar, ADF = acid detergent fiber, NDF = neutral detergent fiber, ADL= lignin, XL= lipids, XA = ash, BGY = biogas yield, MY = methane yield, Meth = methane

Table A8: ANOVA p values for main effect and interaction between plant density and cultivars of morphological parameters (Rauischholzhausen 2008)

parameter	**1st sowing time**			**2nd sowing time**			**3rd Sowing time**		
	CV	**PD**	**CV x PD**	**CV**	**PD**	**CV x PD**	**CV**	**PD**	**CV x PD**
Ph	0.000	0.157	0.135	0.000	0.965	0.785	0.000	0.573	0.707
Tiller pl^{-1}	0.000	0.001	0.007	0.000	0.508	0.777	0.000	0.629	0.394
Tiller m^{-2}	0.000	0.014	0.965	0.000	0.295	0.240	0.000	0.178	0.015
DMY	0.000	0.090	0.487	0.000	0.102	0.358	0.000	0.006	0.842
DM%	0.715	0.033	0.792	0.131	0.771	0.917	0.741	0.098	0.531

Table A9: ANOVA p values for main effect and interaction between plant density and cultivars of quality parameters (Rauischholzhausen 2008)

parameter	**1st sowing time**			**2nd sowing time**			**3rd Sowing time**		
	CV	**PD**	**CV x PD**	**CV**	**PD**	**CV x PD**	**CV**	**PD**	**CV x PD**
XP%	0.000	0.224	0.643	0.001	0.058	0.461	0.000	0.112	0.826
XZ%	0.002	0.442	0.474	0.252	0.198	0.142	0.000	0.218	0.990
XA%	0.177	0.258	0.918	0.001	0.019	0.945	0.000	0.074	0.103
ADF%	0.000	0.787	0.810	0.000	0.191	0.070	0.270	0.435	0.787
NDF%	0.029	0.948	0.906	0.000	0.448	0.131	0.231	0.217	0.743
ADL%	0.000	0.989	0.958	0.000	0.029	0.294	0.189	0.937	0.705
XL%	0.000	0.618	0.872	0.048	0.521	0.551	0.000	0.752	0.833
BGY	0.387	0.134	0.451	0.002	0.146	0.078	0.002	0.052	0.670
MY	0.374	0.111	0.428	0.001	0.132	0.008	0.000	0.115	0.542
Meth%	0.861	0.715	0.372	0.433	0.565	0.018	0.207	0.684	0.029

XP = protein, XZ = sugar, ADF = acid detergent fiber, NDF = neutral detergent fiber, ADL= lignin, XL= lipids, XA = ash, BGY = biogas yield, MY = methane yield, Meth = methane

Table A10: ANOVA p values for main effect and interaction between plant density and cultivars of morphological parameters (Giessen 2009)

Parameter	**1st sowing time**			**2nd sowing time**			**3rd Sowing time**		
	CV	**PD**	**CV x PD**	**CV**	**PD**	**CV x PD**	**CV**	**PD**	**CV x PD**
Ph 1	0.000	0.019	0.130	0.103	0.024	0.304	0.006	0.108	0.310
Ph 2	0.006	0.222	0.307	0.004	0.138	0.843	0.004	0.496	0.175
Ph 3	0.016	0.103	0.384	0.002	0.266	0.233	0.008	0.469	0.437
LAI 1	0.030	0.007	0.322	0.078	0.018	0.019	0.000	0.563	0.005
LAI 2	0.524	0.113	0.509	0.220	0.069	0.972	0.413	0.068	0.241
LAI 3	0.022	0.059	0.197	0.740	0.051	0.925	0.468	0.261	0.976
Tiller m^{-2}	0.000	0.000	0.831	0.000	0.000	0.139	0.000	0.000	0.5137
DM%	0.878	0.802	0.202	0.035	0.020	0.720	0.000	0.338	0.520
DMY	0.000	0.103	0.919	0.000	0.001	0.268	0.063	0.544	0.624

Table A11: ANOVA p values for main effect and interaction between plant density and cultivars of quality parameters (Giessen 2009)

parameter	**1st sowing time**			**2nd sowing time**			**3rd Sowing time**		
	CV	**PD**	**CV x PD**	**CV**	**PD**	**CV x PD**	**CV**	**PD**	**CV x PD**
XP%	0.000	0.297	0.728	0.000	0.014	0.388	0.000	0.465	0.882
XZ%	0.000	0.174	0.756	0.000	0.353	0.018	0.009	0.858	0.0541
XA%	0.000	0.149	0.536	0.000	0.002	0.157	0.004	0.846	0.684
ADF%	0.046	0.219	0.587	0.000	0.306	0.152	0.000	0.829	0.064
NDF%	0.000	0.357	0.071	0.000	0.563	0.005	0.008	0.838	0.102
ADL%	0.055	0.434	0.453	0.009	0.036	0.325	0.337	0.751	0.337
XL%	0.000	0.127	0.113	0.000	0.095	0.800	0.000	0.937	0.333

XP = protein, XZ = sugar, ADF = acid detergent fiber, NDF = neutral detergent fiber, ADL= lignin, XL= lipids, XA = ash

Table A12: ANOVA p values for main effect and interaction between plant density and cultivars of morphological parameters (Gross Gerau 2009)

parameter	**1st sowing time**			**2nd sowing time**			**3rd Sowing time**		
	CV	**PD**	**CV x PD**	**CV**	**PD**	**CV x PD**	**CV**	**PD**	**CV x PD**
LDMP	0.000	0.025	0.298	0.000	0.734	0.189	0.240	0.388	0.318
SDMP	0.000	0.124	0.359	0.000	0.256	0.659	0.000	0.333	0.054
PDMP	0.000	0.208	0.135	0.000	0.416	0.504	0.000	0.715	0.226
Tiller m^{-2}	0.001	0.000	0.394	0.000	0.005	0.064	0.000	0.010	0.000
DMY	0.000	0.437	0.324	0.001	0.402	0.731	0.000	0.405	0.264
DM%	0.616	0.403	0.788	0.642	0.889	0.369	0.248	0.833	0.358

LDMP = leaf dry matter proportion, SDMP = stem dry matter proportion, PDMP = panicle dry matter proportion

Table A13: ANOVA p values for main effect and interaction between plant density and cultivars of quality parameters (Gross Gerau 2009)

parameter	**1st sowing time**			**2nd sowing time**			**3rd Sowing time**		
	CV	**PD**	**CV x PD**	**CV**	**PD**	**CV x PD**	**CV**	**PD**	**CV x PD**
XP%	0.000	0.372	0.006	0.000	0.671	0.930	0.007	0.711	0.418
XZ%	0.000	0.116	0.580	0.000	0.681	0.788	0.000	0.639	0.538
XA%	0.132	0.936	0.144	0.311	0.392	0.040	0.511	0.328	0.004
ADF%	0.000	0.963	0.698	0.000	0.347	0.029	0.000	0.287	0.900
NDF%	0.292	0.372	0.128	0.005	0.275	0.125	0.604	0.338	0.405
ADL%	0.000	0.797	0.881	0.000	0.410	0.028	0.000	0.042	0.496
XL%	0.000	0.800	0.326	0.000	0.488	0.072	0.000	0.900	0.106
BGY	0.147	0.397	0.478	0.029	0.710	0.051	0.000	0.300	0.622
MY	0.164	0.389	0.449	0.035	0.832	0.049	0.000	0.284	0.637
Meth%	0.460	0.409	0.617	0.425	0.802	0.503	0.290	0.142	0.946

XP = protein, XZ = sugar, ADF = acid detergent fiber, NDF = neutral detergent fiber, ADL= lignin, XL= lipids, XA = ash, BGY = biogas yield, MY = methane yield, Meth = methane

Table A14: ANOVA p values for main effect and interaction between plant density and cultivars of morphological parameters (Rauischholzhausen 2009)

Parameter	**1st sowing time**			**2nd sowing time**			**3rd Sowing time**		
	CV	**PD**	**CV x PD**	**CV**	**PD**	**CV x PD**	**CV**	**PD**	**CV x PD**
Tiller m^{-2}	0.000	0.018	0.236	0.006	0.005	0.649	0.000	0.075	0.069
Tiller Pl^{-1}	0.008	0.266	0.857	0.000	0.386	0.157	0.001	0.634	0.656
DM%	0.120	0.253	0.0203	0.595	0.269	0.695	0.073	0.024	0.097
DMY	0.000	0.015	0.091	0.000	0.000	0.0896	0.000	0.063	0.306

Table A15: ANOVA p values for main effect and interaction between plant density and cultivars of quality parameters (Rauischholzhausen 2009)

parameter	**1st sowing time**			**2nd sowing time**			**3rd Sowing time**		
	CV	**PD**	**CV x PD**	**CV**	**PD**	**CV x PD**	**CV**	**PD**	**CV x PD**
XP%	0.000	0.007	0.1753	0.000	0.250	0.831	0.000	0.900	0.892
XZ%	0.000	0.314	0.772	0.001	0.471	0.069	0.618	0.495	0.711
XA%	0.013	0.985	0.374	0.000	0.676	0.363	0.091	0.331	0.771
ADF%	0.206	0.902	0.863	0.000	0.125	0.000	0.048	0.523	0.742
NDF%	0.236	0.695	0.868	0.000	0.051	0.000	0.068	0.603	0.775
ADL%	0.457	0.828	0.889	0.000	0.1329	0.000	0.234	0.452	0.643
XL%	0.016	0.928	0.617	0.000	0.280	0.034	0.001	0.483	0.793

XP = protein, XZ = sugar, ADF = acid detergent fiber, NDF = neutral detergent fiber, ADL= lignin, XL= lipids, XA = ash

Declaration / Erklärung

I declare: this dissertation submitted is a work of my own, written without any illegitimate help by any third party and only with materials indicated in the dissertation. I have indicated in the text where I have used texts from already published sources, either word for word or in substance, and where I have made statements based on oral information given to me. At any time during the investigations carried out by me and described in the dissertation, I followed the principles of good scientific practice as defined in the “Statutes of the Justus Liebig University Giessen for the Safeguarding of Good Scientific Practice”.

„Ich erkläre: Ich habe die vorgelegte Dissertation selbständig und ohne unerlaubte fremde Hilfe und nur mit den Hilfen angefertigt, die ich in der Dissertation angegeben habe. Alle Textstellen, die wörtlich oder sinngemäß aus veröffentlichten Schriften entnommen sind, und alle Angaben, die auf mündlichen Auskünften beruhen, sind als solche kenntlich gemacht. Bei den von mir durchgeführten und in der Dissertation erwähnten Untersuchungen habe ich die Grundsätze guter wissenschaftlicher Praxis, wie sie in der „Satzung der Justus-Liebig-Universität Gießen zur Sicherung guter wissenschaftlicher Praxis“ nie dergelegt sind, eingehalten.“

Athar Mahmood

Giessen, October 29, 2011 **(Athar Mahmood)**

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At the end I admit that errors that remain are mine

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