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Food, Agriculture and Fisheries, and Biotechnology

Specific International Co-operation Actions
Small or medium scale focused research project

Sweet Fuel

Sweet Sorghum
an alternative energy Crop

SWEETFUEL / Grant Agreement n° 227422

WP6

Deliverable 6.2:

Report on technological assessment

Composition of the consortium

CIRAD
ICRISAT
EMBRAPA
KWS
IFEU
UniBO
UCSC
ARC-GCI
UANL
WIP

SWEETFUEL:
Sweet Sorghum: an alternative energy crop

Deliverable 6.2:
Report on technological assessment

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1 Introduction

Bioethanol is one part in the increasing use of biofuels. Worldwide, sugar cane is the main source of bioethanol; however, the cultivation of this crop cannot be realised in water-limited or temperate regions. On this background, sweet sorghum (*Sorghum bicolor* (L.) Moench) has several advantages due to its efficiency in both, water use and nutrient uptake. Furthermore, the production of food, feed and fuel can be combined in one crop. This is an important asset on the background of the currently increasing discussion on fuel production and food security.

As the more widespread use of energy sorghum for bioethanol production is primarily limited by the lack of cultivars specifically bred for this purpose, a project funded by the European Commission with the title “Sweet Sorghum: an alternative energy crop” (SWEETFUEL) was launched (Grant agreement no. 227422). This project aims at developing sweet sorghum and biomass sorghum cultivars for tropical, semi-arid and temperate environments. The focus lies on tolerance to cold, drought and acid soil as well as on a high production of stalk sugars, easily digestible biomass and grains. The focus is thereby dependent on the environment the crop is cultivated in and the purpose it is used for. The project is split in seven work packages (WPs). WPs 1-5 focus on breeding aspects as well as cultivation and harvest practices. Based on the results of WPs 1-5, WP 6 performs a global assessment while WP 7 transfers project results to the stakeholders.

WP 6 “Integrated assessment” of this project provides a multi-criteria evaluation of the sorghum production and use pathways taking into account technological, environmental, economic and social aspects. The outcome of the integrated assessment will be a set of optimised, sustainable sorghum production and use systems.

This report is the outcome of Task 6.1 “Technological assessment” as part of WP 6 “Integrated assessment” of the SWEETFUEL project. It was composed by CIRAD in collaboration with IFEU and with contributions from all partners, namely ARC, EMBRAPA, ICRISAT, KWS, UANL, UCSC, UNIBO and WIP. It provides definitions and settings as a basis for the whole work package. Included are the descriptions of system boundaries and settings, the definitions and descriptions of sweet and biomass sorghum scenarios as well as of respective reference systems. Furthermore, the methodology and results of the technological assessment are presented.

Concerning the scenarios, all target systems and corresponding sorghum variants are considered. Concerning the reference systems, all by-products such as bagasse and all alternative land use scenarios are assessed. The technological assessment demonstrates potentials and technological constraints of all three sorghum variants under investigation.

The following chapter of the report defines general specifications and settings as well as the methodology of the technological assessment (chapter 2). In chapter 3 the descriptions of sweet and biomass sorghum scenarios are presented. The results from the technological assessment are described in chapter 4. The report is concluded in chapter 5 and recommendations are given. Chapter 6 lists references and chapter 7 specifies abbreviations and terms that need to be defined.

2 General settings and methodology

To guarantee consistency between all assessments conducted in work package 6, general specifications and settings are necessary as described in subchapter 2.1. In the subsequent subchapter (2.2) the principle of life cycle comparisons is defined and in subchapter 2.3 the methodology of the technological assessment is specified.

2.1 General specifications, settings and definitions

For the analysis of the investigated scenarios, general definitions and settings are necessary. They are used to assess environmental, economic and social implications and guarantee their consistency. The general definitions and settings are described and explained below.

Definition of sorghum variants

In the plant breeding community, it is quite common to distinguish crops into lines, varieties and hybrids:

Line: Breeding material which tends to be genetically identical.

Variety: Elite lines that are ready to be released as open pollinated variety.

Hybrid: Offspring resulting from the interbreeding between two parental lines. Hybrids cannot be reproduced by farmers.

Cultivar: Plant or group of plants selected for some desirable characteristics. Cultivar is a general word that includes lines, varieties and hybrids.

For further descriptions of sorghum lines and hybrids see “Energy sorghum handbook” /Khawaja et al. 2013/.

Sorghum is a crop which has quite a large diversity in phenotypic variability and composition. In the SWEETFUEL project the following terminologies are used:

Sweet sorghum: Sorghum cultivars with juicy stems and high juice sugar content in their stalks; potentially used as an energy and / or food crop.

Biomass sorghum: Sorghum cultivars with high lignocellulosic biomass yield, potentially used as energy crop.

Energy sorghum: Sweet and biomass sorghum cultivars used in this project.

Grain sorghum: Sorghum cultivars with high grain yield established as food and feed crop.

Fibre sorghum: Sorghum cultivars with a high content of fibre; potentially used as fibre or energy crop.

This project mainly focuses on sweet and biomass sorghum, whereas grain sorghum is treated as a reference system. Fibre sorghum cultivars are not investigated in this project.

For the sake of simplicity the differentiation between lines, varieties and hybrids is only used in the further course of this report if a distinction is essential.

Time frame

In this project the use of sweet and biomass sorghum for both, 1st generation as well as 2nd generation fuel technologies is assessed. The former, i. e. the production of bioethanol is already well-established. In contrast, second generation technologies such as the production of ethanol from lignocellulose or the biomass gasification for so-called BtL (Biomass-to-Liquid) fuels are not yet commercially available, however, pilot and demonstration plants are operated in some countries (e. g. Europe, USA, Brazil, China, India). In this project prospective conditions given in the year 2020 are considered as main scenario since it is expected that the technology described will be mature then and thus comparable with other 1st generation ethanol production technologies. Additionally, the situation in 2015 is described for some scenarios since this reflects the state of the art at the end of the project which is currently existent in Brazil for instance.

Geographical coverage

Sweet sorghum: In general, sweet sorghum is a manifold plant which can be cultivated in many parts of the world. Due to its high efficiency in water use and light exploitation it is particularly suitable for semi-arid and subtropical areas. Additionally, however, it is also thoroughly suitable for tropical regions. Thus, the following scenarios are defined for sweet sorghum cultivation:

- Subtropical / semi-arid climate with around 700 mm rainfall
- Tropical climate with around 1,200 mm rainfall per year.

Biomass sorghum: In future, biomass sorghum will be mainly cultivated to obtain high biomass yields for biogas production. This requires protruding growing conditions. Coming along with the recent discussion on fuel versus food as well as political regulations, biomass sorghum has a high potential to be cultivated especially in temperate regions. Thus, for this investigation biomass sorghum scenarios are only settled in those areas.

Within the regions investigated in this project, there might be great differences due to differences in environmental conditions as well as due to varying production practices and conditions in different countries. These differences are captured by sub-scenarios and sensitivity analyses taking into account different yields, uses of the (by-)products or production costs etc. It is outside the scope of the project to analyse every single country where sweet or biomass sorghum could be produced. However, if country specific conditions have a significant influence on the results, single countries may be chosen to show these dependencies. This might be the case for labour costs or emissions from electricity generation.

Functional unit

The functional unit has to be chosen depending on the questions to be answered. As the project aims at increasing the output of the crop by developing improved cultivars and since land usually is the limiting factor, the use of sorghum cultivars from 1 hectare of land is assessed.

Alternative land use options

The alternative land use defines how the land would be used if energy sorghum was not cultivated. It also comprises any change in land cover induced by the cultivation of energy sorghum. As agricultural land is becoming increasingly scarce, more and more natural land (e. g. forests or grass land) is transformed into arable land. Such land use and land cover changes may have considerable influences on the outcomes of the ecological assessment since e. g. the area’s carbon stock or biodiversity are influenced. For example, a decline in above-ground and below-ground carbon stocks leads to greenhouse gas emissions, which have to be included in the greenhouse gas balance. Beside direct land use changes also indirect changes can occur. This is the case if for example the cultivation of sweet sorghum displaces the production of a food crop to other areas. Depending on use and / or land cover of that area, the displacement can cause different environmental effects.

The alternative land use also needs to be taken into account if energy sorghum is cultivated on areas that become free due to the intensification of existing land use. Since on these areas natural ecosystems could emerge if energy sorghum was not cultivated, these potential ecosystems need also be taken into account as reference systems.

In this project, the standard scenario refers to reference systems where the difference in carbon stock between initial vegetation and energy sorghum cultivation is close to zero. This includes reference systems such as degraded soils, degraded pastures or land that becomes free due to the intensification of existing land use. Furthermore, also idle land can be used to cultivate energy sorghum. In the further course of the report all these land use options are referred to as **“idle land”**.

In order to derive a bandwidth of different vegetation types for the alternative land use, two reference systems are identified which are captured by sensitivity analyses:

- Dense thickets / sparse forests (carbon loss around 60 t carbon / hectare)
- Wooded grassland / planted pastures / (carbon loss around 15 t carbon / hectare)

This classification is mainly oriented at the carbon difference which occurs if reference vegetation is replaced by energy sorghum cultivation. The carbon loss given here serves the purpose to characterise the reference systems. They do not reflect real carbon contents but serve as an indicative differentiation between the different reference systems defined.

Since the alternative land use differs among scenarios, more detailed descriptions are specified within respective scenario descriptions (see subchapters 3.1 and 3.2).

Technical reference

The technical reference describes the technology to be assessed in terms of plant capacity and development status / maturity. As the investigated scenarios cover both, “central” and “decentralised production at village level” two main technical references were defined:

- 25,000 – 120,000 t ethanol per year production capacity in the case of centralised production.
- 3 t syrup per day in the case of decentralised production.
- For all plant capacities, mature, full industrial plants will be assessed.

2.2 Principles for scenario settings

All scenario descriptions and the flow charts for the energy sorghum scenarios presented in subchapters 3.1 and 3.2 follow the principle of so-called life cycle comparisons. A schematic overview can be seen in Fig. 2-1. The whole life cycle of a product, e. g. of sweet sorghum ethanol, is assessed. The life cycle follows the “cradle-to-grave approach” starting from cultivation through production, use, end-of-life treatment, recycling and final disposal. All inputs into and outputs from the system are taken into account. During production, several by-products may be obtained. For example, in ethanol production from sweet sorghum, bagasse is derived as a by-product. The by-products substitute conventionally produced equivalent products. For bagasse this may be electricity from the grid if bagasse is combusted for bioenergy production. These conventional products do not have to be produced anymore. In the environmental assessment, this substitution is included with a credit that is given for the energy and emission savings in order to produce the equivalent products.

Finally, the whole life cycle of the product is compared to the use (and thus to the life cycle) of a conventional product that is replaced. As an example, sweet sorghum ethanol replaces conventional gasoline, thus both life cycles are compared.

In order to understand and consequently optimise the scenarios under investigation, selected life cycle stages are varied and different production and use conditions are assessed with sensitivity analyses.

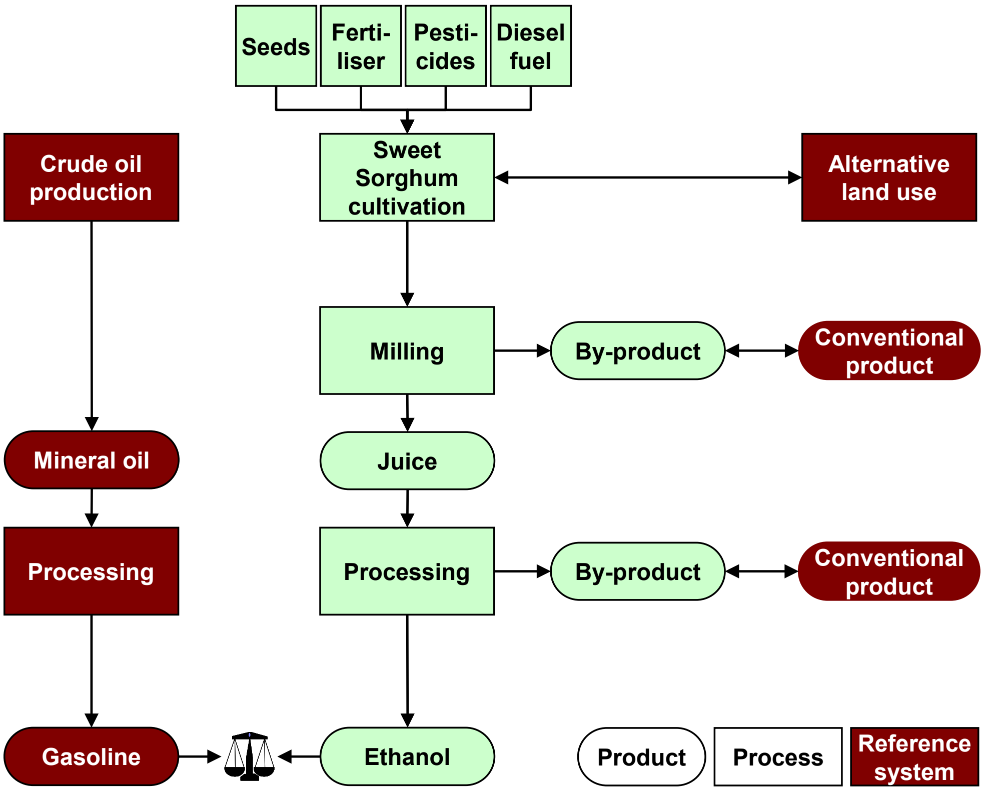

Fig. 2-1 Basic principle of life cycle comparison between sweet sorghum ethanol and gasoline

2.3 Methodology of technological assessment

The technological assessment assesses differences in technology of energy sorghum cultivation and processing systems investigated in this project. For that, different indicators were defined and evaluated. A special focus was laid on cultivation aspects since those can differ greatly due to different growing regions coupled with various production practices, environmental conditions and economic resources.

The following indicators have been identified and are applied in the technological assessment:

- **Cultivation experience**

  This parameter indicates the level of experience to cultivate sorghum variants.

- **Relative importance of sorghum**

  This indicator demonstrates the relative importance of sorghum cultivation.

- **Level of used production technology**

  This indicator describes the dependence of sorghum productivity on production technology.

- **Suitability of sorghum cultivation**

  This indicator describes if sorghum can be cultivated in various regions in the world.

- **Annual / perennial**

  This indicator describes if the cultivars need to be sown after each growing cycle (annual) or if they sprout without sowing (perennial).

- **Seed production**

  This indicator states if seeds from in-house production can be used or if seeds need to be bought externally.

- **Availability of improved material**

  This indicator would precise if the seeds of cultivars are available on the market and in which quantity.

- **Breeding potential**

  This parameter describes the potential to breed new ideotypes carrying a higher yield (e. g. by prolonging the growing season) or being more resistant to salt, drought or pests.

- **GMO technology**

  This indicator states if genetically modified organisms (GMOs) are used or involved.

- **Need for pesticide application**

  This indicator describes the vulnerability of all three investigated sorghum variants to pest infestations.

- **Need for fungicide application**

  Describes the vulnerability of sorghum variants to fungi infestations.

- **Need for irrigation**

  The indicator describes the need for artificial irrigation.

- **Need for nutrients**

  The indicator describes the need for nutrients, especially macronutrients such as nitrogen, phosphorus and potassium.

- **Resistance to lodging**

  The indicator states the resistance of all three investigated sorghum variants against strong winds.

- **Resistance against moderate drought**

  The indicator shows the resistance of sorghum variants to moderate drought events.

- **Moisture content**

  This indicator describes the moisture content of the sorghum part which is harvested (depends on the cultivar e. g. grains, biomass or stalks) at the time of harvest.

- **Harvest technology (today)**

  The indicator shows if mature harvest technology dedicated for each sorghum variant is in existence.

- **Harvest technology (potential)**

  The indicator shows if there will be access to mature harvest technology specified for each sorghum variant in future.

- **Storage capability of juice**

  This indicator covers the capability to store sweet sorghum juice without yield loss.

- **Storage capability of syrup**

  This indicator covers the capability to store syrup.

- **Juice extraction efficiency**

  This parameter describes the juice extraction efficiency from sweet sorghum stalks.

- **Use of sorghum plant parts**

  This indicator describes if other parts of the plant besides juice can be used.

- **Potential use options of lignocellulosic by-products**

  In the future, lignocellulosic by-products from sorghum cultivation or processing (e. g. bagasse) may be used for other purposes than for cogeneration, fertilising or feeding.

- **Use of sorghum plant parts**

  This indicator describes if other parts of the plant besides juice can be used.

- **Conversion efficiency (today)**

  This parameter describes the conversion efficiency of juice or biomass to the respective end product as well as of juice to syrup.

- **Conversion efficiency (future)**

  The parameter shows the potential of conversion technology to be more efficient in future.

- **World market potential**

  This indicator is related to the potential to sell stalks / juice, syrup, biomass or grains of all three investigated sorghum variants on the world market.

- **Technological challenges / bottlenecks**

  This indicator pinpoints further challenges which have to be resolved.

- **Policy regime**

  This parameter indicates favourable pricing policies to promote new feedstocks such as sweet and biomass sorghum.

3 Results: Scenarios

The following subchapters contain all scenario descriptions illustrated by flow charts (subchapters 3.1 and 3.2). Scenarios follow general specifications and settings defined in subchapter 2.1 and are based on principles specified in subchapter 2.2. In subchapter 3.3 all scenarios are summarised.

3.1 Sweet sorghum scenarios

First of all, this section describes the cultivation environment, the ethanol production systems and the use options of ethanol for all sweet sorghum scenarios investigated in this project. Subsequently, all sweet sorghum scenarios are presented in detail and described with flow charts and some short explanations (subchapters 3.1.1 to 3.1.4). The descriptions follow the life cycle of sweet sorghum production and processing until the use of the main product and all by-products (including conventional products that are replaced). They also cover the definitions and descriptions of respective reference systems. Sensitivity analyses are described in subchapter 3.1.4. An overview of all scenarios is given in subchapter 3.3.

Cultivation environment and production systems

The breeding objectives of sweet sorghum scenarios target two cultivation environments: tropical or sub-tropical climates with summer rains and acid soils in tropical, moist savannahs (about 1,200 mm rainfall per year), where soil acidity is the most important abiotic constraint. Or semi-arid climates (about 700 mm rainfall per year), where rainfall and thus water availability is the limiting factor. Besides water use efficiency and sensitivity to soil acidity, sweet sorghum differs regarding grain production, stalk juice and sugar content. The yield differ-

ences and related differences in cultivation practices (e. g. the amount of fertiliser as well as harvesting expenditures) are parameters that considerably influence the outcomes of the economic and environmental analyses. The influence of yield differences and thus cultivation practices on the overall results is assessed via sensitivity analyses (see subchapter 3.1.4). The target systems are centralised production systems (subchapters 3.1.1 and 3.1.2) as well as decentralised production systems with part of the production being realised at village level (subchapter 3.1.3).

Use of ethanol

In this project, the main purpose to produce sweet sorghum as an energy crop is to produce ethanol and use it as a biofuel for transportation. The focus is thereby on first generation ethanol as the technology is already available and wide-spread. Second generation will most likely not be established in the foreseeable future.

As a further option in this scenario, the use of ethanol for the production of cooking gel has been suggested. For doing so, ethanol is heated together with calcium acetate and water. The cooking gel is storable over a longer period of time and can be used in stoves, replacing the use of wood, paraffin or liquefied petroleum gas (LPG). Its use is especially promoted in Africa as more environmentally friendly and, more important, less harmful to health than wood or paraffin.

First experiences with the sale of cooking gel have been made in South Africa and Kenya. However, there is evidence that cooking gel might only be of limited use for household application due to following reasons:

- Firstly, cooking gel burns a lot cooler than liquid ethanol. Therefore, food that requires a hot flame for cooking cannot be prepared. All other food preparation consumes much more time, as less heat is getting into the pot.
- Second – because there is the additional process of turning it into a gel – it is more expensive. It is very unlikely that people on low incomes want to use gelfuel as a heating fuel – this seems more to be a product for the more affluent societies. People may find it expensive even as a cooking fuel.
- Finally, it gives out more pollutants – and this is because of its gelling nature – so although people say it is safer as it is a gel – the pollutant levels are higher and we’re all trying to get fuel as clean as possible to reduce levels of respiratory illness. It is said, that if you get hot burning gelfuel on your hands, it is very dangerous indeed. Without the gelling agent, ethanol is intrinsically very clean – when it burns efficiently, there are minute amounts of pollutant – it goes all to water vapour and carbon dioxide. By adding a gelling agent, not enough air gets into the mix and it gives off substantially more pollutant – and at the same time, the carbon in the pollutant that should have been creating heat is left unburnt. This is nowhere near the levels for wood fuel – but it is not ‘fixable’.

Therefore, gel pathways are not investigated in detail. Nevertheless, a basic scenario for sweet sorghum ethanol use as gel is considered already by the main scenario substituting gasoline by sweet sorghum ethanol, because less ethanol is available as a transportation fuel if it is used as a cooking fuel.

Furthermore, there were also trials to use liquid ethanol for cooking; however, since the perspectives for a commercialisation are also limited, we did not include this scenario as well.

Generally, sweet sorghum cultivation and use is described in three different scenarios: cane fallow, grain to food and syrup production. In all scenarios the main product is ethanol. However, the scenarios differ with respect to the processing of the sugar juice and the use of the by-products. In the cane fallow and syrup scenarios (see subchapters 3.1.1 and 3.1.3) grains are either used as fertiliser, for ethanol production or as feed. In the syrup production scenario the sugar juice is in a first processing step boiled down to syrup which is used to produce ethanol in a proceeding conversion process. The focus of the grain to food scenario (see subchapter 3.1.2) lies on the use of sweet sorghum as multi-purpose crop to limit food / fuel trade-offs. This means that the grains are used as food whereas juice is used for energy production. In the following subchapters all scenarios are described in detail.

3.1.1 Cane fallow scenarios

In the cane fallow scenarios sweet sorghum interacts as an intermediate food crop e. g. after a 5 year sugar cane cycle, replacing intermediate crops such as soy or peanuts. Growing sweet sorghum instead of other intermediate crops broadens the production processing window of sugar cane ethanol plants which has great economic advantages. Thus, in Brazil, for instance, where the sugar cane industry has a high local value, this scenario is already realised sporadically nowadays. However, in the future, this scenario is also conceivable in other regions cultivating sugar cane. To further guarantee the production of former intermediate crops, they need to be grown on alternative land which often needs to be transformed primarily into arable land. Alternative land use options could be several, such as dense thickets, wooded grasslands or degraded soils and pastures. Those options are described in more detail in subchapter 2.1. Furthermore, sweet sorghum can also be cultivated on fertile land that has not been used for crop cultivation yet as it can be found e. g. in the southeast of Mexico. Methodically, this leads to the same land use comparison as if sweet sorghum was cultivated as an intermediate crop. In the further course of this report all these scenarios are referred to as **“cane fallow”** even though it covers scenarios in which sweet sorghum is cultivated as intermediate crop as well as scenarios in which sweet sorghum is cultivated on “idle land”.

In this project prospective conditions imaginable for the year 2020 are considered as main cane fallow scenario. Additionally, the situation in 2015 is described since this reflects the state of the art at the end of the project. Both scenarios are almost identical except the use of grains. In 2020, it is expected that the grains of sweet sorghum are used for ethanol production; however, in 2015 grains of sweet sorghum remain on the field, replacing mineral fertiliser.

Cane fallow

An overview of the cane fallow scenario is given in Fig. 3-1. After harvest, the sweet sorghum stalks and grains are transported from the villages to centralised ethanol facilities. The leaves either remain on the field (1 a), replacing mineral fertiliser or are used for energy production (1 b).

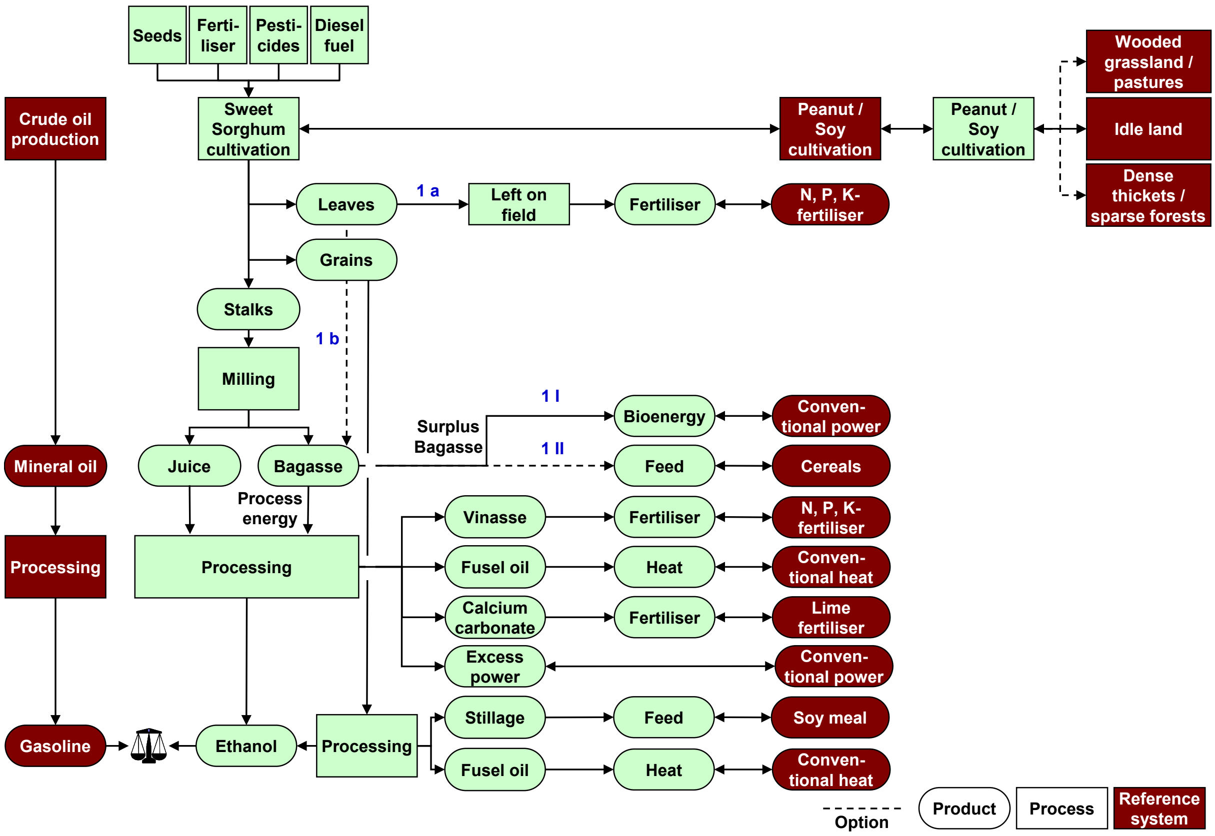

Fig. 3-1 Schematic overview of the cane fallow scenario (scenario 1); numbers indicate scenario numbers (for a summary, see Table 3-1)

In the central ethanol production units, the sweet sorghum stalks are crushed and the juice is pressed out, leaving bagasse. The juice is fermented into ethanol which is used as transport fuel, replacing conventional gasoline (for other ethanol use options (e. g. cooking gel) see explanations in subchapter 3.1 “Cultivation environment and production systems”).

From the bagasse process energy is generated which is used internally in the ethanol production process. Surplus bagasse is either used for generating green power that is fed into the power grid replacing conventionally produced electricity (1 I) or as animal feed, replacing cereals (1 II). In certain regions, bagasse is a very popular animal feed. For example in India, feed traders travel up to 100 km in order to buy the bagasse.

Other by-products derived during ethanol production are vinasse, stillage, excess power, fusel oils and carbonation lime. Vinasse is obtained as by-product if sugar juice is processed and can be used as fertiliser, replacing mineral fertiliser. Stillage is a by-product which occurs if grains are processed to ethanol and can be used as feed, replacing soy meal. Excess

power occurs while process energy is generated from the bagasse, replacing conventional power. For energy generation, bagasse is combusted in a combined heat and power unit. If the heat demand is covered but less power is needed for the conversion process, excess power occurs which can be sold. Fusel oils are converted into heat, replacing conventional heat. For fusel oils, the use in the aroma industry has been indicated as one use option. However, the extraction of fusel oils for a use in industry requires a lot of energy. Up to now, there is no evidence that this is realisable at acceptable efforts and costs. Thus, this option is not analysed within this project. In case of ethanol production from juice, carbonation lime is also derived as a by-product. Carbonation lime is used as fertiliser replacing lime fertiliser.

Also the capture and use of CO_2 in the beverage industry has been suggested. However, CO_2 is a by-product in many different processes and is already produced at large scale. Since the market is not big enough at the moment to absorb additional amounts of CO_2 and since there is no evidence that this market will considerably grow in future, this option is not assessed.

Cane fallow 2015

An overview of the cane fallow scenario 2015 is given in . Cane fallow 2015 is almost identical to the cane fallow scenario (see subchapter “cane fallow”), except that nowadays sugarcane or forage harvesters are used for harvesting sweet sorghum. This technology works fine for stalks but grains and leaves are cut and left on field, thus a usage of both is not pursued. Consequently, by-products derived from ethanol production out of grains are not considered in the cane fallow 2015 scenario. By-products derived from ethanol production out of juice are identical to those of the cane fallow scenario. Surplus bagasse can either be used for generating green power, replacing conventional power (2 I) or as animal feed, replacing cereals (2 II).

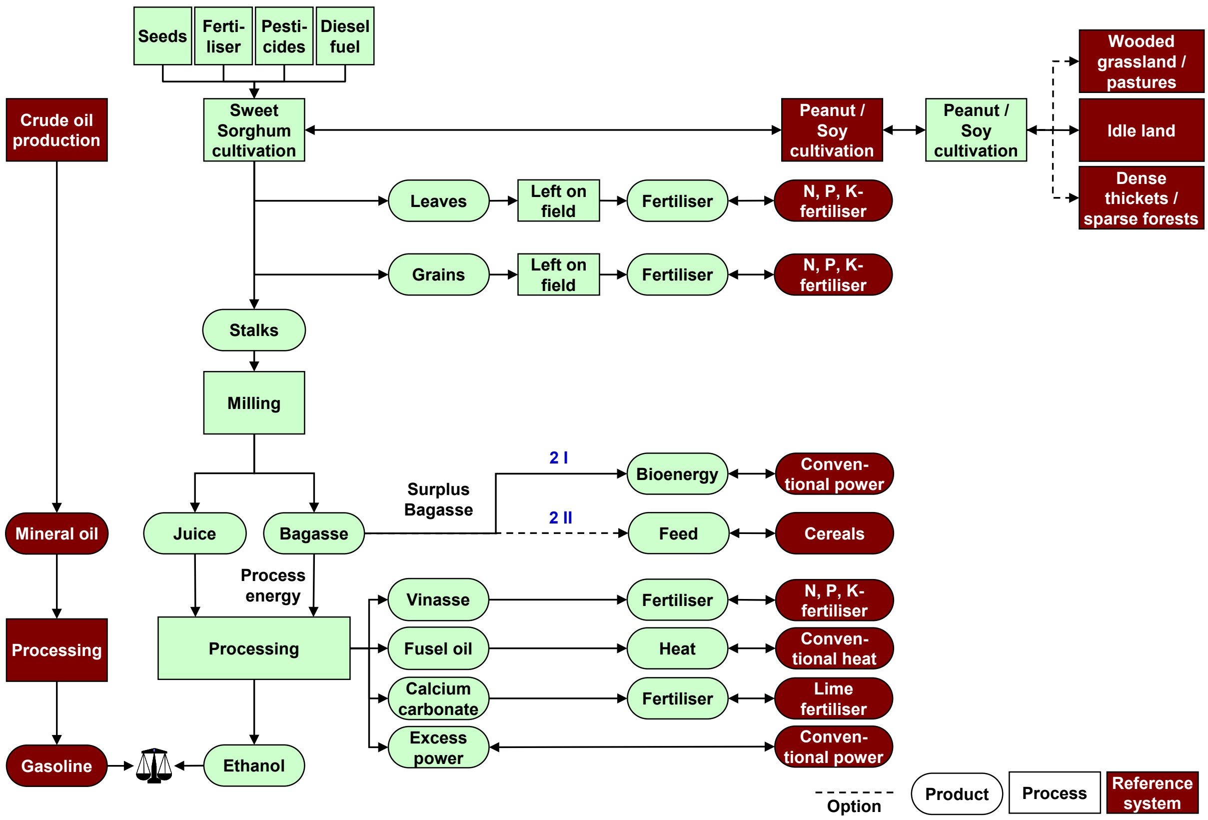

Fig. 3-2 Schematic overview of the cane fallow scenario 2015 (scenario 2); numbers indicate scenario numbers (for a summary, see Table 3-1)

3.1.2 Grain to food scenarios

In some regions sweet sorghum might not be grown as intermediate crop but replace grain sorghum cultivation. This has not been current practice so far but is conceivable in the future e. g. in semi-arid regions such as Southern Africa or North-eastern Mexico. We assume that sweet sorghum cultivars grown in those areas produce less grain than grain sorghum. Since the grains of grain sorghum are used in some countries for food and in others for feed, replacing grain sorghum with sweet sorghum might jeopardise food / feed security in those areas (Fig. 3-3, "Initial situation"). To further guarantee food / feed security, differences in grain yield need to be balanced by cultivating additional grain sorghum. This requires an additional area which is e. g. in Southern Africa, transformed out of idle land that becomes free due to the intensification of existing land use or that is not used at present (see Fig. 3-3, "Grain to food"). For example: If the grain yield of sweet sorghum is 2.5 t / (ha*year) and of grain sorghum 3 t / (ha*year) an additional area of 0.17 ha is needed to balance the difference of 0.5 t of grain yield (see Fig. 3-3). Some people argue that there are sweet sorghum hybrids which produce more grains than grain sorghum if cultivated on the same ground and under similar cultivation and climate conditions. However, this is far of today's reality and there is still a lot of research and breeding necessary to be able to use such hybrids commercially. Thus, as it cannot be foreseen whether those breeding efforts can be successfully,

especially since also grain sorghum can be further developed, this scenario is not considered in this report.

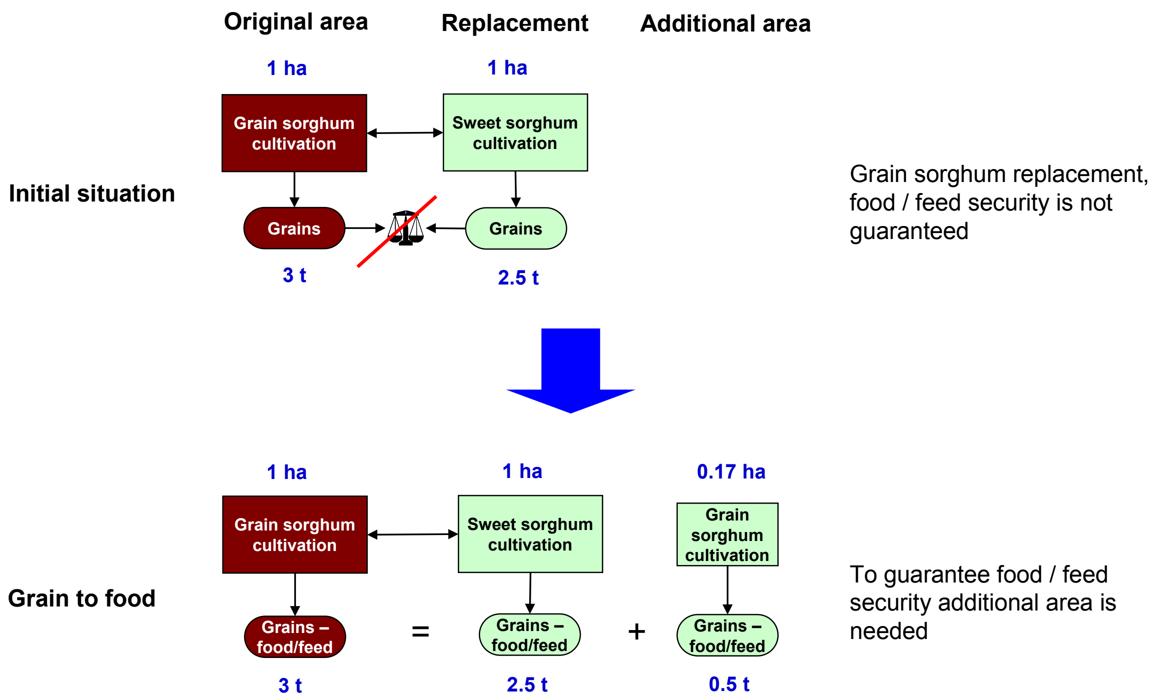

Fig. 3-3 Schematic overview of the grain to food scenario. Blue numbers are examples for illustration, see text.

Grain to food scenario

An overview of the grain to food scenario is given in Fig. 3-4. As described above, in this scenario grains of sweet sorghum are used as food / feed to guarantee food / feed security. Leaves are separated during harvest and remain on the field, replacing mineral fertiliser (3 a). Since also the use of leaves as animal feed is promoted and might be an option in some regions, also this use is assessed. In this case, cereals are replaced as feed (3 b). Stalks are processed in a central ethanol production unit which correspond to the processing (including all by-products) described in the cane fallow scenario (see Fig. 3-1 and corresponding descriptions).

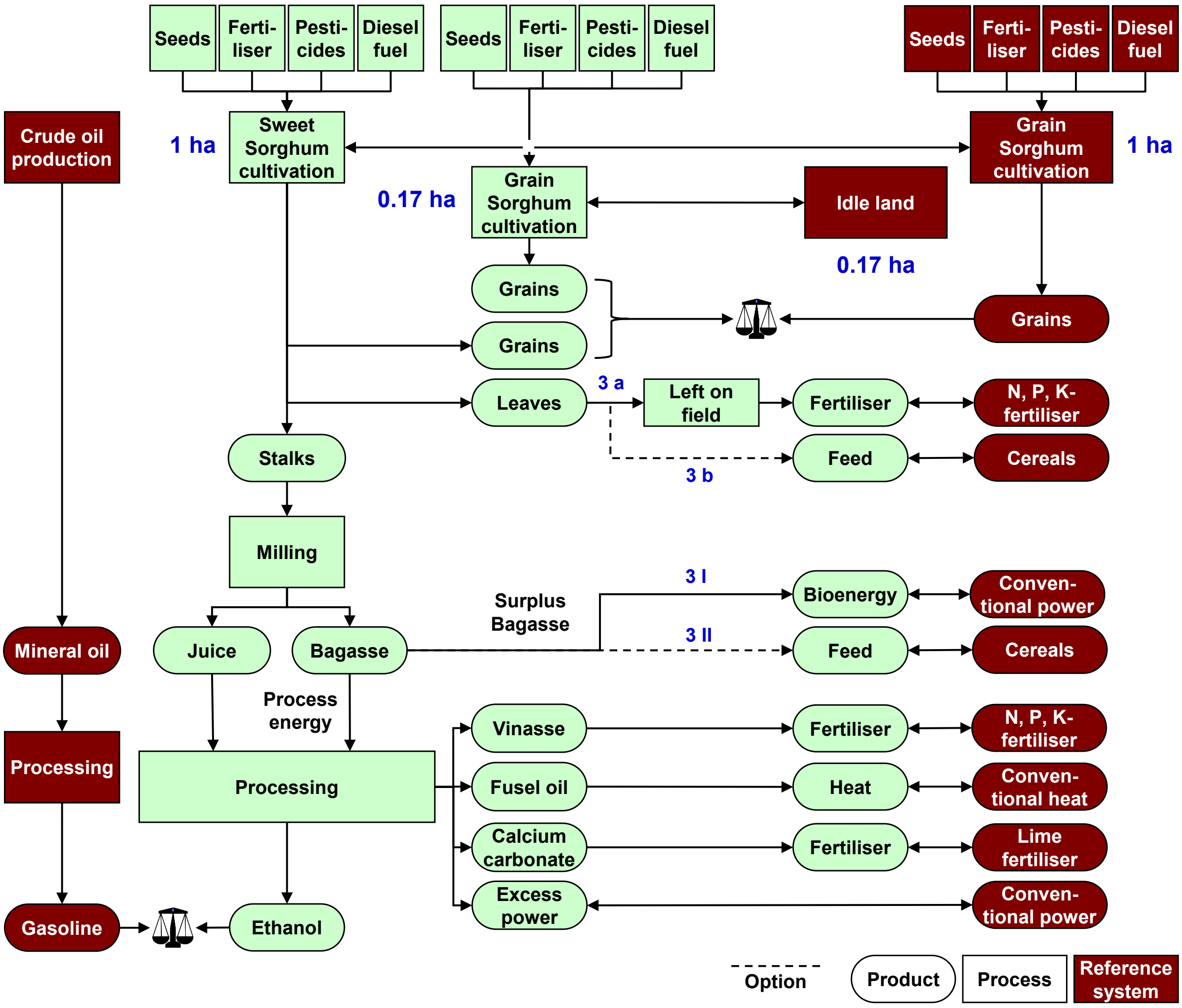

Fig. 3-4 Schematic overview of the grain to food scenario (scenario 3); small numbers indicate scenario numbers (for a summary, see Table 3-1). Large blue numbers are examples for illustration, see text.

Extra high yield scenarios

Besides semi-arid regions grain sorghum is also cultivated in regions such as Central-western Mexico with conditions preferable for extra high yield. Three land use options are conceivable in those regions as described in the following paragraphs (Fig. 3-5).

Option I

This option is identical to the grain to food scenario described before (see Fig. 3-3 and Fig. 3-4 and corresponding explanations); however regions such as Central-western Mexico are characterised by preferable environmental conditions (e. g. high annual precipitation) which allow high grain yields of about 10 t per hectare and year. Since in those regions sweet sorghum yield might also be higher than in semi-arid regions grain sorghum is here replaced by high-yield sweet sorghum. However, since there is no idle land in Central-western Mexico anymore, the additional area needs to be recruited in other regions where yields are ex-

pected to be lower. For example: If the grain yield of sweet sorghum is 7 t / (ha*year) and of grain sorghum 5 t / (ha*year) an additional area of 0.6 ha is needed to balance the difference of 3 t of grain yield if grain sorghum is cultivated (Fig. 3-3).

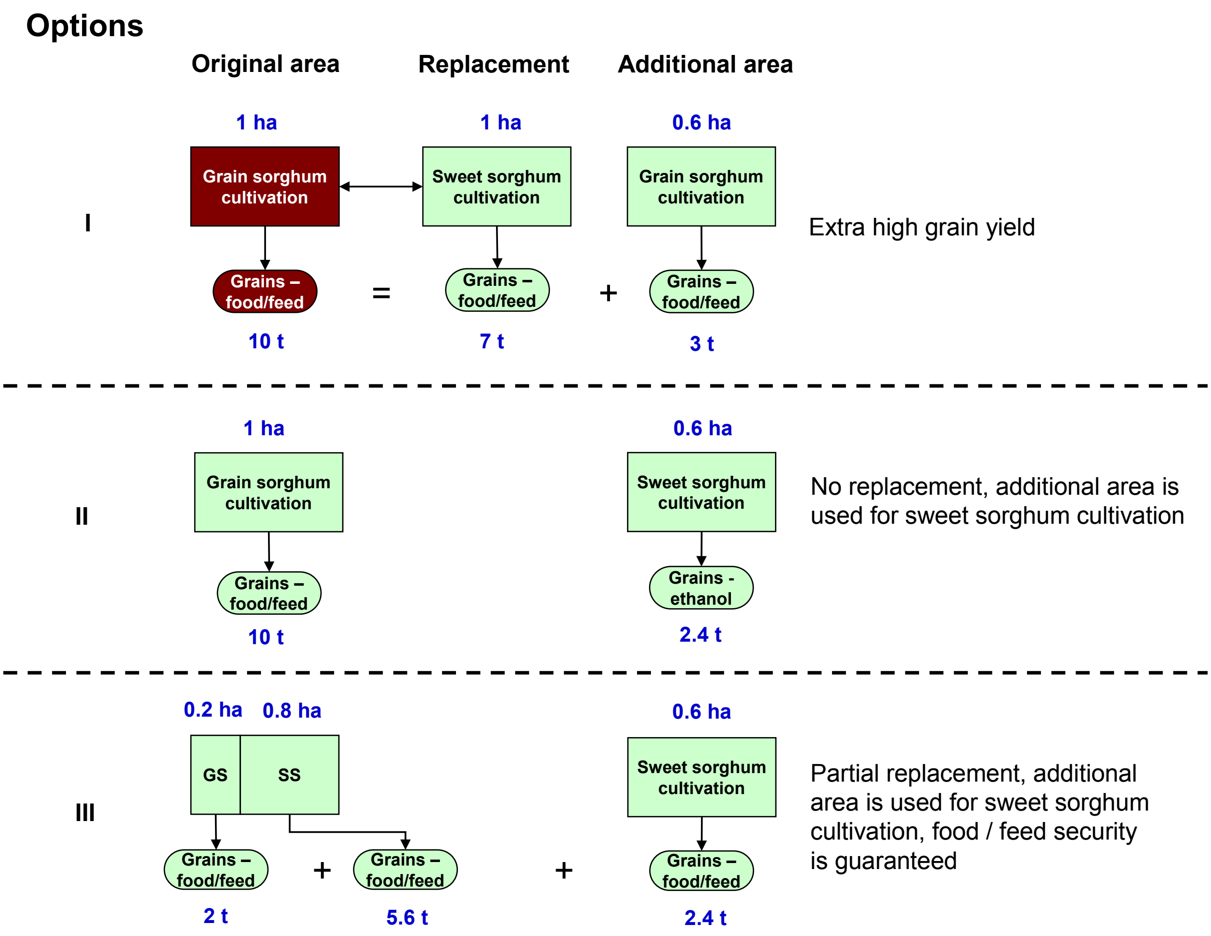

Fig. 3-5 Schematic overview of the two land use options of the extra high scenario. Blue numbers are examples for illustration, see text.

Option II

The same production area as in option I is assumed (Fig. 3-5; option II). Grain sorghum is not replaced and sweet sorghum is only grown on the additional area. Grains of grain sorghum are used as food / feed to guarantee food / feed security, whereas grains and juice of sweet sorghum are processed to ethanol in a central ethanol production unit which corresponds to the processing described in the cane fallow scenario (see Fig. 3-1 and corresponding descriptions). For example: High grain yield of grain sorghum cultivation is about 10 t and grain yield of sweet sorghum cultivation on the additional area is about 2.4 t, if high case sweet sorghum cultivation as described in the grain to food scenario (grain yield: 4 t / (ha*year)) is taken as a basis.

Option III

Another option, assuming again the same production area as in option I, contains a partial replacement of grain sorghum (Fig. 3-5, option III). Thus, sweet sorghum is cultivated on parts of the original grain sorghum cultivation area and on the additional area. The proportion was thereby chosen in the way that grains out of sweet and grain sorghum cultivation still guarantee food / feed security. Thus, grains from grain and sweet sorghum are used as food or feed and the juice of sweet sorghum is processed in a central ethanol production unit which correspond to the processing described in the cane fallow scenario 2015 (see Fig. 3-2 and corresponding descriptions). For example: If grain yield of sweet sorghum which is cultivated on the additional area is about 2.4 t, sweet sorghum can be grown on 0.8 ha (if high yield sweet sorghum as described in option I is taken as a basis) and grain sorghum on 0.2 ha (if extra high yield grain sorghum as described in option I is taken as a basis) of the original area to gain still a grain yield of 10 t in total.

3.1.3 Syrup production scenario

In some cases, infrastructure for biomass transportation to large centralised production units may be insufficient or not existent. Therefore, partially decentralised processing might be another option to grow and use sweet sorghum. Additionally, central ethanol producers often face the difficulty of a rather narrow production window where large amounts of sweet sorghum need to be processed. In such cases the syrup production from sweet sorghum juice might be an advantage. Since the syrup can be stored slightly longer than the sweet sorghum juice, the ethanol production facility can ease production and expand the production window. This scenario was already tested in two pilot projects in India, where the technical feasibility could be shown. In these cases sweet sorghum is most likely replacing other crops. However, to further guarantee the production of those crops, they need to be grown on additional land which needs to be transformed into arable land. The alternative land use options such as dense thickets, wooded grasslands or degraded soils and pastures are described in more detail in subchapter 2.1 ("alternative land use options").

An overview of the syrup scenario is given in Fig. 3-6. In this scenario the sweet sorghum stalks are milled at village level and the juice is further processed into syrup which is transported to central ethanol units. The grains are separated before harvest and used as feed or food, replacing cereals.

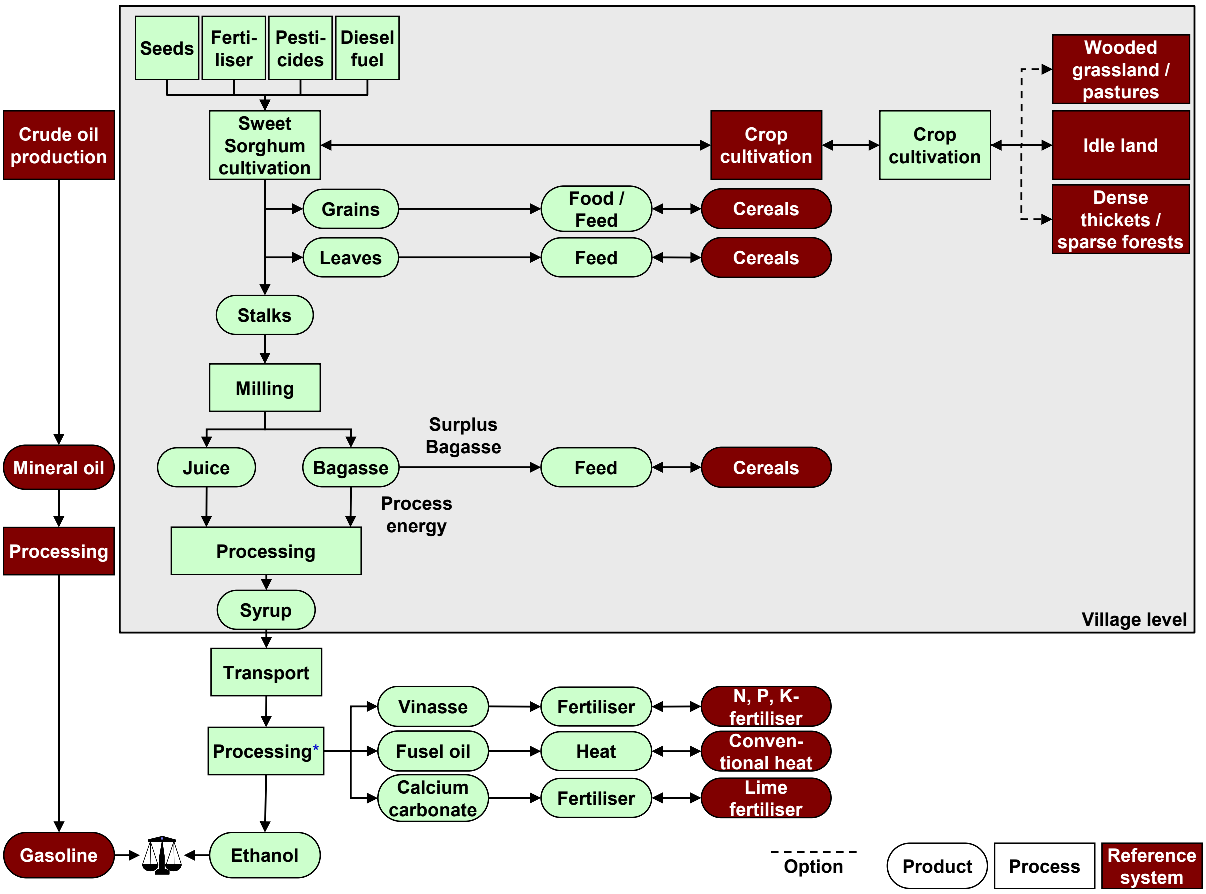

Fig. 3-6 Schematic overview of the syrup production scenario for a decentralised production (scenario 4); numbers indicate scenario numbers (for a summary, see Table 3-1) *For the ethanol production unit in the syrup scenario external energy carriers are needed which can either be fossil energy carriers (4 I) or bagasse from joint processes (4 II).

The leaves are used as feed, replacing cereals. The bagasse which is obtained during stalk milling is used at village level for heat production that is needed to concentrate the juice into syrup. If there is surplus bagasse, it is used as animal feed, replacing cereals.

The syrup is transported to a centralised ethanol production unit and treated just as the juice in the cane fallow scenario (see subchapter 3.1.1). For the description of the use of the by-products such as vinasse, fusel oils and carbonation lime see also subchapter 3.1.1.

For the central ethanol unit, external energy carriers need to be used since the bagasse from syrup production is left in the villages. External energy carriers can be:

- Fossil energy carriers such as coal or oil (4 I).
- Bagasse that is left over from joined processes (4 II).

The following joint processes are addressed:

- In some regions the ethanol units may process syrup from decentralised stalk processing along with sweet sorghum stalks from fully centralised systems. The bagasse obtained from stalk milling might be enough to fuel both processes.
- In some regions the joined processing of sweet sorghum and sugarcane is planned and there might be enough bagasse from sugarcane processing. In these cases, left-over bagasse from sugarcane processing is used for process energy generation for sweet sorghum processing.

Since in both joint processes bagasse is a residue, there are no expenditures for bagasse production but the loss of its use for electricity production or for feed (if there is no connection to the electricity grid) is calculated as expenditure.

The syrup that is produced in the villages could also be used as food. However, this is not within the objective of this study since it aims at optimising sweet sorghum breeds for energy production. Therefore, this option is not assessed.

3.1.4 Sensitivity analyses

As already specified in the general settings and in the proceeding scenario chapters, sweet sorghum is cultivated in various regions covering multiple climatic conditions and cultivation practices (e. g. the amount of fertiliser as well as harvesting expenditures) which can result in strong variations in yield. The influence of those yield differences are assessed via sensitivity analyses. Thus, low, typical and high case values were defined to cover the bandwidths of such parameters.

Since there are also variations in the juice content of stalks and the sugar content of juice, also, low, typical and high datasets were determined to cover a certain bandwidth.

Furthermore, due to various process technologies used in multiple regions different conversion efficiencies may occur. Thus, also for this parameter, low, typical and high datasets were defined to cover a bandwidth of the parameter.

Besides yield differences also alternative land use options were analysed via sensitivity analyses (for detailed descriptions see subchapter 2.1, “alternative land use options”).

Cane fallow and grain to food scenarios

The typical dataset can be described as follows:

- Average biomass yield
- Average juice content in stalks and sugar content in juice
- Medium conversion efficiency

For the low dataset of the cane fallow and grain to food scenarios, yield variable parameters are set assuming low biomass yields as well as a low juice and sugar content. The conver-

sion efficiency parameter is set in the way that the lowest possible expenditure savings are achieved:

- Low biomass yield and sugar content
- Low juice content in stalks and sugar content in juice
- Low conversion efficiency

For the high dataset of the cane fallow and grain to food scenarios, yield variable parameters are set assuming high biomass yields as well as a high juice and sugar content. The conversion efficiency parameter is set in the way that the highest possible expenditure savings are achieved:

- High biomass yield and sugar content
- High juice content in stalks and sugar content in juice
- High conversion efficiency

Syrup scenario

For the syrup scenario the same sensitivity analysis are conducted as for the cane fallow and grain to food scenarios. However, in the syrup scenario the extraction efficiency differs, since it is not expected that in a decentralised production system the extraction efficiency is 95 % as it is assumed for the processing in a centralised production unit. Thus, low, typical and high datasets are defined to assess the influence of extraction efficiency differences in the syrup scenario. Furthermore, in the syrup scenarios, external energy carriers are needed for the ethanol processing in the central ethanol unit since the bagasse from syrup production is left in the villages. Thus, a sensitivity analyses is conducted for different external energy carriers such as coal, oil or bagasse from joint processes.

Grain sorghum as reference system

Since the yield of grains produced by grain sorghum is also dependent on climate conditions low, typical and high datasets of grain yield were defined for grain sorghum as reference system as well.

3.2 Biomass sorghum scenarios

Besides sweet sorghum, biomass sorghum is also considered in this project. Biomass sorghum is cultivated mainly to gain high biomass yields for biogas production.

The target systems are centralised, mechanised systems in industrialised settings. The focus lies on high biomass yields, whereas sugar content and grain yields are of less importance. Accordingly, the crop is used as a whole. Several options of energy production from biomass sorghum are assessed in order to give a bandwidth on different use options and to include both first and second generation technologies. The main focus is laid on biogas and bio-methane production. Alternatively, the combustion of the biomass and the production of fuel is analysed with the focus on second generation technologies. Two options are assessed here: first, second generation ethanol produced from lignocellulose and second, biomass gasification with the synthesis of the gas into biofuel.

Biomass sorghum in the temperate climate, e. g. in Germany, is grown analogous to maize used as energy crop. It is mainly cultivated on land which becomes free due to the intensification of existing land use. In other places also idle land can be used to grow biomass sorghum. In the further course of the report all these land use options are referred to as "idle land". Forest conversion is forbidden in all countries within Europe. Also a conversion of grassland is undesired from a nature protection point of view and forbidden throughout Europe. Therefore, forest and grassland will not be assessed as agricultural reference systems. Thus, no sensitivity analyses for alternative land use options are conducted.

The yield differences due to multiple climatic conditions in the temperate zone are assessed via sensitivity analyses (see subchapter 3.2.5).

3.2.1 Biogas and biomethane production

An overview of biogas and biomethane production is given in Fig. 3-7. For the biogas production, the biomass sorghum is chopped and ensilaged after harvest. Subsequently, the silage is fermented into biogas. Biomass sorghum can be fermented together with co-substrates such as manure or corn. However, the main objective is to assess the use of biomass sorghum from a certain area. Therefore, biomass sorghum digestion will be assessed without any co-substrate. The biogas is either used for heat and power (5 I A) or only for power production (5 I B), replacing conventionally produced heat and power or power only, respectively.

Alternatively, the biogas can be further processed into biomethane and used

1. for heat and power production which replaces conventional heat and power (5 II A), or
2. as a transport fuel, replacing conventional gasoline (5 II B) and natural gas (5 II C), respectively.

In all processes, digestate is produced as a by-product. It is used as fertiliser, replacing mineral fertilisers.

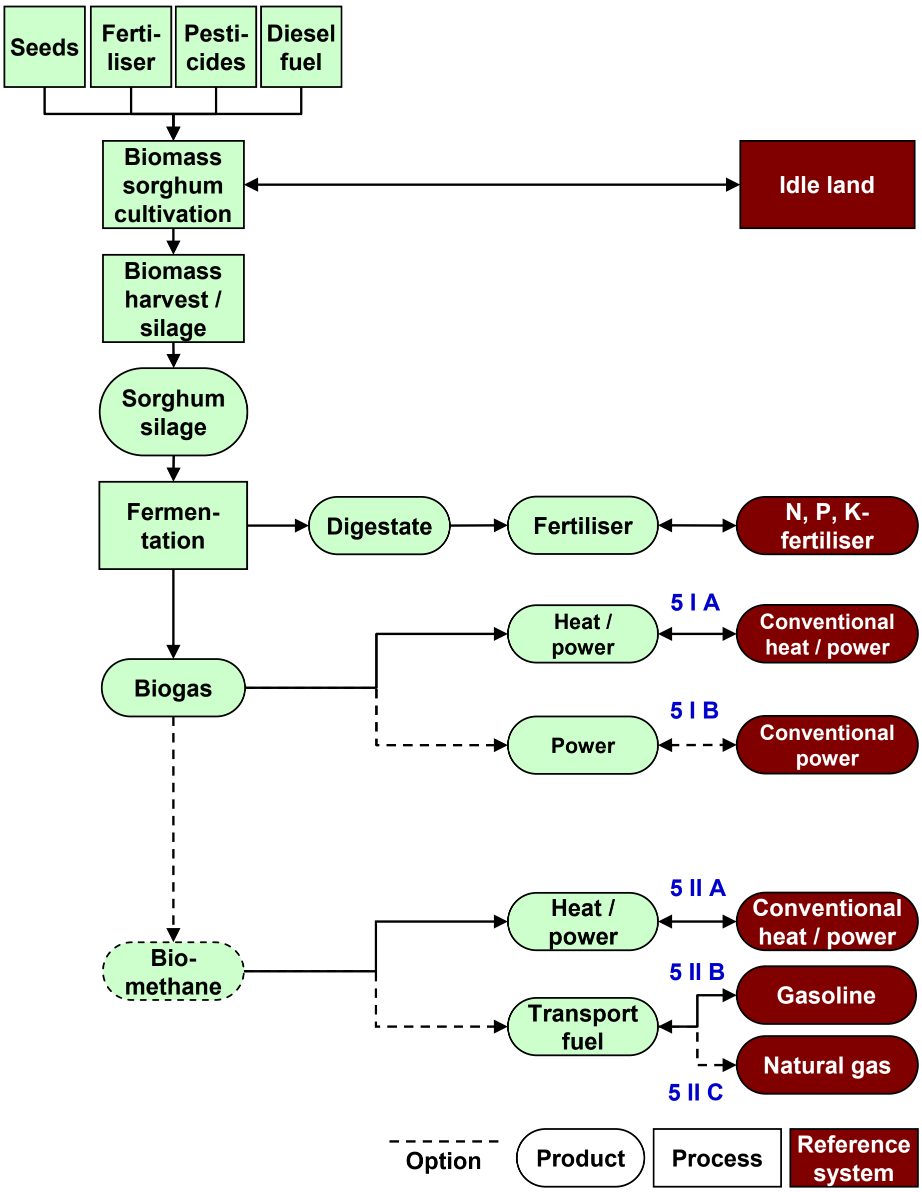

Fig. 3-7 Schematic overview of biogas production from biomass sorghum for the temperate climate (scenario 5); numbers indicate scenario numbers (for a summary, see Table 3-2)

3.2.2 Second generation ethanol

An alternative to the conversion of biomass sorghum into biogas or biomethane is the production of ethanol from the lignocellulose fraction of biomass sorghum (5 a). An overview of this scenario is given in Fig. 3-8. The biomass is harvested and pre-treated in order to render the cellulose and hemicellulose accessible for a subsequent hydrolysis step. After the hydrolysis of the cellulose and hemicellulose for breaking down the long chains into C6 sugars (e. g. glucose) and C5 sugars (e. g. xylose), the substrate is fermented. In order to maximise the efficiency of the overall process, the fermentation of both glucose and xylose is desirable, however fermentation efficiency of C5 sugars still needs to be improved. The

ethanol is used as transport fuel, replacing conventional gasoline. Digestate is obtained as by-product and used as fertiliser, replacing mineral fertiliser. If there is surplus bioenergy from the process, it is fed into the grid and replaces conventional power production.

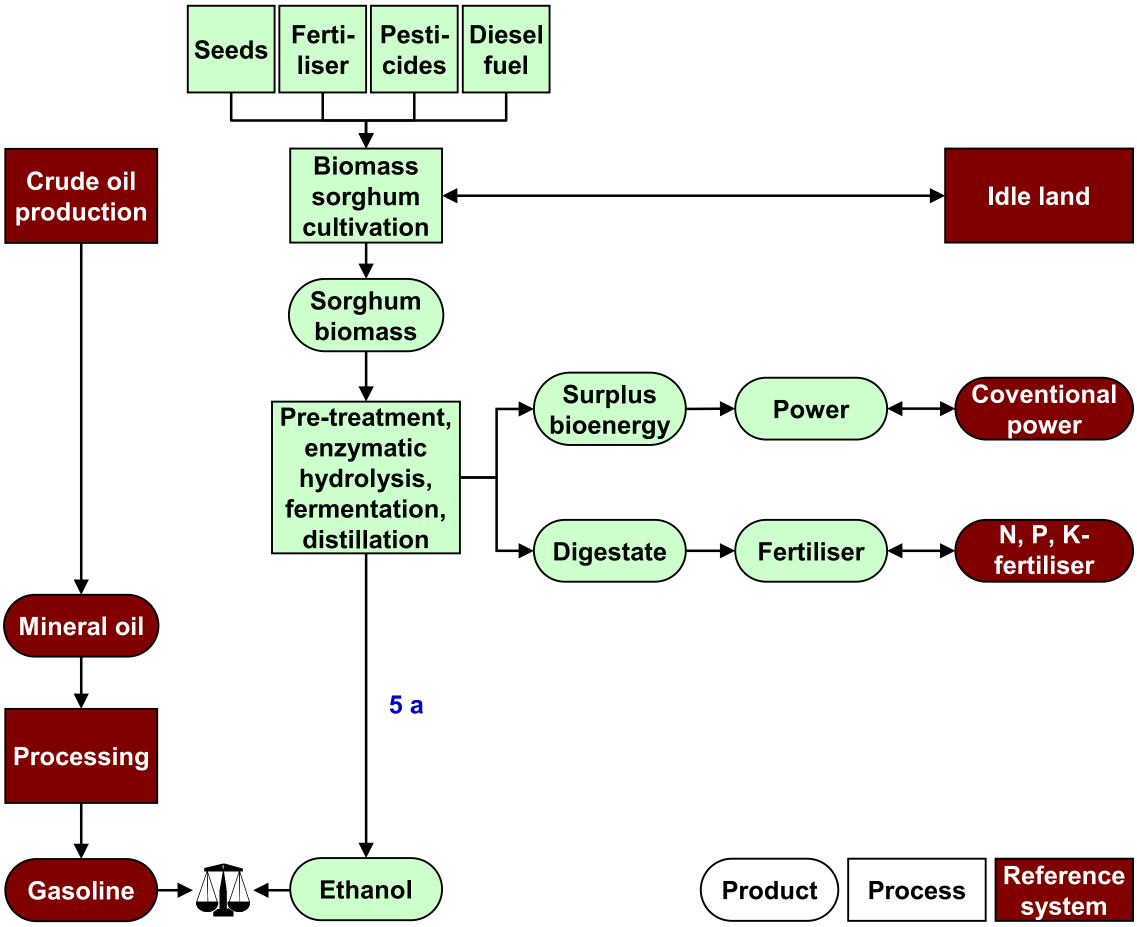

Fig. 3-8 Schematic overview of second generation ethanol production from biomass sorghum lignocellulose for the temperate climate (scenario 5); numbers indicate scenario numbers (for a summary, see Table 3-2)

3.2.3 Direct combustion

Another option to convert biomass sorghum into energy is direct combustion (Fig. 3-9). Since this process requires comparatively dry biomass, direct combustion is especially feasible in the southern regions of Europe such as in the southern part of Spain, Italy or Greece. Here, the stalks remain on the field after harvest for drying. After collection, they can be directly used for combustion in the direct combustion process.

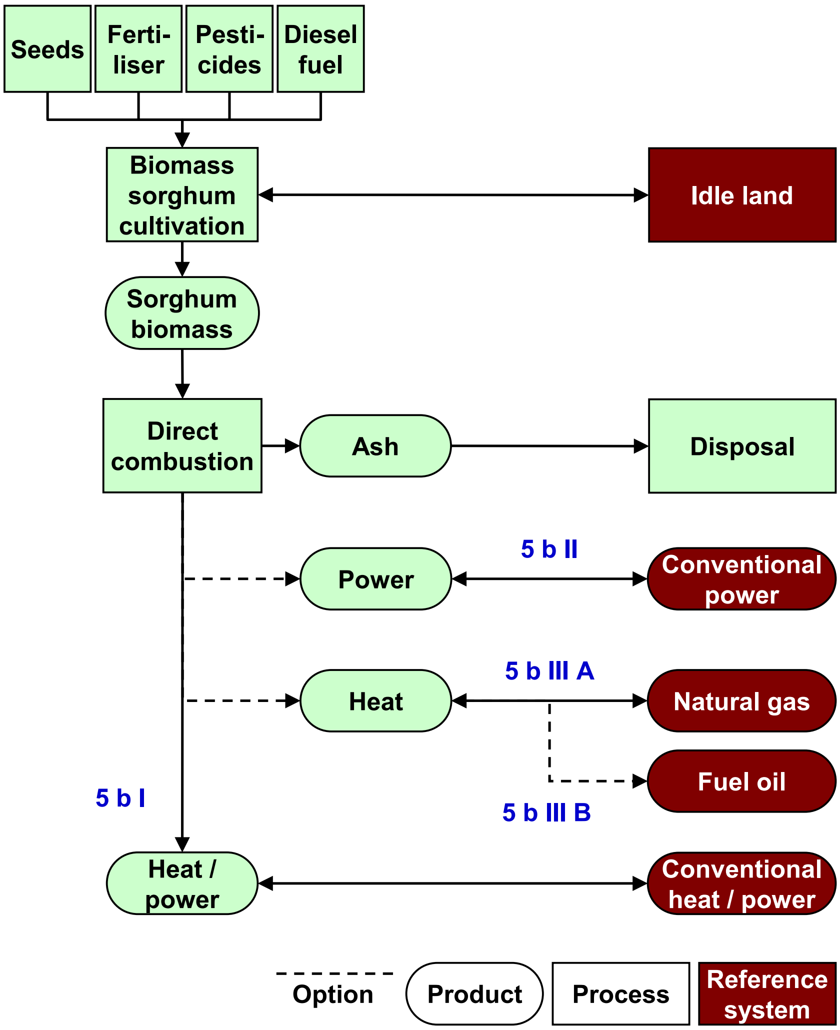

Fig. 3-9 Schematic overview of direct combustion of biomass sorghum for the temperate climate (scenario 5); numbers indicate scenario numbers (for a summary, see Table 3-2)

During the combustion process, heat and power are produced that replace conventionally produced heat and power (5 b I). Furthermore, either power or heat could be produced separately. Power production replaces conventional power (5 b II) while heat production either replaces natural gas (5 b III A) or fuel oil (5 b III B).

In all processes ash is produced as by-product which has to be disposed in landfills.

3.2.4 Gasification

Besides direct combustion, dry biomass is also needed for biomass sorghum gasification (Fig. 3-10).

For biomass gasification, two options are analysed: first the direct gasification (5 c I), second the gasification with a prior pyrolysis of the biomass (5 c II).

For both options, the biomass needs to be comparatively dry as a pre-treatment. Concerning energy supply for drying waste heat from the gasification process can be used in the case of direct gasification. For the pyrolysis, however, external energy supply is needed.

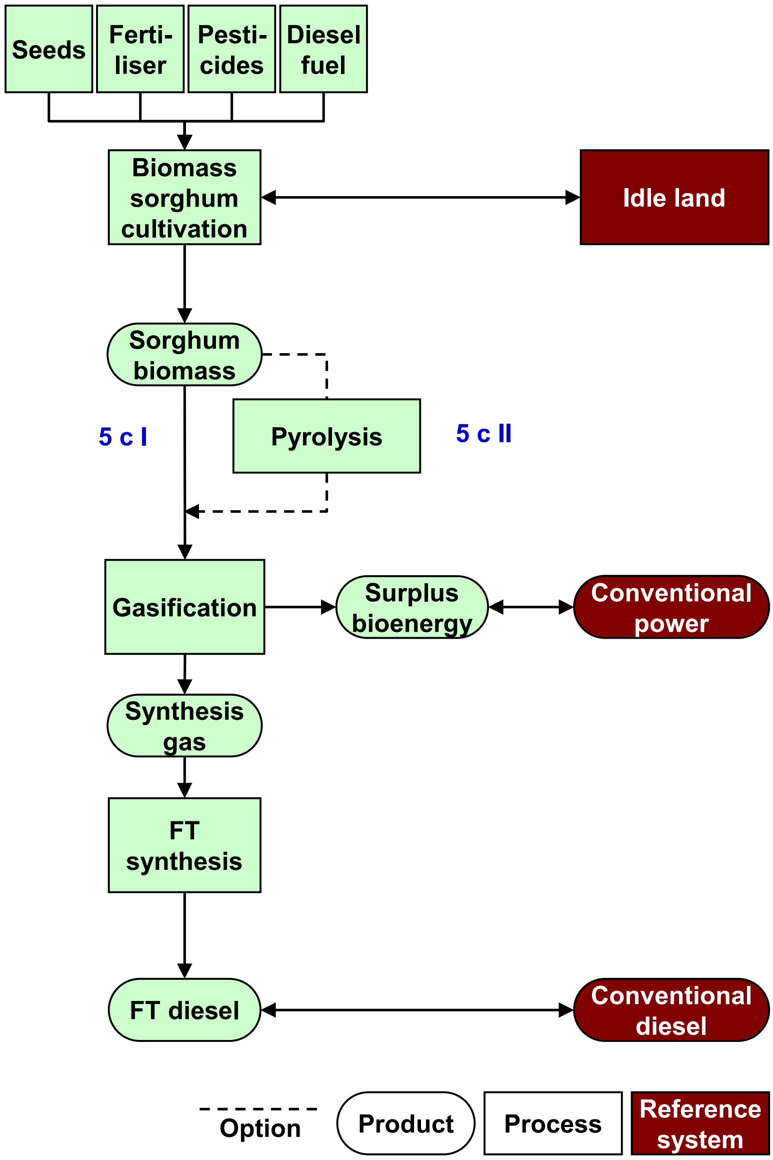

Fig. 3-10 Schematic overview of FT diesel production from biomass sorghum gasification for the temperate climate (scenario 5); numbers indicate scenario numbers (for a summary, see Table 3-2)

As a next step, the biomass or the pyrolysis oil is gasified into a synthesis gas. It is a mixture of hydrogen and carbon monoxide. After cleaning the gas, it is synthesised into the so-called BtL (Biomass-to-Liquid) fuels. The standard synthesis is the Fischer-Tropsch synthesis where FT diesel is produced as a main product. If there is surplus bioenergy from the process, it is fed into the grid and replaces conventional energy.

3.2.5 Sensitivity analyses

Similar as for sweet sorghum, biomass sorghum is also cultivated in various regions covering different climate and soil conditions as well as cultivation practices (see subchapter 2.1 for details). The influence of those yield differences are assessed via sensitivity analyses. Thus, low, typical and high cases were defined to cover the bandwidths of such parameters.

For the biogas scenarios also different conversion efficiencies and plant sizes (including differences in the storage of the digestate) are considered. Thus, also for this parameter, low, typical and high datasets were defined to cover a certain bandwidth.

Thus, the typical dataset for the biogas scenarios can be described as follows:

- Average biomass yield
- Medium conversion efficiency
- Typical plant size

The low dataset of the biogas scenarios contain:

- Low biomass yield
- Low conversion efficiency
- Small plant

The high dataset of the biogas scenarios can be described as follows:

- High biomass yield
- High conversion efficiency
- Big plant

3.3 Scenario summary

Table 3-1 and Table 3-2 summarise all scenarios under investigation. The numbers are also displayed in the flow charts depicted in the previous chapters.

Table 3-1 Summary of all sweet sorghum scenarios

	Sweet sorghum				
	Scenario	**Option**	**Use of surplus bagasse**	**Option****	**Use of leaves**
1	**Cane fallow**	**1 I**	Bioenergy	**1 I a**	Fertiliser (left on field)
				1 I b	Together with bagasse
		1 II	Feed	**1 II a**	Fertiliser (left on field)
				1 II b	Together with bagasse
2	**Cane fallow 2015**	**2 I**	Bioenergy		Fertiliser (left on field)
		2 II	Feed		
3	**Grain to food**	**3 I**	Bioenergy	**3 I a**	Fertiliser (left on field)
				3 I b	Feed
		3 II	Feed	**3 II a**	Fertiliser (left on field)
				3 II b	Feed
4	**Syrup**	**4 I***	Feed		Feed
		4 II*	Feed		

* For the ethanol production unit in the syrup scenario external energy carriers are needed which can either be fossil energy carriers (4 I) or bagasse from joint processes (4 II).

** The option numbers listed here are combinations of the alternative use pathways of surplus bagasse and of leaves.

Table 3-2 Summary of all biomass sorghum scenarios

	Biomass sorghum				
	Conversion process	**Option**	**Main product / method**	**Option***	**Use of main product**
5	**Biogas production**	**5 I**	Biogas	**5 I A**	Heat and power
				5 I B	Power
		5 II	Biomethane	**5 II A**	Heat and power
				5 II B	Transport fuel replacing gasoline
				5 II C	Transport fuel replacing natural gas

Table 3-2 (continued)

Alternatives					
5 a	**LCF-ethanol production**	5 a	Ethanol		Transport fuel
5 b	**Direct combustion**	5 b I	Heat & power		Heat and power
		5 b II	Power		Power
		5 b III	Heat	5 b III A	Natural gas
				5 b III B	Fuel oil
5 c	**Gasification**	5 c I	Direct gasification		FT diesel
		5 c II	Gasification with prior pyrolysis		FT diesel

* The option numbers listed here are combinations of the alternative methods of biomass conversion and of the use pathways of the main product.

4 Results: Technological assessment

This chapter deals with the outcome of the technological assessment of sorghum cultivation and processing in the SWEETFUEL project. A special focus is laid on the cultivation aspects since those can differ greatly due to different growing regions coupled with various production practices, environmental conditions and economic resources.

In subchapter 4.1 results of each assessed parameter of the technological assessment is described in detail. A summary is given in subchapter 4.2.

4.1 Specific results

In the following subchapter all key technological parameters are described in respect to their influence on the sorghum variants investigated in this project.

Cultivation experience

This parameter indicates the level of experience to cultivate sorghum variants. Grain sorghum has a long cultivation history, thus farmers collected a lot of experience to gain maximum yield. However, the history of cultivating sweet and biomass sorghum is relatively short; thus, level of experience is comparatively low even though gained experiences can be

adapted from other row crops such as maize. Thus, it is expected that with raising cultivation experiences crop yield will be further enhanced.

Relative importance of sorghum

This indicator demonstrates the relative importance of sorghum cultivation. For a sustainable production system, even in centralised ethanol production units, sweet sorghum should be rotated with legume crops, such as dry beans, soybean, etc.. A rotation system like this has the advantage that the cultivation of legumes can improve soil fertility and reduce the amount of mineral fertilisers needed for sorghum cultivation. Furthermore, legumes can also be used as food in some cases. However, in small scale production farms, sweet sorghum might represent an additional crop due to the fact that other crops, such as corn, dry beans, grains or other food crops may represent the main crops used as food. Nevertheless, depending on the region, the production system (decentralised or centralised) and the cultivated crops, sweet and biomass sorghum cultivation can have a relatively high importance.

Level of used production technology

This indicator describes the dependence of sorghum productivity on production technology. That means, the more professional the applied technology of the production system is, the higher the expected yields. In a centralised production system, usually the latest technology is applied since economic resources are available. Thus, the level of technology is considered as being high for a centralised production system, to produce sweet or biomass sorghum. Since in decentralised production systems, however, economic resources are often limited, the level of technology is considered here as low to medium. Grain sorghum can be grown in both, regions with low and high economic resources, thus the level of technology for grain sorghum cultivation is considered as medium to high.

Suitability of sorghum cultivation

This indicator describes if sorghum can be cultivated in various regions in the world. Depending on the climatic conditions, different cultivars can be used to grow sweet or biomass sorghum in different parts of the world. However, for biomass sorghum the availability of water might be limited e. g. in arid regions to gain adequate yields. Thus, the cultivation of biomass sorghum is slightly more limited than of sweet sorghum.

Annual / perennial

This parameter shows if the variants need to be sown after each growing cycle (annual) or if they sprout without sowing (perennial). An annual plant has the advantage that it can be easily integrated in many cultivation systems. Even though some *Sorghum bicolor* L. (Moench) cultivars are perennial they are typically cultivated as annual crop. Thus, sorghum can be integrated in other cultivation systems such as sugarcane.

Seed production

This indicator states if seeds from in-house production can be used or if seeds need to be bought externally.

- **Sweet sorghum:** Depending on the economic resources of the farmers, seeds are either produced in-house (in case of varieties) or externally (in case of lines and hybrids).
- **Biomass sorghum:** For the cultivation of biomass sorghum seeds need to be bought externally since mainly hybrids are used which are licensed.
- **Grain sorghum:** Depending on the farmers’ economic situation seeds are bought externally or produced in-house.

Availability of improved material

This indicator would precise if the seeds of cultivars are available on the market and in which quantity. In Brazil, the demand of sweet sorghum hybrids may be huge if all the sugar cane industrials decide to integrate sweet sorghum in their annual agenda: each year 20% of the sugar cane surface area (currently 1.8 millions ha) is potentially available for sweet sorghum production. Planting such area with new sorghum hybrids would require more than 15 000 tons of seeds. Thus, the seed availability may be a limiting factor, if the demand increases too much. In other countries, however, the development of the value chain will be much slower and it can be expected that a shortage in sweet, biomass or grain sorghum hybrid seeds will not occur.

Breeding potential

This parameter describes the potential to breed new ideotypes carrying a higher yield (e. g. by prolonging the growing season) or being more resistant to salt, drought or pests.

- **Sweet sorghum:** Sweet sorghum has just a little breeding history, thus the breeding enhancement gaining new ideotypes is estimated as moderate to high.
- **Biomass sorghum:** Breeding trials for biomass sorghum are just in their beginning, thus a great breeding potential is expected.
- **Grain sorghum:** Grain sorghum has been an established crop for years now, thus, the breeding enhancement is estimated as relatively moderate.

GMO technology

This indicator states if genetically modified organisms (GMOs) are used or involved.

- **Sweet sorghum:** Sweet sorghum is regarded as GMO free.
- **Biomass sorghum:** Biomass sorghum is GMO free since the acceptance in Europe for genetic modified organisms is low. Thus, it is more beneficial to access European markets with GMO free biomass sorghum.
- **Grain sorghum:** GM sorghum cultivars are not commercialised yet.

Up to now no GMO is or was used in cultivating sweet sorghum, biomass sorghum or grain sorghum anywhere in the world.

Need for pesticide application

This indicator describes the vulnerability of all three investigated sorghum variants to pest infestations. The less vulnerable those crops the less pesticide need to be applied. Since

there are pests for all variants such as the midge fly which infests grain sorghum in Mexico or diatrea which infests sweet sorghum in areas adjacent to sugarcane, there is no distinction of pest resistance between sweet, grain and biomass sorghum. Thus, the need for pesticide application is estimated as moderate.

Need for fungicide application

Describes the vulnerability of sorghum variants to fungi infestations. The less vulnerable those crops the less fungicide need to be applied. Since all three investigated sorghum variants have the same potential risk to be infested by fungi, there is no distinction between sweet, grain and biomass sorghum. The need for fungicide application is estimated as moderate.

Need for irrigation

The indicator describes the need for artificial irrigation. Since biomass sorghum is grown in temperate regions where precipitation is mostly not the limiting factor hardly any artificial irrigation is needed. For sweet and grain sorghum applies: if artificial irrigation is possible, it might be helpful to maintain high productivity.

Need for nutrients

The indicator describes the need for nutrients, especially macronutrients such as nitrogen, phosphorus and potassium. For all three investigated sorghum variants the applied amount of fertiliser is considered to be optimal based mainly on the amount of nutrients removed by harvest.

Resistance to lodging

The indicator states the resistance of all three investigated sorghum variants against strong winds. Especially biomass sorghum has a great contact surface due to its tall habitus. However, biomass sorghum has a high hemicelluloses content in the stems which makes them in turn resistant to lodging. Grain sorghum is much smaller than sweet or biomass sorghum, thus contact surface is reduced which makes grain sorghum less vulnerable to lodging. For both, biomass and grain sorghum, the vulnerability to strong winds is estimated as low. The habitus of sweet sorghum is taller than of grain sorghum and hemicelluloses content is less than of biomass sorghum, thus, the vulnerability to strong winds is estimated as moderate.

Resistance against moderate drought

The indicator shows the resistance of sorghum variants to moderate drought events. *Sorghum bicolor* L. (Moench) as a C4 plant has a high water use efficiency in general; however since crops can be grown in different regions, the need to be resistant against drought varies strongly.

- **Sweet and grain sorghum:** There are cultivars of sweet and grain sorghum which can be grown in semi-arid regions, thus, the resistance against drought can be relatively high.

- **Biomass sorghum:** Biomass sorghum may be cultivated especially in regions where precipitation is mostly not the limiting factor. Thus, moderate resistance to drought can be acceptable.

Moisture content of biomass

This indicator describes the moisture content of the sorghum part which is harvested (depends on the variant e. g. grains, biomass or stalks) at the time of harvest.

- **Sweet sorghum:** Moisture content is high.
- **Biomass sorghum:** Moisture content of harvested biomass depends on its further processing. Thus, it can be low to high.
- **Grain sorghum:** Moisture content is comparatively low.

Harvest technology (today)

The indicator shows if mature harvest technology dedicated for each sorghum variant is existent.

- **Sweet sorghum:** So far, sugarcane harvesters are used for harvesting sweet sorghum. This technology works fine for stalks but grains and leaves are cut and left on field, thus a usage of both is not pursued. In rural areas, as described in the syrup scenario, sweet sorghum is hand-picked.
- **Biomass sorghum:** For harvesting biomass sorghum forage or maize harvesters can be used; however since there is a lack of experience it needs to be checked if the harvesters still need some fine tuning.
- **Grain sorghum:** For grain sorghum harvester technology is existent which fits to the purpose of its cause.

Harvest technology (potential tomorrow)

The parameter shows the potential of dedicated harvest technology given in the future.

- **Sweet sorghum:** For sweet sorghum there might be differences in harvest technology depending on the region sweet sorghum is cultivated. In rural regions (as e. g. in the syrup scenario), harvest technology might not be existent due to sparse money resources. However, in regions, where money is not a limiting factor, harvest technology might be adapted to harvest stalks, grains and leaves. In Brazil for example, there are trials with modified forage harvesters for sweet sorghum harvest at the moment, thus, the potential is high that there will be dedicated harvest technology available in the future.
- **Biomass sorghum:** For biomass sorghum it is expected that harvest technology might also be adapted to biomass sorghum needs.
- **Grain sorghum:** Already existent technology for grain sorghum might be improved further.

Storage capability of juice

This indicator covers the capability to store sweet sorghum juice without yield loss. After harvest sugar within sweet sorghum juice deteriorate rapidly depending on several parameters such as temperature or storage conditions.

Storage capability of syrup

This indicator covers the capability to store syrup. Since sweet sorghum juice is quite sensitive to temperature one possibility to expand storage time is to produce syrup from sweet sorghum juice. This can have great economic advantages since the production window of ethanol production factories is broadened.

Juice extraction efficiency

This parameter describes the juice extraction efficiency from sweet sorghum stalks. As long as the extraction process is run in a central production unit (as conducted in the cane fallow and the grain to food scenarios) the extraction efficiency is relatively high. However, in small scale distilleries (as in the syrup scenario), the extraction efficiency is comparatively lower due to non-industrialised extraction technologies.

Use of sorghum plant parts

This indicator describes if other parts of the plant besides juice can be used. Unlike e. g. *Jatropha*, which has plant parts that are toxic, all parts (grains, leaves, stalks) of biomass and sweet sorghum can be used either as food, feed, fertiliser or for industrial purposes depending on the production system (centralised or decentralised) and the sorghum variant. In Mexico, e. g., bagasse, leaves and grains of sweet sorghum are used as feed. Furthermore, grains are also used as food.

Potential use options of lignocellulosic by-products

In the future, lignocellulosic by-products from sorghum cultivation or processing (e. g. bagasse) may be used for other purposes than for cogeneration, fertilising or feeding. Such purposes might include the production of lignins or the incorporation of bagasse into biocomposites, which may be economically more interesting than burning bagasse or use it as feed. Those options are especially conceivable in centralised production systems since in decentralised production systems, infrastructure for an industrial use of bagasse will assumedly be lacking. For grain sorghum cultivation, alternative use options of straw might include the production of second generation ethanol or biochemicals via integrated biorefinery concepts such as BIOCORE /O’Donohue 2013/ or SUPRABIO /Bhattacharya 2013/.

Conversion efficiency (today)

This parameter describes the conversion efficiency of juice or biomass to the respective end product as well as of juice to syrup (excluding juice extraction). As long as the conversion process is run in a central production unit (as conducted in the cane fallow, the grain to food and in the biomass scenarios) the conversion efficiency is very high. However, in the syrup scenario, due to non-industrialised conversion technologies the transformation of juice to syrup can be less efficient.

Conversion efficiency (future)

The parameter shows the potential of conversion technology to be more efficient in future. For a decentralised syrup production as contemplated in the syrup scenario, there is a relative high potential for further development since for now only non-industrialised process technologies are used. For a centralised sweet and biomass sorghum processing, technology is already established and the potential to further enhance the technology is relatively low.

World market potential

This indicator is related to the potential to sell stalks / juice, syrup, biomass or grains of sorghum variants on the world market. Since sugar within sweet sorghum juice deteriorates rapidly after harvest, stalks or juice probably are rather sold at regional scale. The transportation of biomass sorghum involves high transport costs, thus, most likely transportation distances will be kept as short as possible. Since syrup can be transported over long-distances with no or only small impacts on syrup quality the potential to be traded on the world market is estimated as moderate. Grains are already traded at the world market, thus grains might also be a world market commodity in future.

Technological challenges / bottlenecks

This indicator pinpoints further challenges which have to be resolved. Since grain sorghum is cultivated for years now, there will be only little challenges which need to be resolved in future. However, since for biomass and sweet sorghum cultivation the level of experience is low, it is expected that there will be plenty of challenges to be resolved. One of the big challenges is to optimize cultivation techniques including improved sowing and fertilising methods. Another limitation is the short harvesting season resulting in a limited feedstock supply period. The available storage techniques to store sweet sorghum stalks are costly, new technologies to reduce those costs are required. A big challenge is to move up the sugar content in the juice and produce new lines to increase efficiency in seed production.

Policy regime

This parameter indicates favourable pricing policies to promote new feedstocks such as sweet or biomass sorghum. The policy can thereby have influence on e. g. the ethanol pricing, food vs. fuel considerations, the development of infant industry to mature factories, the removal of the policy bias towards selected feedstocks, the implementation of mandatory blending requirements, etc.

4.2 Summary

In the following table the key indicators of the technological assessment are summarised as described in detail in the previous subchapter.

Table 4-1 Key technological indicators for the three sorghum cultivars cultivated in this project

Indicator	**Sweet sorghum**		**Biomass sorghum**	**Grain sorghum***
	Centralised	**Decentralised**		
Cultivation experience	low	low	low	high
Relative importance of sorghum	medium to high	medium to high	medium to high	—
Technology level	high	low to medium	high	medium to high
Annual / perennial	cultivated as annual	cultivated as annual	cultivated as annual	cultivated as annual
Seed production	externally or in-house	externally or in-house	externally	externally or in-house
Availability of improved material	low to high	high	high	high
Breeding potential	moderate to high	moderate to high	high	moderate
GMO technology	no	no	no	no
Need for pesticide application	moderate	moderate	moderate	moderate
Need for fungicide application	moderate	moderate	moderate	moderate
Irrigation	no (helpful)	no (helpful)	no (helpful)	no (helpful)
Need for nutrients	high	high	high	high
Resistance to lodging	moderate	moderate	low	low
Resistance against moderate drought	moderate to high	moderate to high	moderate	moderate to high
Moisture content	high	high	low-high	low
Harvest technology (today)	not fully adjusted	not existent	fine tuning	existent

Indicator	**Sweet sorghum**		**Biomass sorghum**	**Grain sorghum***
	Centralised	**Decentralised**		
Harvest technology (future)	existent	not existent	existent	further improved
Storage capability juice	low	low	—	—
Storage capability syrup	—	high	—	—
Juice extraction efficiency	high	low	—	—
Use of plant parts	high	high	high	high
Potential use options of ligno. by-products	plenty	little	—	plenty
Conversion efficiency (today)	high	low	high	—
Conversion efficiency (future)	low improve-ments	high improve-ments	low improve-ments	—
Technology level	high	low to medium	high	medium to high
World market potential	low	moderate (syrup)	low	high
Technological challenges / bottlenecks	plenty	plenty	plenty	little
Policy regime	high	high	high	moderate

*Food production only. Necessary for the reference system (see subchapter 3.1.2)

5 Conclusion and recommendations

The technological report was conducted in order to provide definitions and settings for the whole work package 6 “Integrated assessment” of this project. In detail, it determines general settings and specifications, describes scenarios and specifies technological key parameters.

SWEETFUEL scenarios were divided into sweet and biomass sorghum scenarios including three or four sub-scenarios, respectively. Those scenarios consider that *Sorghum bicolor* L. (Moench) with its cultivars can be an all-purpose plant, applicable in various regions facing different climatic conditions and cultivation practices. Furthermore, due to different infrastructures and economic resources in different cultivation regions various process technologies are applied resulting in different end- and by-products. All those differences are captured by sub-scenarios and sensitivity analyses. Technological differences are described in the technological assessment showing discrepancies e. g. in the breeding potential or harvest technologies of sorghum. Thus, scenario descriptions and the technological assessment show broad bandwidths regarding differences in environmental conditions, cultivation practices and production techniques. Those differences hold high potentials for development, thus a great enhancement of economic benefit can be expected in future.

To exploit maximum enhancement the following is proposed:

- Continue breeding trials for better adapted ideotypes since there is still a high to moderate breeding potential of sweet and biomass sorghum.
- Continue cultivation of energy sorghum since there is a huge potential for development of improved production systems due to the lack of cultivation experience which will be reduced with every additional growing cycle.
- Develop dedicated harvest technology e. g. those for sweet sorghum which also include the harvest of leaves and grains. This would further increase yield success and economic benefit since leaves and grains are widely applicable and often highly valuable.
- Since the processing of sweet and biomass sorghum as an energy crop has not been well-established so far and primarily sugar cane or maize / forage processing techniques are used, respectively, there is a great potential for development by adapting those technologies to the needs of sweet and biomass sorghum. Thus, processes become more efficient and with it more profitable.

To summarise *Sorghum bicolor* L. (Moench) is widely applicable, but has not been well-established as an energy crop so far. That leads to high variations in cultivation practices, experiences and process technologies for both, sweet and biomass sorghum, holding a huge potential for development in the future.

6 References

/Bhattacharya 2013/ Bhattacharya, A. (coordinator): EU-funded project: SUPRABIO – Sustainable products from economic processing of biomass in highly integrated bio-refineries. http://www.suprabio.eu

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/O'Donohue 2013/ O'Donohue, M. (coordinator): EU-funded project: BIOCORE – Biocommodity refinery. http://www.biocore-europe.org

7 Glossary and abbreviations

1st generation biofuels
Biofuels e. g. produced from sugar, starch, vegetable oil or animal fats using conventional technologies being already established.

2nd generation biofuels
Biofuels e. g. produced from non-food biomass such as lignocellulose and waste biomass (stalks of wheat or corn) using innovative technologies being not yet fully established on the market.

ARC
Agricultural **R**esearch **C**ouncil, Potchefstroom, South Africa; http://www.arc.agric.za/

Bagasse
Fibrous matter that remains after stalks are crushed to extract the juice.

Biomass sorghum
Sorghum cultivars with high lignocellulosic biomass yield, potentially used as energy crop.

BtL
Biomass-**t**o-**L**iquid; synthetic biofuels produced via biomass gasification.

C4-Plant
Plants using a 4-carbon molecule as a first product in the carbon fixation pathway (in contrary to a 3-carbon molecule of C3-plants) which leads amongst others to higher water use efficiencies.

CIRAD
Centre de **C**oopération **I**nternationale en **R**echerche **A**gronomique pour le **D**éveloppement, Paris, France; http://www.cirad.fr

Cultivar
Plant or group of plants selected for some desirable characteristics. Cultivar is a general word that includes lines, varieties and hybrids.

EMBRAPA
EMpresa **BRA**sileira de **P**esquisa **A**gropecuária, Brasília, Brazil; http://www.embrapa.br

Energy sorghum
Sweet and biomass sorghum cultivars used in this project.

Excess power
Surplus power which occurs as a result of the generation of process energy from the bagasse.

Fibre sorghum
Biomass sorghum cultivars with a high content of fibre; potentially used as fibre or energy crop.

First generation biofuels
Biofuels e. g. produced from sugar, starch, vegetable oil or animal fats using conventional technologies being already established.

Forage harvester
A forage harvester is an implement that harvests forage plants to make silage.

FT diesel
Fischer-**T**ropsch diesel; synthesis which converts carbon monoxides and hydrogen into liquid hydrocarbons which can be further processed into low-sulfur diesel.

Fungicide
Funicides are substances used to kill or inhibit the growth of fungi or fungal spores.

GMO
Genetically **M**odified **O**rganism; organism, whose genetic material is modified by genetic engineering techniques.

Grain sorghum
Sorghum cultivars with high grain yield established as food or feed crop.

Hybrid
Offsprings resulting from the cross between two genetically dissimilar parental lines. Usually, seeds from hybrids don’t consistently provide the desired characteristics, so hybrid seed should be repurchased by growers for each planting season.

Idle land
Reference systems such as degraded soils or land that becomes free due to the intensification of existing land use.

Ideotype
Model plant which is expected to gain maximum yield in a specified environment.

ICRISAT-IN
International **C**rops **R**esearch **I**nstitute for the **S**emi-**A**rid **T**ropics, Patancheru, **In**dia; http://www.icrisat.org

IFEU
Institute **F**or **E**nergy and **E**nvironmental Research Heidelberg, Germany; http://www.ifeu.de

KWS
KWS Saat AG, Einbeck, Germany; http://www.kws.de

L.
Linné

Line
Breeding material which tends to be genetically identical.

LCF-ethanol
Ligno**C**ellulose **F**eedstock; ethanol production from lignocellulose feedstock.

Molasses
Viscous by-product of the refining of e. g. sugarcane, grapes, or sugar beets into sugar.

Pesticide
Pesticides are substances meant for preventing, destroying or mitigating any pest.

Second generation biofuels
Biofuels e. g. produced from non-food biomass such as lignocellulose and waste biomass (stalks of wheat or corn) using innovative technologies being not yet fully established on the market.

SWEETFUEL
Project "Sweet Sorghum: an alternative energy crop"; supported by the European Commission in the 7th Framework Programme to exploit the advantages of sweet sorghum as potential energy crop for bio-ethanol production.

Sweet sorghum
Sorghum cultivars with juicy stems and high juice sugar content in their stalks, potentially used as an energy and food crop.

UANL
Universidad **A**utónoma de **N**uevo **L**eón, México; http://www.uanl.mx

UCSC
Università **C**attolica del **S**acro **C**uore, Piacenza, Italy; http://www.unicatt.it

UNIBO
UNIversità di **Bo**logna, Italy; http://www.unibo.it

Variety
Elite lines that are ready to be released as open pollinated variety.

Variant
Term used here to summarise sweet, grain, biomass, energy and fibre sorghum.

Vinasse
By-product of the fermentation of molasses to e. g. ethanol.

WIP
WIP Renewable Energies, Germany; https://www.wip-munich.de

WP
Work package (being a work item of the SWEETFUEL project).