

REVIEW ARTICLE

Newly established drought-tolerant plants as renewable primary products as source of bioenergy

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Abstract

Drought-tolerant plants, also called xerophytes, have developed during evolution a huge spectrum of morphological, physiological and metabolic adaptations to a shortage of water. Due to global climate change large areas of land are threatened by increasing water limitation and therefore drought stress. In addition, energy becomes limiting for an increasing world population and renewable local energy sources are needed. The major food and fodder plants such as wheat, rice, corn and soybean do not show high drought tolerance. There are a number of genetic approaches to increase drought tolerance of these species; some of the genetically modified plants show good results in the greenhouse but when the plants are challenged by field conditions the promising results cannot be reproduced. One option to overcome the problem is to develop new crop plants from already highly drought-tolerant plants. We would like to focus on drought-tolerant plants grown on non-arable land as primary source of bioenergy. Some plants species are already locally used. Promising ecotypes could be used in breeding programs to improve the agricultural and economic values of these plants. For the selection and the development of new crops plants as sources for bioenergy the description of an optimal plant could be the starting point. It will be reported about promising preliminary results and economic uses of xerophytes from the genera *Jatropha*, *Balanites* and *Euphorbia* as new crop plants for the production of ethanol, biodiesel, biofuel, biogas and biomass-to-liquid. Finally, the pros and cons of plants as source of bioenergy in water-limited areas will be discussed.

Key words: Drought-tolerance, New crop species, Non-arable land

1. Introduction

The supply of fossil fuel will gradually decrease (Longwell, 2002; Tsoskounoglou et al., 2008). Therefore, efforts are made to substitute fossil energy sources. One of these sources is solar energy that is unlimited and plants have the capability to capture this energy through photosynthesis. The yield of photosynthesis is stored as biomass and has the potential to contribute to the energy needs. Selecting inexpensive and abundant biomass feedstock is important to obtain biofuel production with minimal cost. This has led to the large scale conversion of arable land for cultivating energy plants (Klein-Goldewijk et al., 2004). However, global warming makes agriculture facing a range of

serious environmental problems such as depletion of water resources and the increase of dry areas (Dai, 2012).

Therefore it is important to find plants for growing on marginal and non-arable land in which food crops cannot be cultivated. Drought stress is one of the major environmental limitations with tremendous effects on the plant growth and development (Harb et al., 2010; Song et al. 2012). Drought stress causes a decrease in the crop productivity and nearly 28% of the world's soil surface is too dry for regular crop yields (Bray et al., 2002; Ambrosone et al., 2013). In addition, the area of agricultural land decreased, for example between 2004 and 2011 from 37.9% to 37.6% (The World Bank Annual Report, 2013). One important factor for this decrease is the climate change. According to US National Oceanic and Atmospheric Administration (2008) combined global land and ocean surface temperature from January to December 2008 was 0.49°C above the 20th century average of 13.9°C. Since 1880, the annual combined global land and ocean surface temperature has increased at a rate of 0.05°C per decade. This rate has increased to 0.16°C per

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decade over the past 30 years (US National Oceanic and Atmospheric Administration, 2008). The trend in rainfall variability has created a greater frequency of dryer years, roughly doubling the number of dry areas in the world from about 15% in 1950 to 30% in 2005 (The World Bank Annual Report, 2013) and finally resulting in huge degraded land areas (Table 1). In addition there is an increase in the world population with expected 9 billion in the year 2050 increasing the need for food and energy. On the one hand the remaining land has to be used for the production of food, on the other hand fast decrease in mineral oil resources make a big demand to search for renewable resources in fuel and there is an increasing demand for energy locally produced with low technically input. One solution might be the cultivation of stress-tolerant plants as renewable primary products as source of bioenergy. Biodiesel has been already produced from several edible plant oils such as soybean, sunflower and coconut, but with the reduction in the agricultural land in the world, this could make a competition between the food crops and oil crops for biodiesel (Hill et al., 2006; Chapagain et al., 2009). In this review, different aspects of the cultivation of new drought-tolerant crop plants as source of energy will be elucidated from different point of views.

Table 1. Globally available land (data are taken from Metzger and Hüttermann 2009).

Use	Area (in billion ha)
Arable land	1.54
Pasture	3.39
Forest	3.95
Deserts	2.56
Steepland	1.47
Degraded areas (former fields, forests, grazing land)	3.50
Total land area	12.91

2. Morphological, physiological and metabolic adaptations of xerophytes to drought

Plants respond to drought stress by reprogramming a number of metabolic and physiological mechanisms (Morison et al., 2008; Ahuja et al., 2010; Park et al., 2012) to overcome the water deficit. The reduction in plant water content induces stomatal closure resulting in a reduced transpiration rate, a reduced rate of photosynthesis and finally in a decrease of growth and gain of biomass. In parallel, an accumulation of reactive oxygen species (ROS) and of compounds such as proline and mannitol is observed. Higher

concentration of abscisic acid and the synthesis of new proteins in response to water deficit can be measured (Lichtenthaler et al., 1981; Yordanov et al., 2003).

Among xerophytes, a term referred to plants that have adapted to live in dry and arid habitats, are approximately 20,000 useful plant species (Wickens, 1998; Akashi et al., 2011). Xerophytes have distinct morphological characters helping the plant to survive in arid and dry ecosystems. The root systems are well developed and richly branched with a long tap root, the stem covered with wax and hairs often stores water and becomes succulent, and the overall surface area, especially of the leaves, is reduced. Sometimes the leaves fall down soon after they have been created (*Euphorbia* species). In *Opuntia* species the leaves have a spine-like structure whereas *Bromelia* species show a rosette arrangement which helps the leaves in severe light to minimize the transpiration. Some desert grasses (*Ammophila* and *Stipa* species) present unifacial leaves, where the stomata exist on the upper epidermis to stop the transpiration (Bendre and Kumar, 2010).

About 85% of the plant species are so called C₃-plants and fix carbon dioxide (CO₂) directly to the C₅ body 1,5-ribulose-bis-phosphate by the enzyme 1,5-ribulose-bis-phosphate-carboxylase-oxygenase (RubisCO). The first measurable organic carbon molecule containing the fixed CO₂ consists of three carbon atoms and it is either used for the production of C₆ sugars or for the regeneration of the C₅ body in the Calvin Cycle. At higher temperature and under dry condition when the CO₂ concentration in the chloroplasts decreased below 50 ppm, RubisCO binds and fixes increasing amounts of oxygen instead of CO₂ leading to the process of photorespiration which consumes energy and makes photosynthesis less efficient for the plant (Moore et al. 1995). In the early response of water stress when the relative water content in the leaves decreases to less than 70%, there is a negative effect on the C₃ photosynthesis by decreasing the photosynthetic activity and the stomatal conductance, and by increasing the CO₂ assimilation to recover and balance the effect of water stress (Cornic et al., 2000; Ghannoum, 2009). When the leaf water stress decreased to 30% in C₃ plants even with high CO₂ concentration and saturating light, the efficiency of photosynthesis is affected and it shows a reduction in CO₂-uptake under drought stress due to stomatal closure (Kaiser, 1987; Cornic et al., 1991).

Many grasses are drought-tolerant due to their C₄ metabolism when a pre-fixation of CO₂ to a C₃

body occurs spatially separated from the normal Calvin cycle because of their higher water use efficiency. About 10% of the plant species adapted to high temperature and water deficiency use alternative CO₂ fixation ways such as the Crassulacean Acid Metabolism (CAM). Cacti, orchids and species from the Asclepiadoideae subfamily, such as the wax plant, *Hoya carnosa* (L.f.) R.Br. (1810) which has distinct waxy foliage for example, take CO₂ up at night and fix it into malic acid which is stored in vacuoles for photosynthesis. Under dry conditions and to reserve water, the stomata are closed during the day and CO₂ is released from malate and fixed through the Calvin cycle (Moore et al. 1995). So the stomatal closure during the day reserves the water from evaporation under heat condition or water stress. Some plants change from C₃ to CAM under water stress or other environmental conditions (Bastide et al., 1993). In summary, CO₂ can be bound also under low water conditions with closed stomata during the day, however, the plant has to invest about three times more energy to produce the same amount of biomass than a C₃ plant.

3. Methods for quantifying drought tolerance

Stomatal conductance and infrared thermography are techniques that can be useful in the analysis of drought tolerances (Jones, 2007). Under drought stress conditions stomatal closure leads to a reduction of water loss for the plants. Conductivity and leaf temperature measurements allow the observation of stomata behavior. Both are non-destructive methods. Stomata conductivity measurements with a porometer have the disadvantage that the measurement is done only punctually on a leaf. This results in a large mean variance of the data. It is possible to investigate the stomatal behavior and thereby temperature changes of a leaf or even of complete plants with infrared thermography. The differences in stomatal conductance and the leaf temperatures between drought and control groups are significant for many plant species and the determination of these parameters can be used for the identification of drought tolerant species and genotypes (Jones et al., 2002; Guretzki and Papenbrock, 2013). The suitability of chlorophyll fluorescence measurements as an early valuable indicator of stress impact on plants was assumed by many researchers based on its high sensitivity. Therefore it was used in many screenings for drought tolerant genotypes. However, for several species analysis of chlorophyll fluorescence does not appear to be sensitive enough to detect early symptoms of

drought stress. Under mild to moderate drought stress, the closing of the stomata is the main reason for changes in photosynthesis as summarized by Medrano et al. (2002). The factor "variable fluorescence" divided by the "maximal fluorescence" (F_v/F_m) is considered as a meaningful, fast-measured indicator for stress on plants. For non-stressed C₃ plants values of about 0.83 are expected, a decline in F_v/F_m indicates a lower potential tolerance against oxidative stress (Björkman and Demmig, 1987). In several studies only severe water limitation for a longer period of time lead to a significant reduction of F_v/F_m in comparison to the control group (Woo et al., 2008). The response of these plants matches with the "Threshold for Tolerance Model" (Sperdoui and Moustakas, 2012). According to this model, tolerance mechanisms are started with a lag time or are induced by threshold concentrations (Barcelo and Poschenrieder, 2002). Moderate stress causes less damage to the plant, because stress adaptation processes and repair mechanisms start in the plant whereas during mild drought conditions the stress threshold was not reached. Therefore, the plants are more affected under mild drought stress reflected by stronger altered chlorophyll fluorescence values in comparison to the moderate group (Lichtenthaler, 1998; Sperdoui and Moustakas, 2012). Important for the characterization of drought tolerance in different species and genotypes is therefore the application of the appropriate strength of drought stress, then chlorophyll fluorescence measurements might be used efficiently (Guretzki and Papenbrock, 2013). Overall, a combination of infrared thermography and porometer measurements in conjunction with traditional growth parameter like biomass investigations is advisable for analyzing plants grown under greenhouse conditions. These methods are also suitable for many species because measurements are easy and quick to handle. Thereby the different effects of drought stress on the plant can be analyzed in order to filter out drought-tolerant genotypes from a selection of genotypes (Guretzki and Papenbrock, 2013).

Currently, many approaches are used to improve the drought tolerance of well-established crop plants. In conventional breeding drought tolerance is selected together with plant productivity. On commercial varieties displaying drought tolerance are crossed with susceptible, higher-yield plants. Marker-assisted breeding assists and speeds up conventional breeding. In addition, the genetic factors responsible for part of

the phenotypic variation observed for a quantitative characteristic, named quantitative trait loci (QTL), are being identified opening a great potential to accelerate the whole process (Xoconostle-Cazares et al., 2010). Plant breeding through genetic engineering opened a wide range of possibilities to improve the ability of the plants to grow in drought stress. However, one has to keep in mind that drought tolerance is a multigenic trait. Several genes were used to produce transgenic plants; these genes were noted in other plants or microorganisms to be induced under abiotic stress, so far with limited success (Xoconostle-Cazares et al., 2010). However, instead of producing transgenic plants, exploitation the potential of already stress-tolerant plants as new crop plants might be more promising.

4. From promising preliminary results to economic use of xerophytes as new crop plants

4.1. Overview on the production of bioenergy from plant biomass

There are different ways how crop plants can be used for the production of bioenergy. Currently, a lot research is going on to find the optimal way for certain plant species with respect to yield, cost, practicability and sustainability. Plants can be used to produce biogas, ethanol, petrol, biodiesel or biomass can be converted by the Fischer-Tropsch process to liquid synthetic fuels (BTL).

4.1.1. Biogas

Biogas is a product of the anaerobic digestion of solid organic biomaterials resulting gaseous mixture mostly methane, carbon dioxide and some impurities such as H₂S, NH₃, water vapor, N₂, dust and siloxanes (Deublein and Steinhauser, 2011). The weak points of this method are odors and producing corrosive volatile sulfur compound (Ward et al., 2008). This process is theoretically an energy balance. The energy of organic material built up by photosynthesis is balanced with the degradation of organic material plus methane combustion (Deublein and Steinhauser, 2011). The result of combustion (CO₂ and H₂O) can be reused for photosynthesis. Thus, there are no substances lost and the energy circle is closed. To increase the yield of biogas, careful selection of the input material is necessary. The highest methane yield from degradation of the same amount of biomaterial are lipids, then followed by protein and carbohydrates (Deublein and Steinhauser, 2011). Proteins might yield impurities such as NH₃ and H₂S that decreased the efficiency of biogas formation. Biogas can contain 40-70% methane which has a heating value of 5 to 7.7 kWh m⁻³.

Several simple fermentation systems have been developed which can be operated locally also by non-experts. However, it is essential to keep them tight. If only 5% of the produced methane is emitted from the storage tank, the positive climate effect of the energetic use of biogas is completely cancelled because the global warming effect of methane is at least a factor of 23 higher than CO₂ (Weiland, 2003).

4.1.2. Bioethanol

Bioethanol can be produced from very common sugar cane, potato, manioc and corn. Currently, the raw product always contains starch or sugar as fermentable carbohydrates and all plant species used are also valuable food and fodder plants. The basic steps for large scale production of ethanol are: microbial (yeast) fermentation of sugars, distillation, dehydration and denaturing (optional). Prior to fermentation, some crops require the hydrolysis of soluble carbohydrates such as cellulose and starch into simple sugars (Weiland, 2003). Enzymes are used to convert starch into sugar. Because the use of starch and sugar-containing crop plants a starting product the production of bioethanol remains ethically difficult and new ways for bioethanol production are being investigated. The use of ligno-cellulose containing biomass is more sustainable because cellulose, hemicelluloses and lignin are not digestible for humans and feedstock; therefore the tank or plate conflict can be avoided. Recently, a pulping process for lignocellulosis biomass conversion was developed (Alkaline Polyol Pulping, AlkaPolP). Lignocellulosis-containing biomass is dissolved in alkaline glycerol for several minutes at normal pressure. The cellulose-rich pulp is filtered, lignin- and hemicelluloses are separated from the solute which is regenerated for further use. Cellulose, lignin and hemicelluloses can be used after further characterization as raw material for the different industrial uses (Hundt et al., 2013). However, just for the production of bioenergy simpler cellulosic technologies are being developed.

4.1.3. Petrol

There are some species of certain families which accumulate hydrocarbons of high molecular weight (up to 10,000 Da). These petroplants have lactiferous canals in their stem and secrete a milky latex. The latex can be either continuously tapped like *Hevea brasiliensis* (Willd. Ex. Juss) Muell. Arg latex and stored or extracted from the biomass by using the organic solvents. The product rich in long chain hydrocrackable hydrocarbons is called as 'biocrude'. After conversion into short chain

hydrocarbons biocrude yields about 70.6% energy, out of which 22% as kerosene and 44.6% as gasoline. It was hoped that petroplants can yield petroleum more than 40 to 45 barrel acre⁻¹ (Calvin, 1978).

4.1.4 Biodiesel

For the production of biodiesel fatty acid methyl esters (FAME) have to be synthesized from vegetable oil because their physical characteristics are closer to those of fossil diesel fuels than pure vegetable oils (Chapagain et al., 2009). Biodiesel and fossil diesel have different properties. Therefore different additives are needed to improve the characteristics of biodiesel at low temperature and to reduce the oxidation processes. To produce FAME oils and fats from different sources (vegetable, oil, animal fats and waste cooking oils) are transformed in a process called transesterification. In the presence of a catalyst a glyceride reacts with an alcohol and a mixture of fatty acids esters plus alcohol is synthesized. The products of the transesterification reactions are raw biodiesel and raw glycerol. The raw biodiesel needs to be cleaned to obtain the usable biodiesel whereas the glycerol produced can be used for various industrial purposes (food, cosmetics, oleochemistry.) The main feedstocks are oil seeds (rape, sunflower, soybean, oil palm), used cooking oil, waste animal fat (<http://www.biofuelstp.eu/> accessed 15 June 2013).

4.1.5. Biomass to liquid (BTL)

There are several technical processes and devices in the development how biomass such as straw or wood can be converted to liquid synthetic fuel. So far there only pilot systems have been established but the results are promising with respect to yield and CO₂ balance. There are four phases: 1. Gasification, the original energy carrier will be converted into a usable synthetic gas. 2. Gas purification and conditioning for further synthesis. 3. Hydrocarbon synthesis in a Fischer-Tropsch process to more complex hydrocarbons as hydrocarbon raw products (paraffins, oleofines and oxygen-containing compounds) with different chain length. 4. Processing and conditioning. The hydrocarbons are processed to the final fuel. However, the process is not yet technically optimized and needs high level technical equipment (Hundt et al., 2013).

4.2. Optimal, hypothetical plant for the production of bioenergy in a sustainable way

One could speculate about the perfect plant for the sustainable production of renewable energy

under water-limiting conditions. Following aspects might be important: A low need for water, rapid attainment of maximum growth rate (drought avoidance), the capacity to outlive water shortage for a period of time, undemanding for fertilization, easy to propagate promising lines, robust with respect to pathogens, no allelopathy effects for the same species and also for other species for repeated growth on the same field or re-cultivation by other species, perennial due to a higher efficiency, sufficiently high yields also under limiting conditions to make the cultivation economically feasible, suitable for the production of bioenergy by at least one process, and native to the respective flora to avoid escape as an invasive plant.

For many regions in the world the non-xerophyte *Zea mays* L. seems to be an almost perfect plant because it can be easily grown and offers high yields. In the fermentation process the methane percentage is high. In the first generation of energy plants only the starch-containing seeds have been taken based on the existing conversion technology. In the second generation the corn stover, the "leftover" portion of the corn plant after harvest, including corn cobs, stalks and leaves, has been used a lignocellulosic feedstock in pilot devices still in the development of new conversion technologies. In Europe, the biogas from corn is considered to have the highest yield with 5,780 m³ ha⁻¹ year⁻¹ (Weiland, 2003). In temperate regions *Brassica napus* L. is a very attractive plant for the production of ethanol and biodiesel. However, both plants are also an important source of food and both plant species need to be grown on fertile soil. Both plant species are annual plants. It is reported that perennial plants are more sustainable and have a better balance with respect to greenhouse-gas production than annual crop plants on the field. Actually, energy savings and greenhouse gas reductions reached by the use of annual crops are negative or at least lower than those for perennial crops as was shown by life-cycle (Karp and Shield, 2008). For the tropical and subtropical regions *Jatropha curcas* L. was highlighted as a perfect plant for the production of biofuel (see chapter 4.3.4).

4.3. Drought-tolerant plants for the production of renewable primary products as source of bioenergy

Sometimes different market categories for the use of bioenergy crops are defined. They can be used for power generation such as electricity, heat, and a combination of heat and power or they can be used for the production of liquid transport fuels.

Many energy plants or plant organs can be used for both market categories (Karp and Shield, 2008). The bioenergy yield can be either quantified as the amount of dry matter (DM) or biomass (C) per area of land used for the conversion or as the bioenergy obtained from this biomass for the production of bioethanol, biodiesel or heat and electricity. The composition of the plant DM varies considerably among bioenergy crops (for consensus values for quality attributes see (Karp and Shield, 2008) and this has significance for conversion to energy and thus for bioenergy yields.

4.3.1. Plant sources of biogas

Many rhizomatous grasses are used for the production of biogas. Some experiments with drought-tolerant grasses have been conducted. Greenhouse experiments with *Eragrostis tef* (Zucc.) Trotter from Ethiopia has shown that this plant has a methane potential in the same range as corn (about 300 ml g⁻¹). Teff's high methane potential together with its possibility to grow on wastelands makes it an interesting potential substrate for biogas production. Teff can be grown and perform well on abandoned lands e.g. waterlogged or wastelands where other crops such as corn cannot be successfully cultivated. This implies that there could be a window of opportunity to cultivate the crop for biogas production without interfering with food production (Nigatu et al. 2012). Sudan grass (*Sorghum sudanense* = *Sorghum* × *drummondii* (= *S. bicolor* × *S. arundinaceum*) (Steud.) Millsp. & Chase has high yields and only modest requirements on the soil. The species can adapt to dry periods quickly. A disadvantage might be slow growth. Plantations need a labor-intensive start. More breeding progress is needed to optimize genotypes for dry, non-arable land (Bibi et al., 2010).

4.3.2. Production of ethanol

World ethanol production from plants for transport fuel tripled between 2000 and 2007 from 17 billion to more than 52 billion liters, widely used in the USA and Brazil. The main sources are corn in the USA and sugar cane in Brazil (El Bassam, 2010). Advantages are high yields and several harvest per year. On the other hand, their tolerance to abiotic stress, such as drought is low. Currently, there is some progress to identify and breed more drought tolerant sugar cane genotypes (de Almeida Silva et al., 2008). But they also act as food and fodder plants. A more promising plant might be the perennial grass *Miscanthus x giganteus* Greef et Deu, Poaceae, from Southeast Asia, a hybrid of *M. sinensis* and *M. sacchariflorus*. *Miscanthus x*

giganteus is characterized by a very high gain in biomass due to the fact that it is a hybrid and that is C₄ photosynthetic pathway as many other grasses. It has a low demand for fertilization and plant protection, however, it needs watering for optimal growth. Recently, different genotypes of *Miscanthus x giganteus* have been investigated for its drought and salinity tolerance and some QTLs have been identified which could be used for further breeding (Grare, 2010). In Germany it produces up to 30 t ha⁻¹ year⁻¹ dry mass whereas even fast growing trees such as poplar only produce about 16 ha⁻¹ year⁻¹ (Lieberei and Reisdorff, 2012). Another advantage is the simple further post-harvest processing because the above ground shoots die already on the field and are dry at harvest. The technical aspects of using *Miscanthus x giganteus* as a source of biomass, for example in the form of pellets, biofuel and even as construction material are already well investigated because research is massively supported. Therefore if the cultivation of drought and salt tolerant *Miscanthus x giganteus* genotypes on non-arable land will be successful the transfer of knowledge on further processing can be easily done.

Recently, an Agave-to-ethanol project was set up. Two native species from the Agavaceae *Agave tequilana* Weber and *Agave angustifolia* Haw. and varieties thereof were cultivated in semi-arid areas of Mexico. Some varieties possess a three times higher sugar content than sugarcane. These high quality agaves are very good feedstock material for bioethanol due to their high total sugar density and content, their high weight of the fruit and stems and their high density of plants per hectare. The two agave species have low water requirements and need low maintenance during the cultivation and harvest cycles of six years. The researchers estimate that varieties of *A. tequilana* can yield up to 7,000 l ha⁻¹ year⁻¹ of distilled ethanol (Burger, 2008). These data sound very promising and species from this family might be also attractive for cultivation in other semi-arid regions on marginal land. However, still some technical problems of controlled crushing and extracting the sugar need to be optimized.

4.3.3. Plant sources of petrol

Many *Eucalyptus* species contain high contents of essential oils which could be used for the petrol production. *Eucalyptus globulus* Labill. contains about 3.5% essential oils in the leaves. Selection programs for drought tolerant hybrids *E. globulus x nitens* obtained positive results (Navarrete-Campos et al., 2013). Therefore there are a number of examples of cultivating *Eucalyptus* species in the

tropics and subtropics and use them as cash crop, for construction and as a source of energy (Guinand and Lemessa, 2001; Lieberei and Reissdorff, 2012). But *Eucalyptus* species cannot provide the same wide variety of different products as indigenous species and in addition has negative effects on soil fertility, creates soil erosion and dries up the land by influencing the ground water system (Guinand and Lemessa, 2001).

Species from the genus *Euphorbia* in the family Euphorbiaceae have a high milk sap or latex content consisting of diterpene and triterpene esters (with a very high energy content of 46.9 kJ g⁻¹ even in comparison to lipids with 38.9 kJ g⁻¹), resins and proteins. Therefore they are candidates for the production of petrol. *Euphorbia tirucalli* L. has a high salinity and drought tolerance (Janssens et al., 2009; Hastilestari et al., 2013) and it survives in a wide range of habitats even under conditions in which most crops and other trees cannot grow. The coverage of *E. tirucalli* includes tropical arid areas with low rainfall, poor soil condition but it is not frost tolerant (Van Damme, 2001). The same author mentions that *Euphorbia* subg. *tirucalli* consists of ca. 30 species and its distribution is through the Paleotropical region in Madagascar, the Cape region, East Africa, and Indochina. It is also utilizable for other applications such as a source of pharmacological activities as described in Hastilestari et al. (2013). According to Calvin (1978) the hydrocarbon of the latex is able to produce the equivalent of 10 to 50 barrels of oil per acre. However, more recent results revealed that extraction of hydrocarbon to yield methane is less efficient than using the biomass in biogas (Loke et al., 2011).

Sow et al. (1989) reported based on research carried out in Kenya that 80,000 *E. tirucalli* plants per hectare yield 20 t year⁻¹, and its potential annual methane production is around 3,000 m³ per year. Loke et al. (2011) showed based on field experience in Colombia that 30 t ha⁻¹ year⁻¹ yielded 8,250 m³ ha⁻¹ biogas. One m³ of biogas can generate 1.44 kWh m⁻³, so totally the output is 11,880 kWh ha⁻¹ year⁻¹. The authors also reviewed a comparison of different conversion techniques to get electricity and mentioned that biogas production has the highest yield (11,800 kWh) compared to oil extraction (6,600 kWh) and gasifier (3,700 kWh). This biogas yield was calculated from estimated yield of 273 m³ biogas (60% methane) per ton dry matter of *E. tirucalli*. The biogas technique results in 50.7% higher yield than that of oil palm only (5,858 kWh). However, no details on the scientific

data are publicly available. In Europe, the biogas from corn is considered to have the highest yield. Compared to maize (5,780 m³ ha⁻¹ year⁻¹) and forage beet and leaf (5,800 m³ ha⁻¹ year⁻¹), the biogas yield of *E. tirucalli* is smaller; however, it is higher than wheat (2,960 m³ ha⁻¹ year⁻¹) and rape (1,190 m³ ha⁻¹ year⁻¹) (Weiland, 2003). Crops proposed for biogas production should be selected and contain low amount of lignin because lignin structures are normally resistant to degradation under anaerobic conditions (Weiland, 2003). The content of lignin of *E. tirucalli* might be quite low as the stem is highly succulent and non woody.

Euphorbia lathyris L. is an annual native herb to Southern Europe, northwest Africa, and eastward through southwest Asia to western China but was also introduced to the USA. Research on this species was originally initiated by Calvin (1978) in the USA. The biennial plant can well be cultivated on marginal land and produces 20 t ha⁻¹ year⁻¹ dry matter. The hydrocarbons which contain around 30% triterpenoids can be converted in to petrol. By optimizing the cultivation and extraction procedures by organic solvents such as hexane the yield in petrol was between 3,000 and 4,000 L ha⁻¹ (Lieberei and Reissdorff, 2012). The experiments were taken up by researchers in India and *E. lathyris* was successfully cultivated on semi-arid and arid regions of Rajasthan, India. Gain in biomass, hydrocarbon yield and productivity of *E. lathyris* could be improved during subsequent experiments (Garg and Kumar, 1989).

There are a number of other plants containing hydrocarbons, mainly in the form of rubber (Sanderson, 2006). However, some of them are not drought-tolerant, such as *Hevea brasiliensis* (Euphorbiaceae), *Copaifera langsdorffii* and *C. mutijuga* (both Fabaceae), or they are too difficult to cultivate and thus the yield is too low for the production of bioenergy, such as *Euphorbia abyssinica* and *E. resinifera*. (Euphorbiaceae). They still might be a promising source for special kinds of rubber such as *Taraxacum koksaghyz* (Compositae) and *Calotropis procera* (Asclepiadaceae). Some might be interesting drought-tolerant candidates for future research as source of bioenergy, such as *Hardwickia pinnata* (Asclepiadaceae), *Parthenium argentatum* (Asteraceae) and *Dipterocarpus turbinatus* (Dipterocarpaceae).

4.3.4. Plant sources of biodiesel

Many plant species which are adapted to grow in non-arable land and dry ecosystems produce considerable amounts of triglycerides which could

be used in the biofuel production through esterification processes (Chapagain et al., 2009). *Elaeis guineensis* Jacq., the African oil palm has many uses and offers many coproducts. The cultivation on degraded land is well possible. However, the production of palm oil has detrimental effects on the environment and is not considered to be a sustainable biofuel. The deforestation occurring as a result of the growing demand for this plant (15 Mio. ha for biofuel), has made scarce natural habitats for orangutans and other rainforest dwellers. More carbon is released during the life cycle of a palm oil plant for its use as a biofuel than is emitted by the same volume of fossil fuels, also due to a high input of fertilizer and pesticides (Carlson et al., 2012).

Jatropha curcas L., family Euphorbiaceae, is a drought tolerant shrub distributed in central and South America, South East Asia, India and Africa with modest demands for nutrients and capital inputs (Schmook and Serralta-Peraza, 1997; Costa et al., 2010). It was shown that it protects against soil erosion. Cultivation is labor-intensive, at least when starting a plantation, and so far the yields are relatively small maybe due to little cultivation experience worldwide. The plants are propagated through cuttings or by seeds. As a result of the high demand of this plant as a source of biodiesel, biotechnological approaches were used to increase the production through mass micro-propagation and regeneration. Thus a method for in-vitro propagation of *J. curcas* was established through nodal explants and green cotyledon explants for somatic embryogenesis (Kalimuthu et al., 2007). There were some attempts to improve the content of unsaturated fatty acids and to enhance the chilling resistance in *J. curcas* through genetic transformation (Luo et al., 2007). In *J. curcas* seeds the oil content ranges between 30-50% by weight, while in the kernel the range is between 45-60%. From the properties and engine test results it has been established that 40–50% of *J. curcas* oil can be substituted for diesel without any engine modification and preheating of the blends (Pramanik, 2003) or even up to 100% according to Hoa et al. (2012). The properties of diesel and *J. curcas* oil are shown in Table 2 (Hoa et al., 2012).

Table 2. The properties of diesel and *J. curcas* oil from Viet Nam.

Properties	Diesel	<i>J. curcas</i> oil
Density (gm/cc), 300°C	0.836-0.850	0.918
Cetane No.	46	51
Flash point, 0°C	45-60	101
Calorific value (Kcal/kg)	10478	9432
Sulfur (%)	0.43	0.33

Table 2 shows that the cetane value of *J. curcas* oil is higher than diesel, thus it is suitable for diesel engines. The sulfur content in *J. curcas* (0.33) is lower in comparison to diesel (0.43). and therefore, the use of *J. curcas* oil for engines is environmentally better. With respects to safety and storage, *J. curcas* is safer in storage and transport because the flash point of diesel is a half of *J. curcas*. Overall, the calorific value by volume is the same thus it is unnecessary to change the amount of fuel supply. The cetane number and emission parameter are 80% lower from biodiesel when compared by mineral diesel, particularly the emission of hydrocarbons and particulate matter (Makkar et al., 2009). Comparing with oil from *J. curcas* grown in India (Pramanik, 2003) (Table 3) is becomes obvious that cultivation of plants, soil type, use of different genotypes and processing influences the properties of the final oil quality drastically.

Table 3. Comparison with *J. curcas* oil produced in Viet Nam and in India.

Properties	Viet Nam	India
Density (gm/cc), 300°C	0.918	0.93292
Cetane No.	51	38
Flash point, 0°C	101	210
Calorific value (Kcal/kg)	9432	9123.913
Sulfur (%)	0.33	n.d.

n.d. not determined.

As shown in Table 4 the quality of the *J. curcas* oil meets for example the European quality standard for biodiesel. Therefore the biodiesel can be used in today's vehicle fleets already on the market worldwide and may also offer a viable path to sustainable transportation, i.e. lower greenhouse gas emissions and enhanced mobility, even in remote areas.

Table 4. Properties of *J. curcas* biodiesel compared to European standard (Francis et al., 2005).

Properties	<i>Jatropha</i> biodiesel	European standard	Remarks ^a
Density (g cm ⁻³ at 20°C)	0.87	0.86-0.900	+
Flash point (°C)	191	>101	+
Cetane no. (ISO 5165)	57-62	>51	+++
Viscosity mm ² /s at 40°C	4.20	3.5-5.0	+
Net cal. val. (MJ/L)	34.4	-	-
Iodine No.	95-106	<120	+
Sulphated ash	0.014	<0.02	+
Carbon residue	0.025	<0.3	++

^a + indicates that *J. curcas* performs better than the European standard.

Although *J. curcas* possesses a high drought tolerance the original theoretical calculations for the yield of *J. curcas* were based on growth under optimal agricultural conditions and therefore there was a big discrepancy among theoretical yield and actual yields when grown on non-arable yields (Karp and Shield, 2008). Although it was meant to be grown on non-arable land, plantations were then set up on arable land instead of cultivating plants for food production and *J. curcas* plants were cultivated like food plants by watering, fertilizing and pesticide treatments to obtain higher yields. The yield was of course much higher on fertile land but the original idea was foiled (Francis et al., 2005). In addition, it was shown that both seeds and leaves show some toxicity against human beings and animals because of several secondary components such as phorbol esters, curcains, trypsin inhibitors and others. These compounds decrease the benefits to use the seed cake as animal feed because the detoxification process for this compounds is tedious and expensive (Abdulla et al., 2011). Therefore the Indian government stopped the cultivation of *J. curcas* to avoid a competition of food and fodder plants on the fields in a country where enough food is still not available for all human beings.

Another very promising candidate for growth in desert areas might be *Balanites aegyptiaca* L. (Del.). It belongs to the family of Balanitaceae, is a multipurpose xerophytic tree distributed in the tropical and arid lands in Northern Africa, West Asia and Arabia. Its common name is desert date (Hall and Walker, 1991; Bhandari et al., 1995; Chapagain et al., 2009; Anis et al., 2010). *Balanites aegyptiaca* trees grow up to heights of 6 to 8 m and live until 100 years with annually crop production of 125 kg of fruit and the first fruit after 5 to 6 years and the oil could be extracted from the kernel and used through ester preparation to produce biodiesel (Deshmukh et al., 2009). The composition of the fatty acids at different pressing temperatures is shown (Table 5).

Table 5. Fatty acid composition of *Balanites aegyptiaca* kernel oil as a function of pressing temperature (Mohamed et al., 2002).

Fatty acid	50°C	115°C
	mg/g oil	mg/g oil
C16:0	95.6	89.7
C18:0	94.5	89
C18:1	287.6	270.5
C18:2	263.9	259.9
C18:3	12.6	9.7
UFA (%) ^a	74.8	75.14
Total	754.2	718.8

^a Unsaturated fatty acids = (g of unsaturated fatty acids / g of total fatty acids) × 100

Chapagain et al. (2009) reported the production of biodiesel through six different genotypes of desert date. The greatest oil content was 46.7% and the total unsaturated fatty acid content was in *B. aegyptiaca* less than in the soybean (Table 6) and rapeseed and very similar to *J. curcas* and *Argania spinosa* (L.) Skeels. With the decreasing contents of unsaturated fatty acids the viscosity is increased and this is a considerable factor in the quality of biodiesel. The oil quality parameters have been investigated (Table 6) and the produced biodiesel has been tested for engine analysis which gave a good engine performance.

Table 6. Analysis of the quality of Desert date oil extracted from extruder machine and compared with soy oils (Chapagain et al., 2009).

Parameters	Desert date	Soybean
Iodine value	97.7	74.2
Melting point (°C)	3 to 10	8 to 20
Refractive index	1.5142	1.505
Saponification value (mg) NaOH/(g)	175.91	187.4
Unsaponifiable (%)	0.68	1.58
Specific gravity	0.9013	0.9140
Moisture (%)	0.5	0.1
Viscosity (cp)	49	42.4

Another tree plays an already an important role as source of biofuel. *Millettia pinnata* (L.) Panigrahi (formerly known as *Pongamia pinnata*), Fabaceae, is native in tropical and temperate Asia. *Millettia pinnata* is well-adapted to arid zones due to its dense network of lateral roots and its thick, long taproot. The non-edible seed oil has been found to be useful in diesel generators and it is being explored as feedstock for biodiesel produced by transesterification of the crude oil with methanol in the presence of KOH as catalyst. Important fuel properties of methyl esters of *M. pinnata* biodiesel compare well (viscosity mm²/s at 40°C, 4.8; flash point, 150°C) with German biodiesel standards (Karmee and Chadha, 2005). It grows naturally in many arid parts of India and is one of the few crops well-suited to commercialization by India's large rural population. Several unelectrified villages use the *M. pinnata* oil in simple processing techniques, to create their own grid systems to run water pumps and electric lighting. To be able to better exploit the advantages of *M. pinnata* several aspects of its biology are currently under investigation, such as nitrogen fixation (root biology, nodulation), stress tolerance, especially salinity tolerance, ways of propagation, breeding potential, and the regulation of genes involved in fatty acid biosynthesis. Another important aspect in the carbon sequestration in relation to carbon credits. After extraction of oil from *M. pinnata* the leftovers could be used as protein-rich feed supplement for animals (Scott et al., 2008). However, in other non-Asian countries *M. pinnata* distributed quickly and was listed as invasive species. The same property makes the native Chinese tree *Sapium sabiferum* (L.) Roxb., Euphorbiaceae, which is moderately drought tolerant, less usable. Because of its invasive nature it is not recommendable as a new crop plant, except in China.

There are several drought-tolerant C₄-grasses such as *Andropogon gerardii* Vitman (big bluestem), native to the Great Plains of North America and due to its stunted growth even more drought-tolerant *Panicum virgatum* L. (switchgrass) native to North America including Canada and Mexico. Both species are being tested as sources of biomass for the biofuel production, either for bioethanol or biogas. An interesting option for their growth might be a polyculture to exploit their different growth optima in different regions and climatic conditions. Recently, the C₃-grass *Arundo donax* L. (giant reed) native to East and South Asia but now found in many countries with Mediterranean climate. It is promoted in the USA as new source of renewable biomass source but

many environmentally concerned people warn about the invasive nature of this grass (Lieberei and Reissdorff, 2012).

4.3.5. Plant sources of biomass to liquid (BTL)

Virtually all drought-tolerant plants can be used as raw material, however, the processes are technically elaborate, energy-consuming and still in a pilot state.

5. Plants as source of bioenergy: Pros and Cons

There are a number of arguments used by promoters on the one hand and by opponents on the other hand. All arguments, cons and pros, should be carefully proven to select the best plants and follow the best strategy for energy production.

Contra: The cultivation of energy plants reduces the land area for the cultivation of food plants. *Pro*: Energy plants can be cultivated without replacing food and fodder plants. For example, the area in Germany for agricultural use sums up to 16.7 Mio ha, 57% of this area is used for the growth of fodder, 28% for food, and 12% for the growth of energy plants (Metzger and Hüttermann, 2009). If one thinks about the re-cultivation of degraded land worldwide by stress-tolerant energy plants there is a huge area which could be used because about one third of land which could be used for agriculture is degraded (Table 1).

Contra: Energy plants generate monoculture and destroy diversity. *Pro*: Energy plants could also enrich agriculture by cross-cultivation, intercropping, crop rotation and agroforestry of several species.

Contra: Industrialized countries destroy the rain forest. *Pro*: Currently, 2% of the fields worldwide are used for the cultivation of energy plants and about 5% of the palm oil produced is used for energy production (Metzger and Hüttermann, 2009).

Contra: Energy plants need even more fertilizer and pesticides. *Pro*: Energy plants save fertilizer and pesticides because there are less monocultures and there is more crop rotation. Smaller amounts of herbicides are applied because strict monocultural cultivation is not as important for the cultivation of food.

Contra: Energy plants are door openers for genetic engineering. *Pro*: As the example Germany shows, no genetically engineered corn is grown at all.

Contra: Cultivation of plants for the energy production cause worldwide price explosion and hunger crisis. *Pro*: The costs for raw products are controlled and influenced by the global market.

Prices for wheat, corn and soybean increased drastically, almost three times for one ton of wheat since about 2000 according to the FAO (<http://www.fao.org/economic/ess/ess-economic/en/> accessed 30th of June 2013). The rise of people into the middle class leads to a high demand for meat, because the increased consumption of meat is one sign of having risen to the middle class. Fodder consists mainly of wheat and corn. Therefore the growth of plants for energy production contributed only little to the increase in prices for basic foodstuff. Energy plants cannot be used as punching ball.

6. Future perspectives

We have to face the growing world population and their energy demand. Therefore providing renewable resources are absolutely essential. It was shown in this review that there are a number of plants which can be cultivated in a sustainable way on non-arable land. The yields will be not as high as when grown on arable land with irrigation, fertilizer and plant protection agents but the arable land should be reserved for the cultivation of food and to a lower part for fodder plants. Some of the promising plants presented are not native to the respective region of country. However, this is an important aspect because from the plantation of plants, especially of grasses, individuals can escape and invade the native ecosystem. The areas for the cultivation of energy plants are restricted. The utilization of perennial or at least biannual plants is more sustainable and exhibits a better greenhouse gas balance than cultivation of annual plants. There are huge areas of degraded land (about 3.5 billion ha). If only half of this land (1.75 billion ha) could be used for the cultivation of stress-tolerant, mainly drought tolerant, plants a big contribution to the worldwide energy supply could be offered. One quarter (0.9 billion ha) could produce about half of the yearly fuel consumption with an average production of 1.2 t ha⁻¹ of plant oil or ethanol yield. On the other quarter fast growing trees with a yearly average dry biomass gain of 10 t about one third of primary energy consumption could be covered as recommended (Pieprzyk, 2009).

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