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Self-Report on Dissertation

Alternative Energy Production in Agriculture Feasibility of bioethanol production from Sweet sorghum in Portugal

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Abstract (in English)

The subject of energy availability has been in the center of mankind's attention for a long time now. Since our society is nowadays very dependent on petroleum products, which may disappear in the medium-term, alternative resources must be studied, developed and applied, in particular if they have a renewable nature.

In Portugal the significance of liquid fuels consumption has been growing in the last decades and, consequently, the liquid biofuels may be of great importance for the future of the country. On the other hand, the stimulation of agricultural production of biomass that may be used as a source of energy may be a remarkable contribution for this sector of the Portuguese Economy.

Sweet sorghum crop is one of the most versatile species for biomass production, namely in view of its sugar content and potential ethanol production at accessible costs.

The present thesis refers to the feasibility study on importance, ways of cultivation and transformation of Sweet sorghum for biofuel production in the Portuguese region of Beira Interior. In tune with the achieved results, this crop may be considered as a potential contribution to different forms of energy production and to the restoration of the agricultural sector in the Portuguese region of Beira Interior.

Key words: Sweet sorghum; agronomy; industry-linked features; sugars; bagasse; ethanol potential; sorghum syrup.

Abstract (in Portuguese)

O tema da disponibilidade da energia tem estado no centro das atenções da Humanidade desde há bastante tempo. Uma vez que a sociedade de hoje depende muito dos produtos derivados do petróleo, que podem desaparecer a médio prazo, fontes alternativas de energia deverão ser estudadas, desenvolvidas e aplicadas sobretudo se tiverem carácter renovável.

Em Portugal, a relevância do consumo dos combustíveis líquidos tem vindo a crescer nas últimas décadas e, portanto, os biocombustíveis líquidos poderão vir a ter grande importância no futuro do país. Por outro lado, o estímulo da produção de biomassa pelo sector agrícola, com a finalidade de ser utilizada como fonte de energia, pode constituir um assinalável contributo para este sector da Economia Portuguesa.

O Sorgo sacarino é uma das mais versáteis espécies agrícolas utilizável na produção de biomassa, nomeadamente tendo em conta o seu conteúdo em açúcares e o respectivo potencial de produção de etanol a custo reduzido.

A presente tese versa o estudo da viabilidade do cultivo e transformação em biocombustíveis do Sorgo sacarino na região da Beira Interior de Portugal.

Pelos resultados obtidos, pode considerar-se esta cultura como um potencial contributo para a produção de diferentes formas de energia e para a restauração do sector agrícola da região da Beira Interior de Portugal.

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Palavras-chave: Sorgo sacarino; desempenho agronómico; parâmetros industriais; açúcares; bagaço; potencial em álcool etílico; xarope de sorgo.

CONTENTS

1. INTRODUCTION

The study of the feasibility on introducing new crops in the Portuguese agricultural sector that can be used as feedstock for energy production seems very appealing. Bringing sugary crops like Sweet sorghum (*Sorghum bicolor* (L.) Moench) into use, looks like an appropriate choice for biofuels production. In some countries, Sweet sorghum, like Sugarcane (*Saccharum officinarum* L.) is well known for its bioethanol production potential. On the other hand, this crop can also provide a set of co-products that can valorize even more its cultivation.

The present thesis develops around the subject of the feasibility of Sweet sorghum under the conditions of Portugal, and in particular of the inland Beira Interior region, aiming its possible use for biofuels production. As a first approach, agronomic practicability of Sweet sorghum in the area of Idanha-a-Nova and surrounding territories – Castelo Branco and Idanha-a-Nova, all counties of Beira Interior region – was studied in farms served by irrigation infrastructures. Like this, the local areas apparently with more adequate conditions for sorghum production were covered. Sweet sorghum performance was then evaluated from 2007 to 2010, studying the agronomic behavior of the crop as influenced by a set of factors – mainly the effect of cultivar and plant population, but also of panicle ablation, type of soil fertilization and propagation method. A number of its industry-linked characteristics were also evaluated.

From the achieved results, Sweet sorghum reveals to be adaptable to the agricultural reality of Portugal, and in particular to the Beira Interior region. Actually, it showed potential to produce significant amounts of sugars-rich biomass and bioethanol and most likely even other types of biofuels. In terms of bioethanol, for instance, the maximum production per hectare points to a value of 5,111 L/ha. On the topic of the potential use of Sweet sorghum bagasse for co-generation purposes, a HHV of 17.26 MJ/kg is in line with the results obtained by other researchers with such type of biomass and are considered as interesting results. Finally, aspiring a co-use of this sort of materials for food-related purposes, bagasse silage also gave encouraging outcomes as, for such a feedstock, it provided a cattle fodder with attractive levels of crude protein (4.81 % in DM).

As a major recommendation resulting from this study, based in our

experimental results Sweet sorghum will adapt to Portugal, and in particular to its inland region of Beira Interior. It may then be considered in the frame of a new wave of agricultural initiatives for the region, namely for the production of a feedstock that may be converted into one or a set of bioenergy sources.

2. OBJECTIVE OF THE DISSERTATION

The main objective of the present dissertation has been the development of some research and recommendations on the introduction of a new crop – Sweet sorghum (Sorghum bicolor (L.) Moench – in the Portuguese agricultural sector, a crop that can be used as a feedstock for energy production. This possibility is particularly important for the Beira Interior region, which needs a substitute for another industrial crop which production is coming to an end – tobacco. The choice by this sugar-rich plant is also due to the reason that the reality of a vast majority of the country, namely in terms of soils and weather constraints, doesn't allow growing of oil crops, another alternative for bioenergy production. The use of sugar-producing crops, like robust Sweet sorghum, looks then like an appropriate choice for biofuel production. On the other hand, this crop can also provide a set of co-products that can valorize even more its cultivation.

3. METHODOLOGY

The methodology used was based on running Sweet sorghum suitability field trials in the region of Beira Interior (Portugal). These were established at the farm of the College of Agriculture of the Polytechnic Institute of Castelo Branco – IPCB (39º49´18.18" N; 7º27´42.20" W); a second farm close to Ladoeiro, a small place in Idanha-a-Nova county, located some 30 km East of Castelo Branco and served by the irrigation infrastructure of the Idanha-a-Nova dam (of 77.3 million cubic meter useful capacity); and a third place, about 25 km South-West of C. Branco – "Monte da Coutada de Baixo" / "Urgueira" farm (39°40'34.16"N; 7°36'1.02"W), in Vila Velha de Ródão county – which uses irrigation water from a set of small dams.

At first it was planned to carry out the field trials according to a scheme which involved, always when possible, plot trials in the College farm, and commercial-

sized field trials in the three farms described above (including the College). Thanks to this, higher data accuracy was aimed with the plot trials, and more realistic results were intended with the commercial-sized ones. On the other hand, the approach of running field trials in several points of the region was a form of insuring increase of confidence level of its results. Unfortunately, the plot trials at IPCB's College farm didn´t go very well, and in the end generally only commercial-sized tests were ran.

In any case a set of different hybrid cultivars and/or plant populations were tested.

In general, a completely randomized block experimental design was followed, involving the previously mentioned set of factors: the effect of cultivar and plant population, but also of panicle ablation, type of soil fertilization and propagation method. For each factor (or factor set) tested, the aimed data collection involved the study of its influence on total biomass and Dry Matter production per hectare, clean stems/stalks proportion (as a percentage of total biomass production) and harvest (t/ha), and also tillering ability (average number of stalks per plant) and crop lodging vulnerability (as a percentage of total number of stalks). For these measurements, common equipment was used, like a regular portable platform weighing scale (mechanical).

For a random sample of stalks, but representative of each full sample collected, a qualitative analysis of industry-linked parameters was performed, assessing the effect of those already mentioned factors on volume of juice extracted per kilogram of clean stalks (using a metalworking workshop 3-roller plate bender), Brix degree of the extracted juice (by means of an optical refractometer), and bagasse production per kilogram of clean stems, Dry Matter content (ventilated stove, at 65 ºC, for 48 h) and production. Each culm was squeezed three times in a row, whatever equipment was used.

Another important aspect of the overall study was the assessment of Sweet sorghum biomass potential productivity and quality, in view of its valorization for silage production and for co-generation units. For this purpose, silage-related biochemical parameters, and calorific value (using a bomb calorimeter), proximate and ultimate analysis of a set of biomass samples were performed.

4. THEORY AND REFERENCES DISCUSSION

From the main objective of this Dissertation Thesis (chapter 2.) it may be deduced that it relates to the study on possible production and use of a new source of biomass in Portugal, for a set of industrial purposes. Among these, the production of biofuels may be considered as the most relevant.

A biofuel is the final result of any type of biomass preparation for its use as a form of bioenergy (adapted from FAO, 2004), for immediate application or after subsequent stocking. Biomass consists of all the living matter present on planet Earth. This organic matter results from several sources, from growing small life forms, like algae, to plants explored as energy crops and even trees planted, exclusively or not, for energy purposes. Some by-products of a number of activities, like manure from animal production, or organic substances from domestic or industrial wastes may also be included in the broad definition of biomass.

There is an ample assortment of characteristics and properties of those different classes of organic material, as well as a wide choice of its conversion technologies, which include thermal, chemical and biochemical conversion pathways.

Biomass has been a major source of energy for mankind for a long time now, as a source of heat, electrical power, fuel for transportation and also as a feedstock for several industries, e.g. for chemicals. At present, it contributes to around 10-14% of the World's energy supply (Saxena et al., 2009), with a growing interest in the so-called modern biomass, associated to industrial wood residues, energy crops and plantations, bagasses (fibrous by-products from crops like Sugarcane) and other.

A number of advantages may be pointed to the production and use of biomass and biofuels, as for example (IDEA, 2007):

- A neutral CO_2 cycle, with no contribution or even with a positive role in the issue of Greenhouse Gases Emissions;
- Decrease in particles emissions to the atmosphere;
- Reduction in emissions of different contaminants like CO, HC and NO_x;
- Use of some agricultural residues, avoiding its burning in the fields;
- Possibility of using agricultural soils of less agronomic value;
- Significant improvement in rural population's standard of living.

Nevertheless, the environmental benefits from biofuels production and use are still dubious. On the other hand, the limited capacity of energy production, at the present technological levels, represents an important constraint to the implementation of this sort of fuels sources.

Sorghum is a crop which involves a considerable group of annual herbaceous C4-type species. These plants are members of the Poaceae family which are used for centuries now in many countries, especially in the Sub-Saharan Africa. It is also spread in Asia (especially in India and Southeast Asia), Australia and the Americas, mainly in the USA. Some specific types of Sorghum are also cultivated in Europe for centuries, like Broomcorn and Sudangrass. Recently, there is a growing interest in this species also in China and Brazil.

Being a more recent group of plants, but essentially derived from the existing species and its varieties or from their hybridization, Sweet sorghum is also classified as a member of the Sorghum genus, and many of the cultivated Sweet sorghums fall in the subspecies S. bicolor subsp. bicolor. They can also result from the hybridization of plants from this branch with other species of the Sorghum genus, namely from Sudangrass, which aim at more biomass and sugar production (Tew et al., 2008). These cultivars are produced all over the World (but especially in India, China and Australia, and also in Central/Eastern Europe and South and North America) and are at present entering the market. They enable harvests of up to 120 t/ha green matter (or up to 40 t DM/ha) and more.

Some of the more remarkable advantages of Sweet sorghum include:

- It’s highly suitable for the tougher dry land growing areas;
- It produces very high yields with irrigation and higher rainfall-range;
- It is a short-season crop (about 4 months);
- It propagates by seed (ease of seeding);
- It produces some grain for starch fermentation or other uses;
- It has a sweet stalk juice, with important sugar accumulation available for subsequent and immediate fermentation;
- It’s suitable for fully mechanized crop production.

Sweet sorghum is a crop that can be cultivated in a variety of agricultural environments due to the fact it is tolerant to drought and different soil conditions;

varieties exhibit different response to photoperiod; and there is a wide range of genotype diversification (CETA, 2011). In agronomic terms, the crop profits from a thorough seedbed preparation, for adequate emergence. Under Mediterranean conditions, where soil fertility ranges from low to moderate, the fertilization needs are about 100-150 kg N, 60-100 kg P2O5 and 60-100 kg K2O per hectare (CETA, 2011). Nitrogen should be made available in two fractions: the first distributed when sowing (1/3 of total prescribed amount); the remainder about 30-40 days after crop establishment. For that same region, in order to create the conditions necessary for a complete life cycle, Sweet sorghum should be sown early in May. As to irrigation Sweet sorghum requirements will depend on local conditions, as its water balance is affected by the temperature and rainfall regimes of the location. The irrigation system used for the crop also plays a very important role here, as differences will emerge if choosing between sprinkler and drip irrigation (this one more efficient), for instance. Anyway, although it is in general considered a very moderate crop in this department, the truth is that a conscious farmer must always conciliate irrigation dose and the yield he expects. Finally, pest control raises the same problems as corn, with some insects (e.g. stem borers) and fungi as the major issues to overcome.

Ultimately, the value of Sweet sorghum biomass is nowadays considered to exist in its non-structural sugars accumulated in the stalk, namely in its fermentation into alcohols, like ethanol. This sugar content may be assessed by different laboratory methods and techniques, e.g. by means of High-Performance Liquid Chromatography (HPLC). But, as a first approach, the use of a simple optical refractometer for total solubles evaluation (expressed in Brix degrees, or "º Brix"), which relates very closely to sugars' content of such juices, is widespread, namely for its practical simplicity. In fact, based on Bellmer and Huhnke (2007) research results on in-field ethanol production from Sweet sorghum, it is even possible to estimate the ethanol potential of this crop using a linear regression equation that relates biomass yield (in t/ha) with its sweetness (in ºBrix). The equation (with a Coefficient of Determination – R2 – as high as 0.994) is as follows:

Ethanol production (L/ha) = 53.6 x Biomass yield (t/ha) + 256.5 x Juice sugar content (º Brix) - 4290

The use of those sugars for fermentation purposes may, however, happen from direct fermentation of Sweet sorghum fresh juice or after its concentration to a

syrup of 65-85 ºBrix. This other path involves the evaporation of most of the water in the juice, after some impurities (plant tissues particles, waxes, dirt, even starch) are removed by a process of clarification. In the end of the process, syrup is produced at a rate of 6 to 12 liters of juice per liter of syrup (Bitzer and Fox, 2000).

On the other hand, in some regions, Sweet sorghum grain harvest is also an important starchy product that can be used for several food and industrial purposes, including for alcoholic fermentation.

In parallel to this, some co-products have been identified, like the possibility of power electricity and biogas production and even of silage. This is feasible using the fibrous fraction of the plants remaining after juice extraction – called bagasse. In the field of co-generation, for instance, Proximate and Ultimate Analysis and even chemical elemental studies have already been performed on Sweet sorghum bagasse, with very interesting results (Lori et al., 2007).

5. RESULTS

The obtained results have by a significant manner contributed to the main objective of this research, namely by meeting the specific objectives giving justification to the formerly formulated hypotheses.

To the hypothesis of Sweet sorghum being capable to adapt to soils and climate of Beira Interior region. Namely in the locality of Idanha-a-Nova and its surrounding areas of which fields are always under irrigation, the data collected from our field trials tend to prove the above hypothesis.

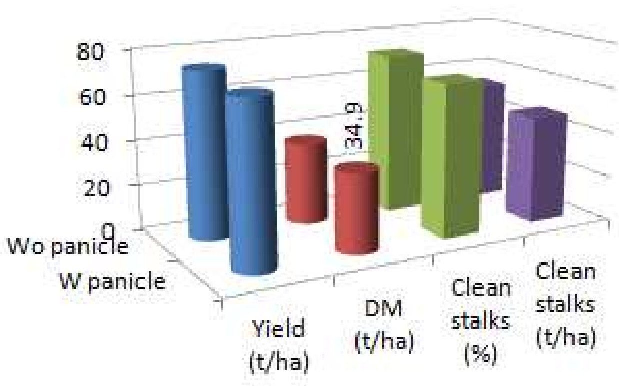

Figure 1. 2007 mean results of Idanha-a-Nova field experiment (T-test statistics; no significant differences, for the 95% confidence level).

As a matter of fact, globally speaking, yield of fresh biomass was in general very acceptable. This reached in many cases mean values well above 60.0 t/ha, as

in 2007, both in Idanha-a-Nova (between 71.1 and 73.6 t/ha, when panicle cut influence was tested; Figure 1) and in Castelo Branco trials (where propagation system – transplanting vs. sowing – fertilization type – fully chemical or a mixture of chemical and organic – and panicle removal influence, were tested in a Split-Split-Plot design), when it was possible to harvest up to 92.6 t/ha (sown plots; Table 1, next page).

It is true that there were also some low yields, like 43.3 t/ha (mean overall value for 2009 harvest, V. V. de Ródão trial). However, the actual gran mean value of yields was 64.8 t/ha (it should be stressed that in different occasions and under specific treatment conditions it has been possible to collect more than 100.0 t/ha).

Table 1. 2007 mean results of Castelo Branco field experiment (Uni-ANOVA statistics; for each factor and parameter, different letters for different levels denote significant differences between levels, for the 95% confidence level).

Factor	Yield (t/ha)	DM (t/ha)	Clean stalks (% of biomass)	Clean stalks (t/ha)
PS				
Transplanting (P)	67.0 a	21.3 a	57.2 a	38.3 a
Sowing (S)	92.6 b	30.4 b	57.9 a	53.8 b
Fertilization				
F1	82.5 c	25.7 c	55.1 c	46.3 c
F2	77.1 c	26.0 c	60.1 c	45.8 c
Panicle				
Wo	82.5 e	25.4 e	61.6 e	50.0 e
W	77.1 e	26.3 e	53.6 f	42.1 f

The same may be said about the Sweet sorghum Dry Matter production per hectare which yielded from 12.0 t DM/ha (2009 V. V. Ródão trials' mean) to 34.9 t DM/ha (Idanha-a-Nova trials' mean, in 2007; please refer to Figure 1). This is extremely remarkable for a crop that remains in the field for just four months. Also because of this, Sweet sorghum is, therefore, a very promising crop and can be adapted to the region in question.

On the other hand, some characteristics typically considered linked to the possible industrial use of Sweet sorghum (or similar crops), revealed to be in line with what was already measured in other experiments run in different Mediterranean countries and around the World (Figure 2, next page).

Some of the most important ones may be mentioned: clean stalks proportion in the biomass (from 57.6 % – 2007 Castelo Branco experiment (overall figure) – to 81.0 % – 2010 V. V. Ródão general test value), its juice sweetness (globally ranging

from 16 – 17 ºBrix, but with extreme values of 10.9 and 19.5 ºBrix) and the amount of juice extractable from Sweet sorghum biomass (global figures from 338 to 550 l/t of clean stalks, free of leaves and panicles).

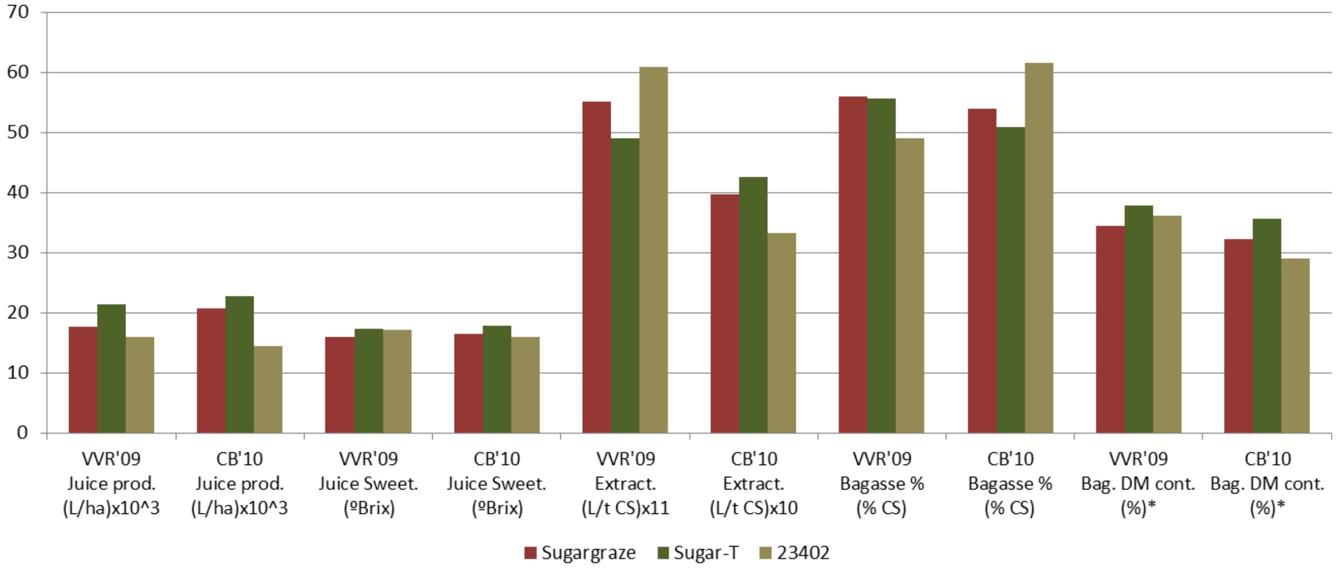

Figure 2. 2009 Vila Velha de Ródão (VVR'09) and 2010 Castelo Branco (CB'10) industry-linked results: factor "cultivar". CS – Clean Stalks; Sweet. – Sweetness; Extract. - Extractability (Uni-ANOVA statistics, for the 95% confidence level; significant differences denoted by *).

In terms of if the Sweet sorghum ethanol production is efficient enough to become a ground for any decision on ethanol production in the region of Idanha-a-Nova at a commercial level, according to the obtained results it will be. As a matter of fact, the ethanol (or the now so called "bioethanol") production depends on the availability of one or a set of sugar rich feedstocks, available at contained and competitive prices. According to our trials with relatively contained inputs, it was possible to produce important amounts of sugar rich juice from the Sweet sorghum crop. But a more reliable answer to this question asks for a more profound set of laboratory tests, involving Sweet sorghum juice fermentation and distillation.

As to the preservation of sugar from Sweet sorghum as syrup for a longer time, in order to extend the annual working period of an ethanol plant based on this crop, it is feasible. Actually, from the preliminary small tests run in 2008 and 2009, it was possible to conclude that Sweet sorghum syrup production was not technologically complex and more important than that is that this syrup is a stable product. It takes months until the syrup loses its main properties. Therefore, we believe that this juice concentration path represents a way of preserving sugars in

the form of a stable product that may definitely help to extend the annual use of an ethanol refinery.

When considering an eventual added value of Sweet sorghum by use of its wastes for co-generation units we can conclude that on basis of our research the amounts of dry matter produced in the form of Sweet sorghum bagasse represents one of the more interesting and promising cases of biomass production for co-generation purposes. Actually, taking into account the fact that the crop stays in the field for only about four months, this constitutes one of very rare examples of species which produce so much biomass per season and leave the field in a good condition and free for other utilization (for food production). On the other hand, although performed only once, both Proximate and Ultimate Analysis (Table 2) gave very good results in terms of the energy-related use of Sweet sorghum or its by-product bagasse. Additionally, a chemical analysis of those materials revealed also other very proper chemical characteristics, like a very small content (2,312.5 ppm) of Chlorine (much better than the 5,400 ppm pointed by Grassi, in 2005). This particular characteristic is of major interest for co-generation plants' maintenance costs, as Chlorine salts attack plants' metal components.

Table 2. Proximate (left) and Ultimate analysis of Sweet sorghum bagasse from 2007 Castelo Branco trials, wt% dry basis, unless stated otherwise (n=2).

Volatile Matter	Fixed Carbon	Ash	Higher Heating Value (MJ/kg)	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur
65.50	27.50	7.00	17.26	43.90	7.51	40.49	0.88	0.22

Finally, to the question if the Sweet sorghum bagasse can be used as fodder for animals because the nutritional value of its silage is good, silages produced from both the bagasse and whole plants (pre-wilted or not) showed very interesting nutritional characteristics for animal feeding. Better results were achieved in the case of whole plant's silage, but bagasse silage showed also important crude protein contents (for the type of feedstock in cause; Table 3, next page). When comparing different three cultivars – Sugargraze, Sugar-T and 23402 – Sugar-T revealed better silage quality, with higher nitrogen and crude protein levels, and also with less ash content.

Table 3. Statistical analysis summary of Sweet sorghum silages' characteristics resulting from Castelo Branco field trials in 2009 – One-way Analysis of Variance homogeneous groups for 95% confidence (n=3).

Factor	OM (in DM, %)	N (in DM, %)	CP (in DM, %)	NDF (in DM, %)	ADF (in DM, %)	ADL (in DM, %)	Ash (in DM, %)
Silage type							
FPS[1]	95.59 a	1.04 a	6.47 a	55.05 a	31.16 a	3.22 a	4.41 a
WFPS[2]	95.67 b	0.96 b	5.96 b	54.39 b	31.76 b	3.40 a	4.33 b
BS[3]	96.83 c	0.77 c	4.81 c	74.53 c	45.46 c	4.88 b	3.17 c
Cultivar							
Sugargraze	95.71 a	0.89 a	5.54 a	61.76 a	37.08 a	4.18 a	4.29 a
Sugar-T	96.55 b	0.96 b	6.02 b	60.41 b	34.78 b	4.19 a	3.45 b
23402	95.82 c	0.91 c	5.69 c	61.80 a	36.51 c	3.12 b	4.18 c

Note: 1 – Fresh Full Plants Silage; 2 – Wilted Full Plants Silage; 3 – Bagasse Silage.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

After all the field trials performed on the feasibility of Sweet sorghum (SS) growing and processing under Portuguese conditions, we are in a position that allows us to answer the main hypotheses formulated at the starting point of this thesis.

1. The first hypothesis was on SS being capable to adapt to soil and climate of Idanha-a-Nova and surrounding counties, under irrigated conditions; our answer is fully positive. There were many data collected during the field trials, which were purposefully spread in the area considered as a potential future beneficiary of Sweet sorghum use for ethanol and other related goods production. Sweet sorghum revealed to be agronomically well adapted to the region.

2. On the other hand, some characteristics typically considered as important variety parameters linked to the possible industrial transformation of SS (or similar crops) like clean stalks proportion in the biomass, its juice sweetness, and the percentage of juice extractable from SS biomass, have shown to be in line with what was already measured by other experiments conducted in different Mediterranean countries, as well as around the World.

3. As to the hypothesis on the SS ethanol production efficiency (will it be provided enough biomass?) to support any decision of ethanol production in the region of Idanha-a-Nova at a commercial scale our answer is also positive. As a matter of fact, the ethanol production depends on the availability of one or a set of sugar-rich feedstocks, available at competitive prices. From our trials with relatively contained inputs we have been encouraged to estimate quite important amounts of SS biomass, sugar rich juices and thus bioethanol derived from the SS. Their volumes mounted up to 92.6 t/ha (Castelo Branco trials, in 2007), 22,723 l/ha (with 17.8 ºBrix; Castelo Branco trials, in 2010) and 5,111 l/ha (using Bellmer and Huhnke (2007) estimate approach), respectively.

4. The hypothesis on the feasibility of preserving sugar from Sweet sorghum as syrup in order to extend the annual working period of an ethanol plant based on this crop; our answer is also positive. Actually, from the preliminary (and quite limited) tests conducted in 2008 and 2009 it was possible to conclude that SS syrup production has no secrets and maybe still more important finding is that the syrup is a stable, non-perishable product; it takes months until it loses its main properties (in our experiments, some samples remain in good condition two years after being produced). Therefore, we believe the juice concentration path means a way of preserving sugar in the form of a stable product which may definitely help extend the annual use of an ethanol refinery up to 10-11 months/year.

5. As to the hypothesis on the biomass productivity potential of Sweet sorghum: it is satisfactory in view of its valorization in co-generation units as to its volume and quality, therefore our answer is clearly positive. From our data gained during the field trials, the amount of dry matter produced in the form of SS bagasse represents one of the more interesting cases of biomass production for co-generation purposes. Actually, taking into account the fact that the crop stays in the field for only about four months, this constitutes a rare example of a species which produces so much biomass per season and makes the field free for other purposes (for instance for food production). On the other hand, although performed in only one year's feedstock, both Proximate and Ultimate Analysis gave very good results in terms of the energy-related use of SS or its by-product bagasse. Additionally, a chemical analysis of those materials revealed also other very good characteristics, like a very small content of Chlorine (which is of major interest for co-generation plant maintenance costs).

6. Finally, as to the hypothesis on the bagasse of Sweet sorghum which can be used as fodder for animals because the nutritional value of its silage is good; our answer is also positive. As a matter of fact, the silage produced of both the bagasse and fresh plants showed very interesting nutritional characteristics for animal feeding; for example, they have an important crude protein content (from 5.96 to 6.47 % CP, in the case of fresh plant silage, and 4.81 % CP for bagasse silage).
But the silage can also be understood as a way of preserving biomass for other uses; like, for instance, a stock of raw material for a biogas plant using bagasse as one of its feedstocks. Thinking ahead, the silage can also work as a means of preserving fibrous feedstocks for second-generation ethanol plants in the short- to medium-term.

6.2 Recommendations

From our experience, some recommendations on Sweet sorghum crop cultivation and industrial use can be made:

1. The Sweet sorghum growing in the area of Idanha-a-Nova and neighboring counties needs irrigated fields for economically interesting yields. However, the maximum irrigation rate used in these trials was of 3,200 m^3/ha per season, well below other crops common in the same region (like maize, which sometimes needs up to 8,000 m^3/ha). On the other hand, the soils used for the trials were in general poor in terms of Organic Matter (values ranging from 0.4 to 2.6 % in the arable layer), but with high to very high levels of Phosphorous and Potassium (up to 526 and 398 ppm, respectively). The climate conditions prevailing in the region during the most reasonable period of the year for the crop – between May and September – didn’t affect the crop performance.
2. Based upon our experimental results the agro-technical basic principles of Sweet sorghum growing include planting as soon as air temperature rises above 14-16 ºC, when soil, after tillage, fertilizer dressing and leveling, is still moist. No irrigation should happen immediately after seed drilling, as this can compromise seedling emergence in the type of soils prevailing in the region (crust formation risk). Only after this the crop will benefit from irrigation, if the soil starts to loose moisture rapidly (which in general happens during May), due to the natural increase in air

temperature (that happens by that time also). Irrigation will then increase in importance until plant flowering. Fertilizers' dressing should allow a nutrient availability compatible with what soil contains in itself (soil sampling before tillage is essential for this) and what the crop needs. In our trials this meant the use of 100-150 or more Nitrogen fertilizing units (depending on the cultivar potential), but, due to Phosphorous and Potassium availability in some local soils, these latter nutrients may be used in a more moderate way. If very high yields are to be obtained, herbicide spraying may be advisable. But Sweet sorghum revealed to be so vigorous since early stages of development that, if timely sown, the crop could even avoid any herbicide spraying. No important plagues or diseases were registered in our trials (although this may be due to the fact that new cultivars were being use, still with no natural enemies in the region).

3. One of the most fragile aspects of Sweet sorghum utilization we identified in the region under study was related to its harvest, as plants may grow up to four meter high. This means that dedicated equipment should be used for any commercial scale operation with this crop, as common forage harvesters (*e.g.* maize harvester) may face some difficulties to collect Sweet sorghum stalks for subsequent juice extraction.

4. In order to start an actual bioethanol business based on Sweet sorghum biomass production in the area Idanha-a-Nova the overall amount of the feedstock to gather will always be crucial for the dimension of the operation to establish. Even if this will depend on several factors – cultivar(s) to be used, quality of the soil to be cultivated, soil fertilization scheme to be implemented, harvesting and preservation technology to apply – in general terms, an operation involving 1,000 hectares will have to aim for an overall production of 80,000-100,000 tonnes of biomass, capable of potentially giving 13,000-18,000 tonnes of sugars and of 3,300-5,700 m^3 of bioethanol.

5. Between the cultivars tested, the Sweet sorghum cultivars recommended for Beira Interior region of Portugal are Sugargraze and, to some extent, Sugar-T. Their most relevant characteristics which are technologically significant (in view of the bioethanol production) are potential high yield and sweetness.

6. In order to extend the annual processing period of a bioethanol plant based on this feedstock, the possibility of preserving its juice as high sugar concentration syrup (65-85 ºBrix) must be considered. Depending on the amount of juice available

and its characteristics, as well as on the concentration rates achieved at the industrial scale (in our tests we obtained from 1:8.1 to 1:10.7 L of syrup/L of juice), this may allow prolonging the period of work by of the bioethanol facility from 2 months/year to 11 months/year.

Closing with some general recommendations, in our opinion the use of Sweet sorghum for energy production in Portugal is an issue that must be discussed. Although more research is advisable in these subjects, the opportunities this crop offers in terms of energy are quite vast. In general, only ethanol is mentioned as a possible product of this plant. But the opportunity of expanding the German model of biogas production based on maize to Portugal and to Sweet sorghum is a question that must be carefully analyzed. On the other hand, if a by-product of ethanol production may be used for animal feeding, the better. Moreover, if this complete set of possible uses of Sweet sorghum may be integrated in a concept of biorefining, then the overall efficiency of the operation may become even more remarkable.

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ACADEMIC DEGREES

Master of Science in Agricultural Engineering (Agricultural Mechanization Management option), Silsoe College/Cranfield University, United Kingdom, since 1995; Dissertation Thesis on "Suitability of reduced tillage techniques for Portuguese forage crops".

Bachelor of Science (with honours) in Animal Production (Scientific and Technologic specialization), University of Évora (Portugal), since 1991. Final work on "Production and free-consumption assessment of haylage in round bales by sheep and bovines".

Other graduations:

- In 2009 – Course *The Alcohol School*, by the *Ethanol Technology Institute* (Milwaukee, EUA), from March 30 to April 4, in Toulouse (France);
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PREVIOUS AND CURRENT SCIENTIFIC AND/OR PROFESSIONAL ACTIVITIES

From 1991 to 1995 – Assistant Lecturer and then Lecturer at the College of Agriculture of the Polytechnic Institute of Castelo Branco; since 1995 – Assistant Professor at the same institution (Vice-Dean 2000-2003; Dean 2003-2006).

PUBLICATIONS AND COMMUNICATIONS

• Monteiro, J., Havrland, B. and Ivanova, T. (2011). An integrated view of Sweet Sorghum (*Sorghum bicolor* (L.) Moench) bioenergy value – ethanol, co-generation, biogas – for

Portugal (awaits publication in *Agricultura Tropica et Subtropica* journal. CULS Prague, Institute of Tropics and Subtropics. Prague, Czech Republic);
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