**CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE**

Faculty of Tropical AgriSciences

Department of Sustainable Technologies


# Utilization of peanut shells waste biomass for energy purposes

Master's Thesis

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**STATUTORY DECLARATION**

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In Prague, 2019

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David Murcia Higuera

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**Abstract**

The current dependency on fossil fuels represents one of the biggest challenges for the coming generations. The emissions associated to its usage, are among the main contributors to the global warming phenomena and are considered as the major greenhouse gasses. The present Thesis is focused one of the oldest sources of energy; biomass, as an alternative to conventional sources of energy in Senegal. In this particular case the peanut shells were selected, due to its high peanuts' production in Senegal, abundancy of residual shells as well as their poor nutritional value for usage as a source of feed for livestock. According to the statistical yearbook of the Food and Agriculture Organization (FAO) in 2017 the production of peanuts in Senegal was 915,000 t, produced on 940,000 hectares, thus every year Senegal generates approximately 274,500 t of peanut shells (30% of the peanuts' weight (Perea-Moreno et al., 2018)), which are commonly disposed in landfills or burned in open air. This indicates the potential of the peanuts shells as an alternative fuel for Senegal. To evaluate the mentioned potential, the main physical and chemical tests were performed; firstly, properties such as calorific value, ash content, emissions and chemical characteristics (Carbon, Hydrogen, Nitrogen and Sulphur) were evaluated. Secondly, physical and mechanical properties (moisture content, dimensions, mechanical durability and bulk density) were analyzed in three forms of the material (loose peanut shells, briquettes and pellets). The obtained results showed good overall quality of peanut shell's based biofuels, and the standard limits were fulfilled for the majority of parameter. However, the ash content was found to be significantly higher comparing to the requirements and literature. Thirdly, a linear regression model was elaborated to predict the production of peanuts in the next 20 years, used to calculate the potential energy production over the same period. The results indicate an approximate electricity generation of 900 MWh per year.

**Keywords**: Senegal, energy, Peanut shells, biomass, solid biofuel, calorific value, moisture content, ash content.

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# 1 INTRODUCTION

The exponential increasement of the global population and the current demands of energy, have forced an excess of exploitation of the natural resources around the world, this phenomenon is directly related with the rapid decrease of natural conventional reserves of energy (petroleum, natural gas, coal, among others). More than 10 tons of oil equivalent energies are consumed annually in the world, of which more than 80% comes from non-renewable fuels (Satio, 2010). Many initiatives had been developed, in order to reduce the dependence on the non-renewable energy sources, by use of solar, wind and wave energy, as well as the hydropower and bio-fuels production.

Lately, the production of biofuels had generated a polemical discussion, either is better to use the land for the food production or to supply the energy required for the industry and transportation goods. Furthermore, the use of agriculture lands for bio-fuels crop production could increase the price of the food commodities (Campbell et al, 2008), which are critical to accomplish one of the most important aims of the Millennium Goals: the food security. Thus, it is vital to develop strategies to guarantee the production of food commodities as a priority and then to formulate the use of the postharvest goods (residues) for different purposes, such as substrate of the soil or bio-energy production.

The edible nuts have been used as an important source of food since the prehistoric period and represent one of the most complete fonts of food in terms of nutritional content. In the current case of study, the production of groundnut will be analyzed, focusing on the generation of organic waste in Senegal and its potential use as a source of energy.

In Senegal the agriculture sector plays an important role of the economy within a share of 17% in the gross domestic product, from which the processed peanuts exports represent the 1.3% (Georges et al., 2016). A worldwide area cultivation of about 22.2 million hectares of land is destined to the production of peanuts every year, which constitutes a 16.3 million of hectares in Asia, 7.39 in Africa and 0.7 in South America and Central America (Maiti & Ebeling, 2002). According to the FAO (2002), in Senegal there was processed 684.000 tons of groundnuts in a total area of 829.000 ha, representing a huge production of organic waste which is usually disposed in landfills or even burnt in open air. The above implies that a large amount of potential source of bioenergy is not properly used.

One of the main issues with the groundnut production, is the generation of organic waste/agricultural residues such as shells which demand a considerable portion of land for its storage. The current alternatives to treat this waste, is to transfer it to the landfills, which represents an extra cost to the farmers and therefore an increasement in the price of the final product. The second alternative is to use the shells as a substrate for the soil enrichment for the next crop production, however it must be done by a composting process to enhance different physical and chemical properties of the soil, such as nutrient content, organic matter, disease control, among others (Grigatti et al., 2007). The third and most used alternative in developing countries for the majority of groundnuts shell, is either to burn or dump the shells in the forest which generates a negative impact in the environment due to the emission of greenhouse effect gases (Nalluri & Vasavi, 2018). However, the Ministry of Environment and Sustainable Development of Senegal, forbids this practice in its Environment Code (Law 201-01, 2003), Title III Protection and enhancement of the environment receptors, Chapter II Air Pollution and unpleasant odors, article L 78.

The above-mentioned practices, demonstrate the necessity of developing alternative techniques to guarantee the protection of the environment, emphasizing the prevention of the air and water pollution. Through this study, one of these alternatives will be analyzed, using the organic waste of the groundnut cultivation for energy purposes, specifically for the transformation of the peanut shells to solid biofuels such as pellets and briquettes.

# 2 LITERATURE REVIEW

In this chapter the most relevant information about the peanut plant (*Arachis hypogaea* L.*),* some definitions about energy and general information regarding Senegal such as the location, climate conditions, renewable energy production and the peanut production are summarized.

## *2.1* Peanut (*Arachis hypogaea* L.*)*

Peanuts (*Arachis hypogaea* L.*)* also known as groundnuts or monkey nuts, are an important source of food around the world, and its production is mainly growth in tropical and subtropical regions of the world, representing a significant source of cash income and food cropping to smallholders, especially in most countries in sub-Saharan Africa (Mbonwa, 2014). The cultivation of groundnuts was originated in south America more precisely in the southern region of Bolivia and the north side of Argentina, approximately in the 1,000 B.C., later the dissemination to Europe, Asia and Africa was done presumably in the sixteenth and seventeenth centuries, and its related to the conquer process from Spain, Portugal and Great Britain (Murata, 2003).

The *Arachis hypogaea* is an herbaceous legume with an intermediate and annual self-pollination, where the fruit is growth under the ground into a pod which contains between 1 to 5 seeds (Department of Agriculture, Forestry and Fisheries -DAFF- of the Republic of South Africa , 2010), with two main subspecies and four botanical varieties, as the Table 2.1 shows. The groundnuts are used in a big range of food products, household use, agricultural inputs, beauty, building material and cellulose, and represent an important commodity for the local staple food in Senegal, reporting an estimated consumption in household level of approximately 30 liters per month of groundnut oil (Georges et al., 2016).

*Table 2.1 Taxonomy and subspecies of Arachis hypogaea* L.

| Order | Genus | Species | Subspecies | Growth habit | Botanical variety | Maturation time |
|---|---|---|---|---|---|---|
| **Fabales** | **Arachis** | ***Arachis hypogaea*** | *hypogaea* | Spreading | *Hypogaea* runner | long 145-165 days |
| | | | | Branching | *Hypogaea* Virginia | |
| | | | *fastigiata* | Erect | *Fastigiata* Valencia | short 90-120 days |
| | | | | | *Vulgaris* Spanish | |

Source: National Plant Data Center, 2000; Murata, 2003; Singh & Simpson, 1994; Shokes & Melouk, 1995

### 2.1.1 Plant morphology and description

As before mentioned, the *Arachis hypogaea* L. is an annual herbaceous legume, self-pollinated through a natural cross-pollination process at rates between 1 and 6% using the typical actions of the flowers or the bees (Department of Agriculture, Forestry and Fisheries of the Republic of South Africa, 2010). As it was shown in the Table 2.1 there are 2 subspecies of the *Arachis hypogea*, the *hypogea* and *fastigiata*. The first one has a spreading growth habit, absence of flowers on the central stem and long growth cycle, whereas, the *fastigiata* has a shorter growth cycle, flowers on the central stem and an erect growth habit (Rami J. *et al*, 2013).

There are three main types of botanical classification of the peanuts (Virginia, Spanish and Valencia), which is mainly based on the number of seeds per pod, as well as the order and pattern of the branching (Astor et al, 2015). In terms of appearance (see Figure 2.1), the plant reaches a growth between 0.20 and 0.60 m of high, with yellow flowers, as one of the most distinctive physical characteristics, when the peanut peduncle is fully elongated after the fertilization of the flower, it bends down into the ground, place where the maturation of the seeds start with a growing period of approximately 5 months (Environmental Protection Agency, 1995).

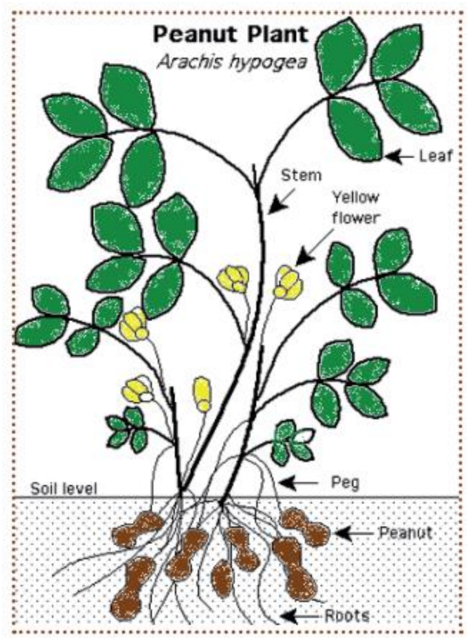



*Figure 2.1* Peanut plant sketch

Source: Department of Agriculture, Forestry and Fisheries of the Republic of South Africa, 2010

2.1.1.1 Stem and branches

Singh (2003) has described that the plant has main stem, with a considerable variation of branches, in which the carrying of the laterals determines the growth habit; either spreading (runner, trailing, procumbent and prostate) or erect (upright, erect bunch and bunch). One of the most common disease of the groundnut occurs precisely in the stem, called as southern blight, also stem and pod rot, is a fungal disease which causes a yellowing and wilt of the branches, and then after evolving it can cause a wilt of the entire plant (Jackson, 2014).

#### 2.1.1.2 Leaves

The leaves are alternate and compound with a size range of 4 $cm^2$ in the seedling, then up to 80 $cm^2$ for fully developed leaves, shown typically after the exponential increase process from 20 to 90 days after sowing. Generally, the *hypogaea* is characterized by dark green leaves, whereas the *fastigata* presents light green and larger leaflets (Singh, 2003). As a defensive technique against the leaf hoppers, the abaxial surface and margins of the leaves have a set of hairs (Singh, 2003).

#### 2.1.1.3 Nuts – Fruits

As reported by the Department of Agriculture, Forestry and Fisheries (2010) "*the pod size varies from 1 × 0.5 cm to 2 × 8 cm, and seed weight varies from 0.2 to 5 g. The number of seeds per pod usually is two in the Virginia and runner types, two or three in the Spanish type, and three to six in the Valencia type*". The pod is an elongated sphere, which reaches the maximum size after 2 or 3 weeks, with a maximum oil content between 6 and 7 weeks and finally with a maximum concentration of protein after 5 weeks (Murata, 2003).

### 2.1.2 Environmental requirements

As it was mentioned at the beginning, the *Arachis hypogaea* is grown in tropical and sub-tropical regions, thus the environmental requirements are characterized by the African and American conditions, as it is shown in the Table 2.2.

*Table 2.2 Climatic requirements for groundnut plant*

| Requirement | Unit | Min | Favorable | Max | Source |
|---|---|---|---|---|---|
| **Air Temperature** | ° C | 20 | 28 | 35 | DAFF, 2010 |
| | ° C | 25 | - | 30 | Murata, 2003 |
| **Soil Temperature** | ° C | 18 | - | 30 | DAFF, 2010 |

| Requirement | Unit | Min | Favorable | Max | Source |
|---|---|---|---|---|---|
| **Rainfall** | mm | 500 | 600 | 700 | DAFF, 2010 |
| | cm | 51 | - | 102 | EPA, 1995 |
| **Soil pH** | Und | 5.5 | 7 | 7 | DAFF, 2010 |
| | Und | 5.5 | - | 6.2 | Murata, 2003 |
| **Soil organic matter** | % | 1 | - | 2 | Murata, 2003 |
| **Soil calcium** | mg/kg | 600 | - | 800 | Murata, 2003 |

Source: Author based on shown sources, 2019

### 2.1.3 Distribution and production

The production of peanuts (with shell) according the Food and Agriculture Organization (FAO) statistical yearbook in 2017 was 47,097,498 tons (see Figure 2.2), produced in 27,940,260 hectares, with Asia as the main producer with 62.5% of the production, followed by Africa with 26.1% and America with 11.3%. This shows the global production of peanuts, in which it is possible to appreciate China as the main producer in 2017 with a total production of 17,092,000 tons, followed by India with 9,179,000 tons, United States in the third position with 3,281,110 tons, whereas Senegal occupies the ninth place with 915,000 tons.

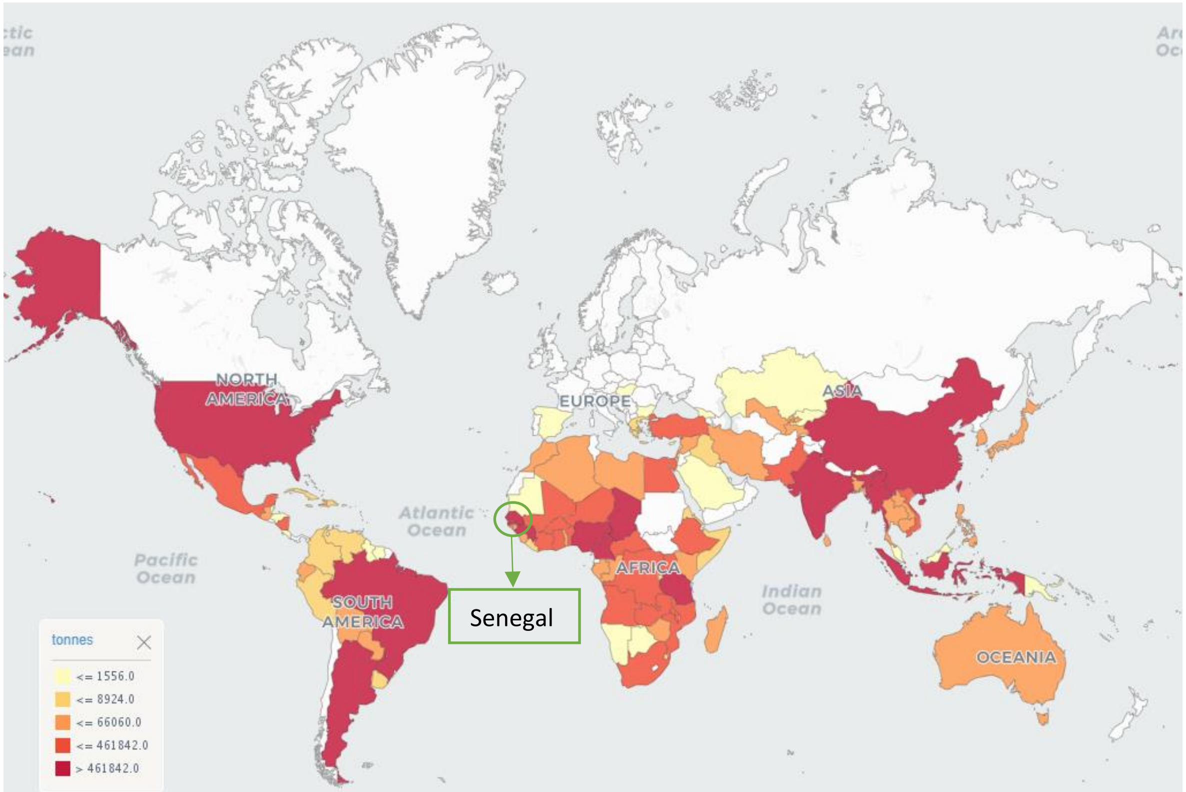



*Figure 2.2 Worldwide peanut production*

Source: FAO, 2018

The Figure 2.3 shows the historical production of peanut worldwide and specifically in Senegal, for the past 10 years (2007 – 2017). The graph shows a clear growth in the production worldwide with a production increment of 958,845 tons (18.54% of area harvested) globally and 583,805 tons (35.4% of area harvested) for Senegal.

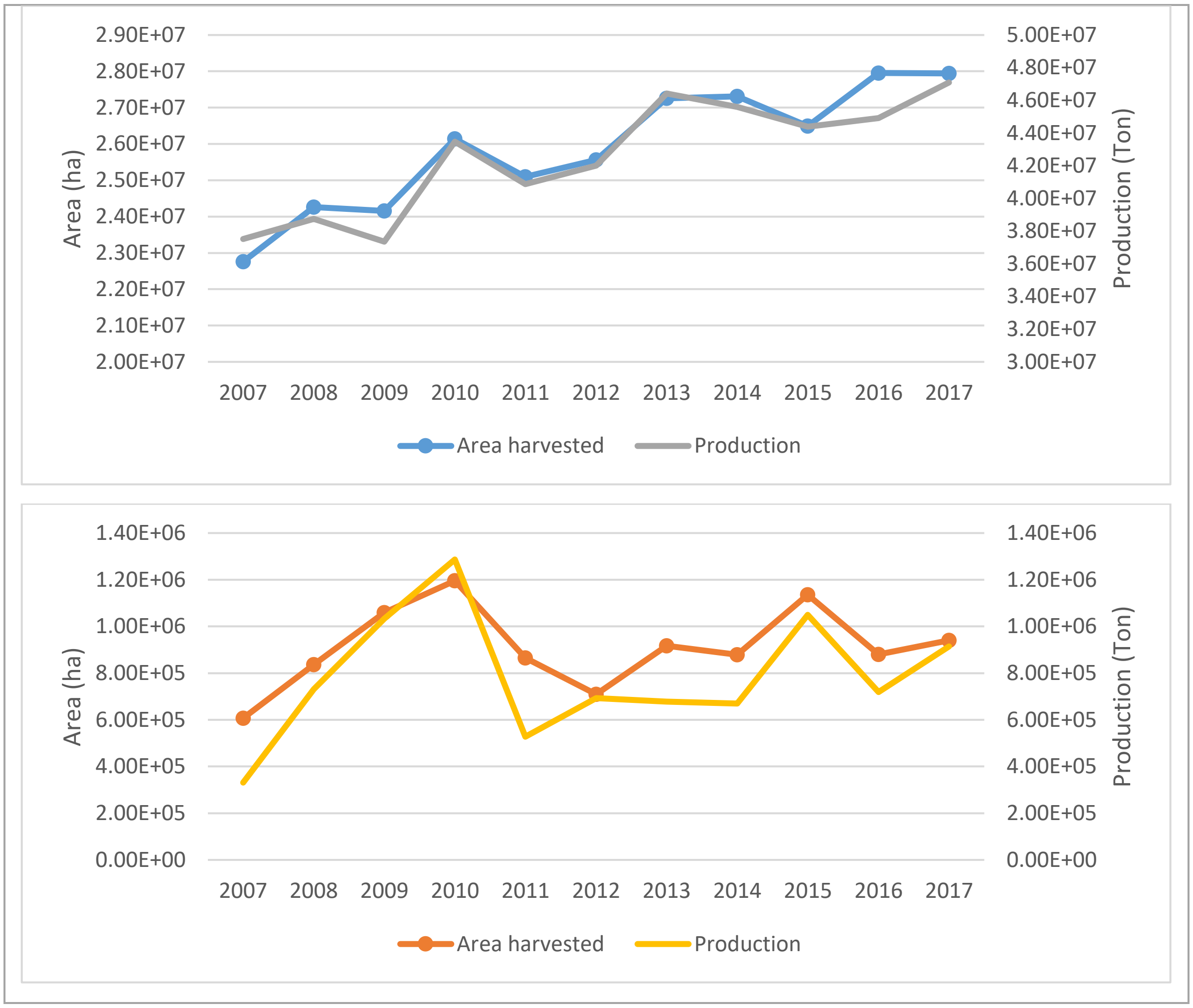



*Figure 2.3 Historical production and area harvested worldwide (top) and Senegal (bellow)*

Source: FAO, 2018

### 2.1.4 Nutritional data

The peanut is one of the most important oilseed crops in the world, due to its oil and protein content; 44-56% and 22-30%, respectively, as well as its mineral content (phosphorus, calcium, magnesium and potassium), as a source of vitamins (E, K and B group), zinc, iron, among others (Mbonwa, 2014). According to the commercial interest the groundnut can be classified in three main categories high, intermediate, and low content oil (also “mouth peanut”) which can be consumed raw, roasted or boiled (Dzondo-Gadet, 2015). The Table 2.3 shows the nutritional content of the groundnut reported by various sources.

*Table 2.3 Nutritional content of the groundnuts*

| Parameter | Units/ 100g | Reported level | | |
|---|---|---|---|---|
| | | Dzondo-Gadet, 2015[1] | Settaluri et al., 2012[2] | USDA, 2018[3] |
| **Water content** | g | 7.58±0.860 | 1.55 | 6.50 |
| **Lipids** | g | 47.43±1.60 | 49.66 | 49.24 |
| **Protein** | g | 32.64±0.26 | 23.68 | 25.80 |
| **Total carbohydrates** | g | 17.56±1.33 | 21.51 | 16.13 |
| **Iron** | mg | - | 2.26 | 4.58 |
| **Potassium** | mg | 2070.00±0.97 | 658 | 705 |
| **Phosphates** | mg | 672.19±0.970 | 6 | - |
| **Calcium** | mg | 45.00±0.6700 | 54 | 92 |
| **Sodium** | mg | 12.5 ±0.500 | - | 18 |
| **Magnesium** | mg | 350.00±0.840 | 176 | 168 |

[1] **Manga** peanut
[2] Dry-roasted peanuts
[3] Raw peanut

Source: Author based on shown sources, 2019

## 2.2 Renewable energy

In order to guarantee a better quality of life to the human communities, it is necessary to provide energy for different purposes (e.g. cooking, lightning, mobility, communication, heat, etc.). As it was explained before, the increasement in the population has forced the use of the natural resources, especially referring to water, air quality, soil and conventional energy resources. As per the urgency to find new sources of energy with low environmental impacts and more important renewable founts, many alternatives have been developed over the years, as it shown in the Table 2.4, (e.g. solar energy, geothermal energy, hydropower, wind energy, among others). According to the Intergovernmental Panel on Climate Change, 2012 *"there are multiple means for lowering of greenhouse gases (from* *now GHG) emissions from the energy system, while still providing desired energy services. Renewable energy technologies are diverse and can serve the full range of energy service needs."*

*Table 2.4 Classification of energy sources*

| Type | Renewability | | Renewable | Non-renewable |
|---|---|---|---|---|
| Conventional | Commercial | | Hydropower (large scale)<br>Geothermal<br>Nuclear (breeder) | Fossil fuels<br>Nuclear |
| | Traditional | Other | Solar (air drying)<br>Hydro (mills, pumps)<br>Wind (mills, pumps and sails)<br>Animate (animal and human) | |
| | | Biomass | Fuelwood "cropping" from natural forest/charcoal<br>Twigs, leaves, sticks<br>Crop residues (straw, husks)<br>Animal residues (dung, tallow)<br>Industrial residues (wood waste, sawdust) | Fuelwood "mining"<br>Charcoal |
| Non-conventional | Novel | | Plantation and marine crops (for distillation, pyrolysis)<br>Biogas | |
| | | Other | Solar (collectors, photovoltaic)<br>Hydro (mini and micro)<br>Wind (wind motors)<br>Tidal, wave power<br>Ocean thermal gradients<br>Heat pumps | Nuclear<br>Petroleum from coal, shale<br>Synthetic natural gas |

Source: Mendoza, 2016 and Gritsevskyi, 2006

The renewable energies nowadays, are playing an important role by providing energy services with sustainable characteristics, particularly fighting the climate change by mitigating the emission of GHG. According to the Global Status Report of Renewables energies written by the Renewable Energy Policy Network for the 21st Century (from now REN21), the estimated share of renewable sources (Figure 2.4) was 19.5% from which 7.8% corresponds to the traditional biomass, 2.2% to nuclear energy and 10.4% to modern renewables (3.7% hydropower, 4.1% renewable sources for heat, 1.7% for power and 0.9% to biofuels for transport), with China leading the power capacity, followed by United States, Brazil, Germany and India. On the another hand, the Figure 2.5 shows the historical and predictive shares of an energy production from 2012 until 2023, from which it is possible to observe the fast grow of the renewable electricity, with an estimated production of almost 30% by 2023.

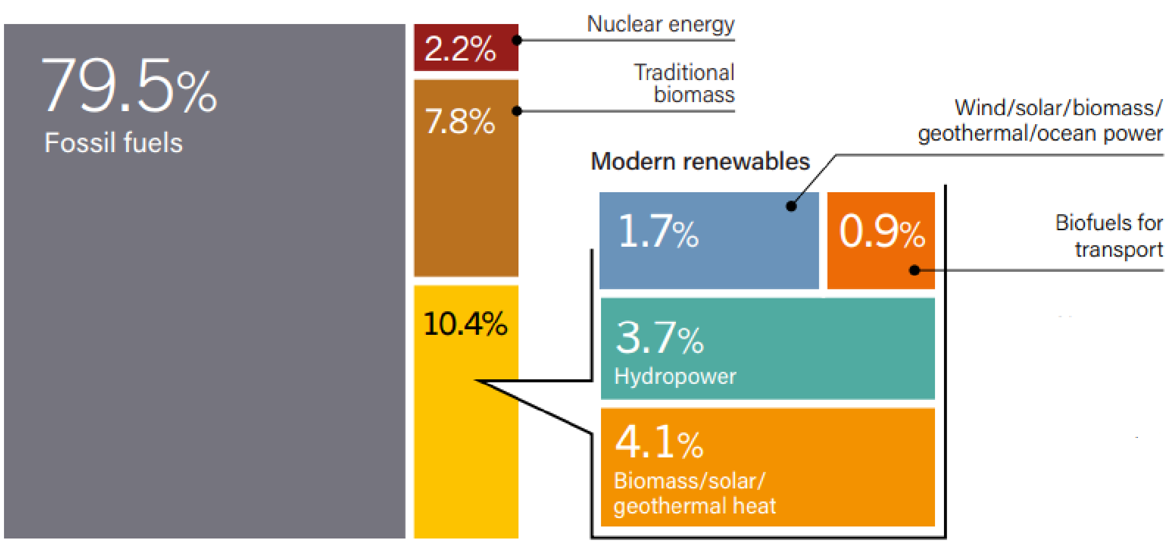



*Figure 2.4  Estimated renewable share of total final energy consumption, 2016*

Source: REN21, 2017

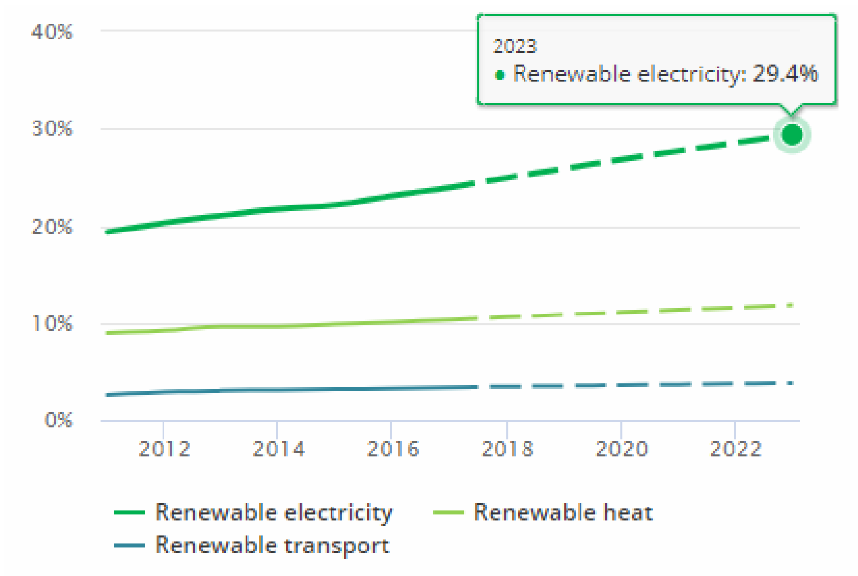



*Figure 2.5 Share of modern renewable energy by sector, 2011 - 2023*

Source: International Energy Agency, 2018

### 2.2.1 Biomass sources

Currently there are multiple sources of traditional biomass around the world, such as the waste coming from agricultural crops, herbaceous, woods production and general organic waste. Some advantages of the biomass sources can be named, in comparison to the traditional fossil sources, the main and the more obvious benefit is the renewability, whereas the fossil sources need thousands of years for the reproduction, the biomass sources are annually renewable or in several years depending on the specific characteristics of the specie (Nonhebel, 2007). The second advantage corresponds to the release of $CO_2$ which is one of the most major GHG, during the growth of the crops the biomass captures considerable amounts of $CO_2$ on the biosynthesis process, later on when the organic waste is transformed into energy the emission of $CO_2$ is generally similar or with little delta differences to the concentration captured. Thus, it could be assumed a balance between the absorption and release of $CO_2$, which is not even compared to the large amounts of $CO_2$ emissions from burning fossil fuels (Cheng, 2018).

Bellow the main sources of biomass are briefly described:

#### 2.2.1.1 Agricultural residues

The agricultural production generates organic residues from either crop or processing activities, which can be used in several ways: as fodder, land supplements, fiber and energy production (Hall & Overend, 1987). The most abundant and cheap crop residues for energy production are the corn stover, wheat straw and rice straw (Cheng, 2018). Overall, in the United States 155 million tons of agricultural residues could be used as a source of renewable energy in 2030 (UCS, 2012). Nevertheless, these residues are not ignored, "*in the Netherlands about 70% of the concentrate fed to pigs, cattle and poultry originate from residues generated by the food processing industry*" (Nonhebel, 2007) thus an overuse of the organic waste from the agriculture could reduce the availability of food for the cattle industry, and therefore an important source of protein for the human consumption.

#### 2.2.1.2 Herbaceous biomass

One of the most attractive qualities of the herbaceous biomass as a feedstock for energy is the richness in the diversity of the species, the high biomass yield production in several years and high carbon content (Cheng, 2018). For example, according to Cherney et al. (1990) the switchgrass (*Panicum virgatum)* is the perennial grass with the highest potential for energy production purposes, due to its tolerance to resist different air temperatures, fast grown, bio-remedial attributes, carbon sequestration.

#### 2.2.1.3 Woody biomass and forestry residues

One of the most important sources of energy, especially in Africa and third world countries is the wood biomass, where about 81% of the households in the Sub-Saharan Africa are using the wood-based biomass energy for cooking purposes (AFREA, 2011). There are two main categories of the woody biomass; the softwoods and hardwoods; the first one with needle-like leaves, gymnosperms and commonly non-flowering, with the pines and spruce as a main example. In contrast, the hardwoods are angiosperms, broad leaves and commonly flowering plants, with poplar, oak and willow as the most common examples (Cheng, 2018). The attractiveness of the woody crops is the relatively short rotation (2-5 years) due to its diversity, environmental tolerance, grown rate and non-necessity of irrigation for the growing of poplar (*Populus*); one of the most common species used for direct combustion, gasification and production of briquettes and pellets (IEA Bioenergy, 2002).

#### 2.2.1.4 Other sources

Many different sources of biomass feedstock are reported by different authors, such as oilseeds (i.e. soybeans, canola, sunflower, oil palm, among other) to produce biofuels (bio-ethanol, bio-diesel, etc.); residues of livestock production (i.e. animal excreta and slaughterhouses waste); microalgae (i.e. suspended algae and attached-growth algae production) for the biogas elaboration (McGowan, 2009).

### 2.2.2 Physical and chemical properties of biomass

The most important properties of the biomass related with the combustion, and its usage as a source of energy are moisture content, calorific value, ash content, bulk density, organic volatile matter and the chemical composition (Rosillo-Calle et al, 2015). In this part of the chapter those properties will be briefly explained, later in the chapter 4.2, the associated calculation formulas of each property according to the International standard will be presented.

#### 2.2.2.1 Moisture content

According to the British Standard, the simplest definition of moisture content is the amount or share of water in a specific material. Therefore, the efficiency of any biofuel in terms of energy production (calorific value) is inversely proportional to the moisture content, thus even if the wood has higher energy value than the crops residues at a determinate moisture content, is possible for the second source to have higher calorific value if the moisture content is lower (Rosillo-Calle et al*.,* 2015).

There are two ways to measure the moisture content: wet bases and dry bases. The first one represents the moisture content of the material calculated using both dry and water weight of the sample, and it is used mostly in the woody biomass industry. The latter one is calculated using the weight of the water and the weight of the dry material and it used mainly for foresters and producers/manufacturers of wood products (McGowan, 2009).

#### 2.2.2.2 Calorific value

According to Rosillo-Calle et al. (2015) the calorific value is defined as "*the measure of the energy content of a substance determined by the quantity of the heat given off when a unit weight of the substance is completely burned",* its commonly measured in calories or joules and expressed in Kcal/kg or MJ/kg. Currently the most efficient source of energy is the bituminous coal with a calorific value of 7,200 kcal/kg (30.15 MJ/kg), followed by the anthracite coal with 6,810 kcal/kg (28.52 MJ/kg), the lignite (at 35% of moisture) with 3,990 kcal/kg (16.71 MJ/kg), wood (at 40% moisture) with 2,880 kcal/kg (12.06 MJ/kg), bagasse (at 50% moisture) with 2,220 kcal/kg (9.29 MJ/kg) and bark (at 50% moisture) with 2,492 kcal/kg (10.44 MJ/kg) (Environmental Protection Agency, 1995).

There are two main ways to determine the calorific value of a fuel: the Gross Calorific Value -GCV- (also called the Higher Heating Value -HHV-) and the Net Calorific Value -NCV- (also

Lower Heating Value -LHV-). The GCV is the total amount of energy released for unit of mass of solids biofuels burned in the presence of oxygen and under specific conditions, it is usually measured by using a Calorimetric Bomb. Whereas the NCV is the value of energy obtained during the combustion of the biofuel under conditions of constant volume and presence of water, which will remain as a water vapor (British Standard Institution, 2010). As reported by Rosillo-Calle et al. (2015) the GCV is always higher than the NCV, since the latter includes the energy to vaporize the water contained in the fuel and the energy to form water from hydrogen contained in the hydrocarbon molecules, and its vaporization. In the Figure 5.2 of the chapter 5.2, multiples values for calorific value for different sources of biomass are shown.

#### 2.2.2.3 Ash content

As per the British Standard definition, the ash is the "*solid mineral residue obtained from a complete fuel combustion*". Therefore, when the ash content of a fuel is high, it will have a lower calorific value. The content of ash plays an important role during the combustion of the solid biomass, since its high ash content causes problems with combustion automatization, maintenance of the stove (for both industrial and small scale heat production), and inhalable particle emissions (Obernberger et al., 2006).

The ash chemical composition of the solid biofuels includes Al, Ca, Cl, Fe, K, Mg, P, Na, S, Mn, Si, and Ti which are related with different environmental and technical issues such as emissions of fine particles, low ash fusion temperatures, increasement of deposit formation, agglomeration, slagging, corrosion and abrasion (Vassilev et al., 2017). The ash content in most of the coals (up to 40% depending the type) is significantly higher than the ash content in biomass (0.2-0.5% for wood, 0.23% for sawdust, 4.7% for shea meal) (Kalembkiewicz & Chmielarz, 2011). Although, the ash is considered as an industrial waste it can be used as fertilizer due to its content of K, Ca, and S; additionally, it is used for different industries such as building and landscaping (Platače & Adamovičs, 2017).

#### 2.2.2.4 Bulk density

The bulk density is the "*mass of a portion of a solid fuel divided by the volume of the container which is filled by that portion under specific conditions*" (British Standard Institution, 2010), thus the bulk density refers to the weight of the biomass material in a given space. Hence, the bulk density is one of the key factors to manage parameters such as transportation and storage, since a high value of bulk density allows more volume of material to be transported/storage in a determined space portion (Larsson et al., 2008). Whereas the bulk density of biomass briquettes and wood pellets can be in average 600 $kg/m^3$, materials like the chopped straw and woodchips could be as low as 100-150 $kg/m^3$ (COFORD, 2003).

In terms of energy production, both bulk density and calorific value are used to determine the energy density, which represents the potential energy content per unit of biomass and is given in $MJ/m^3$ (McKendry, 2002).

#### 2.2.2.5 Mechanical durability

The mechanical durability is one of the most important parameters of the pellet and briquette production. It represents the ability of a solid densified biofuel to resist processes such as loading, transport, unloading and feeding without changing its original shape (Thek & Obernberger, 2010). According to the BS EN ISO 17225-6:2014 the minimal value of mechanical durability for pellets and briquettes is 95%. The importance of the mechanical durability measurement in the solid biofuel lies in the amount of fines; since a considerable quantity of fines can lead to blocks of the feeding screw, therefore extra costs for maintenance and reparations. Moreover, from the ecological, safety and health point of view the particulates emissions can rise, representing a risk of health for the workers and the atmosphere.

### 2.2.2.6 Elemental and chemical analysis

The elemental analysis aims to determinate the percentage by weight of Carbon (C), Hydrogen (H), Nitrogen (N) and Sulfur (S) in the organic solid biofuels. One of the main reasons to measure these values is to determinate the precise air for combustion (stoichiometric air) (Perea et al.,2018), to estimate the emissions from the combustion of biofuels, for instance during the combustion C and H are oxidized by exothermic reactions producing $H_2O$ and $CO_2$ emissions (Valantinavicius & Vonžodas, 2012). In addition, the continent of Sulphur (S), Chlorine (Cl), Fluor (F), Potassium (K) are related with the corrosion in the chamber, whereas the Nitrogen (N), Fluor (F), Phosphorus (K) and heavy metals are related with emissions (Stolarski, 2008).

The Table 2.5 resumes the main effects of the mentioned physical and chemical characteristics during the process of combustion of solid biofuels.

*Table 2.5 Effects of physical and chemical properties in the combustion of biomass*

| | Properties | Effects |
|---|---|---|
| Physical | **Moisture content** | Storage durability<br>Dry-matter losses<br>Low NCV<br>Self-ignition |
| | **Bulk density** | Fuel logistics (storage, transport, handling) costs |
| | **Ash content** | Dust, particle emissions<br>Ash utilization/disposal costs |
| | **Particle dimension and size distribution** | Determines fuel feeding system<br>Determines combustion technology<br>Drying properties<br>Dust formation<br>Operational safety during fuel conveying |
| Chemical | **Carbon, C**<br>**Hydrogen, H** | GCV (positive)<br>GCV (positive) |
| | **Oxygen, O** | GCV (negative) |
| | **Chlorine, Cl** | Corrosion |
| | **Nitrogen, N** | NOx, $N_2O$, HCN emissions |
| | **Sulphur, S** | SOx emissions, corrosion |
| | **Fluor, F** | HF emissions<br>Corrosion |
| | **Potassium, K** | Corrosion (heat exchangers, superheaters)<br>Lowering of ash melting temperatures<br>Aerosol formation<br>Ash utilization (plant nutrient) |
| | **Sodium, Na** | Corrosion (heat exchangers, superheaters)<br>Lowering ash melting temperatures<br>Aerosol formation |
| | **Magnesium, Mg** | Increase of ash melting temperature<br>Ash utilization (plant nutrient) |
| | **Calcium, Ca** | Increase of ash melting temperature<br>Ash utilization (plant nutrient) |
| | **Phosphorus, P** | Increase in ash meting point<br>Ash utilization (plant nutrient) |
| | **Heavy metals** | Emissions of pollutants<br>Ash utilization and disposal issues<br>Aerosol formation |

Source: Mendoza, 2016

## 2.3 Senegal overview

The Republic of Senegal (in French République du Sénégal) is a lower middle-income country located in the west Africa, with a total population of 15.85 million of inhabitants according to the census made in 2017 and Dakar as the Capital and the largest city. The economy of Senegal is leaded by the imports and exports of goods and services, which represents the 70% of the GDP (nominal 16.172 US $ billions), industry with the 21% and the agriculture with the 15% (The World Bank, 2017). The agriculture in Senegal is mainly dominated by sugarcane, groundnuts, and cotton as a primary cash crop, on the other hand the subsistence crops are specially cereals such as rice, millet, sorghum and maize (FAO, 2015).

### 2.3.1 Groundnut production

Senegal is one of the world leadings countries for the exportation of peanut oil, from which its production employs approximately 60% of the rural population, and its price for sales is fixed during the marketing period (October to April) by the government and the National Professional Groundnut Committee (CNIA) (International Trade Center, 2015), where 60% of the annual production is sold through the formal way using the prices fixed by the mentioned entities, to three main companies such as SUNEOR, NOVASEN and CAI Touba, while the 40% rest is sold by the informal channel with higher prices (F.E.W.S NET, 2014). The Table 2.6 shows the groundnut planting and harvesting calendar for the main producer countries.

*Table 2.6 Planting (green) and harvesting (maroon) calendar for groundnut*

| Country | Jan | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **China** | | | | | | | | | | | | |
| **India** | | | | | | | | | | | | |

| Country | Jan | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kharif (summer) | | | | | | | | | | | | |
| Rabi (winter) | | | | | | | | | | | | |
| **USA** | | | | | | | | | | | | |
| **Senegal** | | | | | | | | | | | | |
| | | | | | | | | Planting | | | | |
| | | | | | | | | Harvesting | | | | |

Source: International Trade Center, 2015

### 2.3.2 Climate conditions

Due to its location and proximity to the sea, Senegal has typical climate conditions of the tropic climate zones. The Table 2.7 describes the main climate conditions.

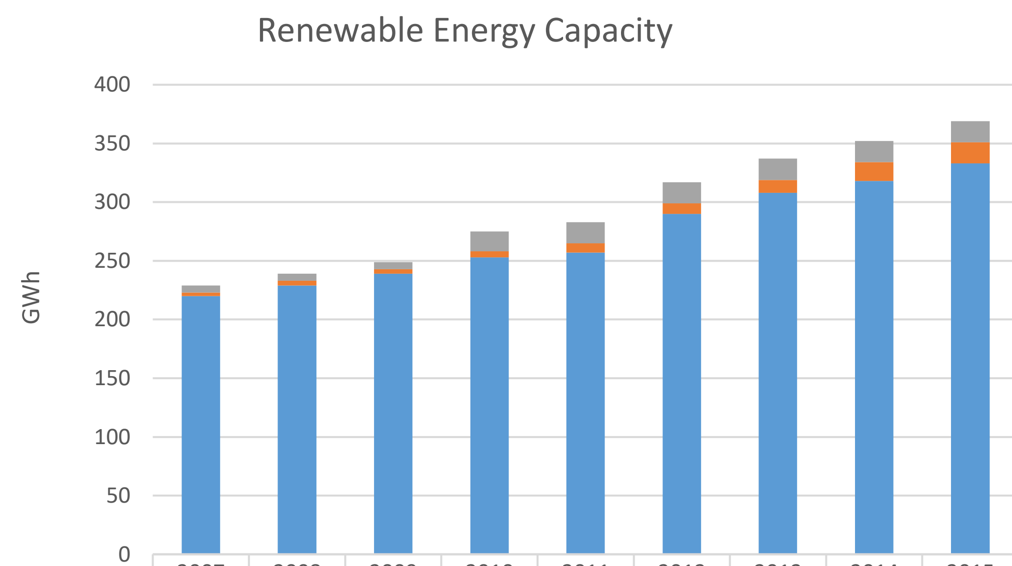
*Table 2.7 Senegal climate conditions*

| Parameter | Unit | Value |
|---|---|---|
| **Air Temperature** | ° C | 17 to 27 |
| **Rainfall** | mm | 760 to 1,270 |
| **Wind speed** | m/s | 5.7 to 6.1 |
| **Rainy season** | - | May to October |
| **Relative humidity** | % | 49 to 81 |
| **Solar Irradiation** | kWh / $m^2$ / year | 2,000 |
| **Daily irradiation** | kWh / $m^2$ / year | 5.43 |

Source: Senegal Marine Corps, 2014

### 2.3.3 Renewable energy production

Senegal has been improving the commitment to the renewable energies during the past years, a prove of it is the restructuration of the country energy policy in 2008 towards the development of renewable energy as a major focus area. This political and policy commitment has placed Senegal as one of the leaders in renewable energy promotion in the Economic Commission of Western Africa (ECOWAS), with the solar, hydropower and bioenergy sources as the priorities (IRENA, 2012). As the Figure 2.6 and Figure 2.7 show, the solar energy capacity and generation has increased by 450% and 500% over the past 10 years, whereas the bioenergy has increased by 177% and 200%, respectively. The hydropower remains as the main source of renewable energy.




| | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|---|---|---|---|---|---|---|---|---|---|
| Bioenergy (GWh) | 6 | 6 | 6 | 17 | 18 | 18 | 18 | 18 | 18 |
| Solar Energy (GWh) | 3 | 4 | 4 | 5 | 8 | 9 | 11 | 16 | 18 |
| Hydropower (GWh) | 220 | 229 | 239 | 253 | 257 | 290 | 308 | 318 | 333 |

*Figure 2.6 Renewable energy capacity in Senegal*

Source: Author based on information from IRENA, 2017

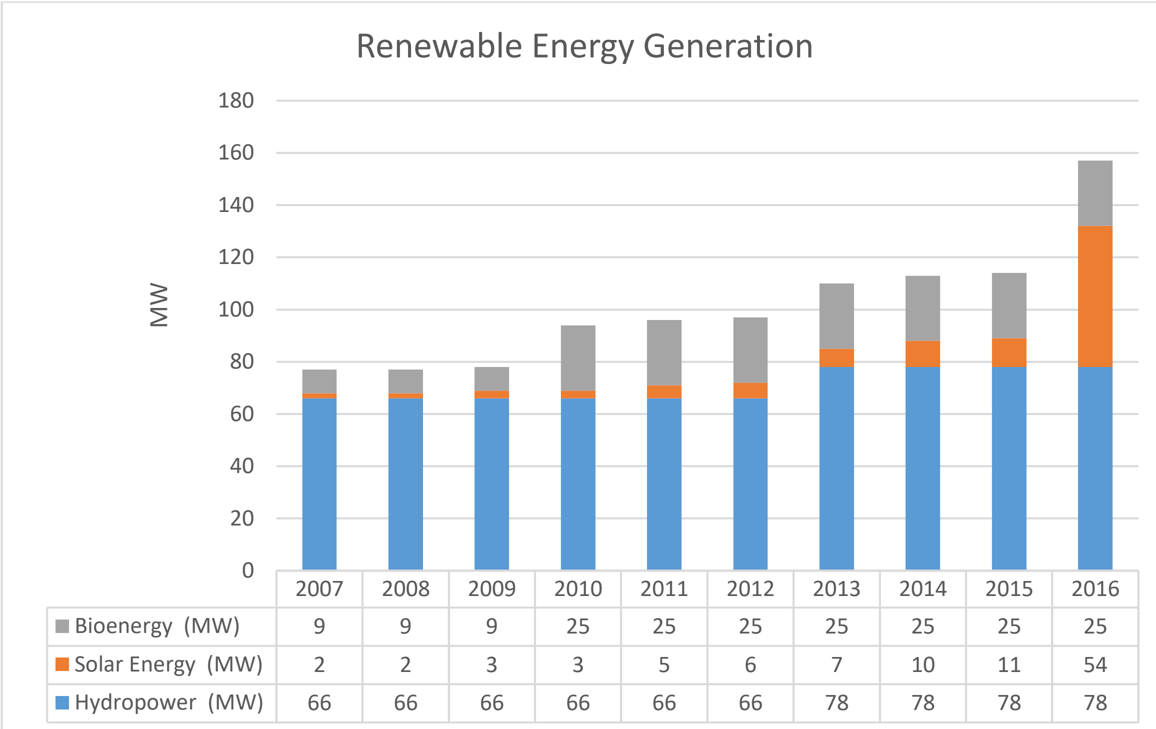



*Figure 2.7 Renewable energy generation in Senegal*

Source: Author based on information from IRENA, 2017

# 3 OBJECTIVES

## 3.1 General objective

The main objective of the Master's Thesis was to analyze the suitability of peanuts shell use as alternative solid biofuels and to assess their quality (fuel properties) as well as theoretical energy potential for Senegal.

## 3.2 Specific objectives

- To determinate and evaluate the physical, chemical and mechanical properties of the peanut shells and produced densified solid biofuels (pellets and briquettes)
- To measure the emission (CO, $CO_2$, $NO_X$) and the coarse particulate matter PM10 from the combustion of peanut shell pellets.
- To calculate the energy potential of the use of the peanuts shells, as an optional source of electrical energy in the households and/or industries in Senegal.

# 4 METODOLOGY

## 4.1 Methodology of literature review

The writing of the theoretical chapter of the Thesis was divided in three parts, first of all the peanut *(Arachis hypogaea* L.*)* was detailly described, including the morphology of the plant, the environmental requirements, production and nutritional data. Then, the basic information regarding to the Thesis focus was explained, such as the sources of biomass and the chemical and physical properties of the solid biofuels. Finally, a brief description of location where the study is based, Senegal, was presented. All the information was obtained from scientific articles using sources as Science Direct, Scopus, and Agris, as well as scientific approved books. Additionally, official data from the World Bank data base, IRENA, International Energy Agency, Food and Agricultural Organization, among other were used.

## 4.2 Methodology of practical research

### 4.2.1 Material

The raw material for the analysis was obtained directly from Senegal, from which approximately 10 kg of peanuts shells were obtained from the region of Thiès, which location is shown in the Figure 4.1. The sample was obtained from different farms in the mentioned region, meaning that it corresponds to a mix in the variety of the species, nevertheless the predominant peanut species in Senegal is *Arachis hypogea* subsp. *hypogea* (McClintock & Makhtar, 2005). The material was obtained after the harvest in 2015/2016, which corresponds to the months of December, January and February, just after the raining season as the Figure 4.2 shows. The laboratory analysis was done between February of 2017 and April of 2018.

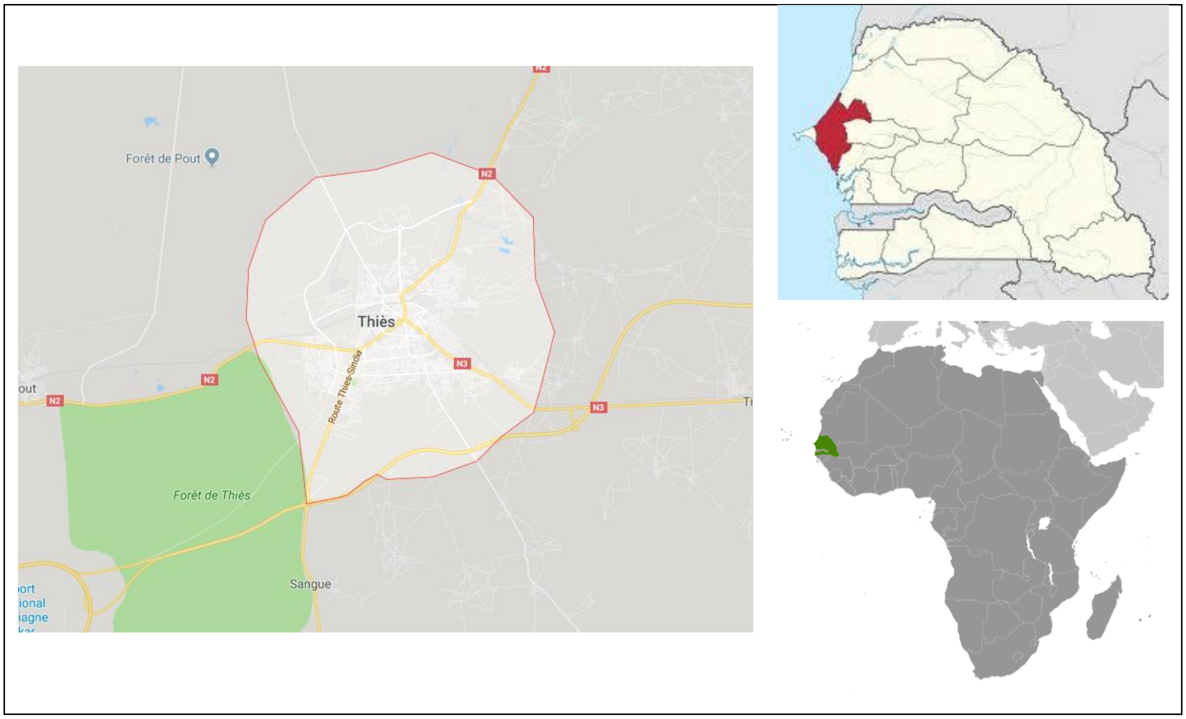



*Figure 4.1 Thiès location*

Source: Author based on different sources: www.maps.google.com; https://es.wikipedia.org/wiki/thies; https://www.drivingdirectionsandmaps.com. 2018.

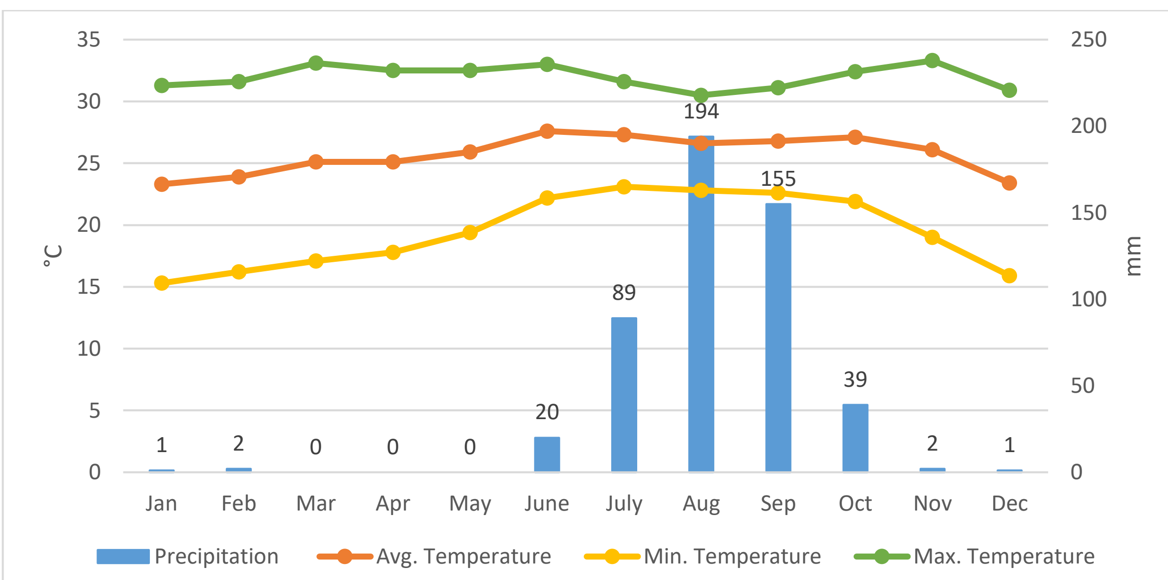



*Figure 4.2 Climate chart of Thiès, Senegal, 2018*

Source: Author based on information from https://en.climate-data.org/africa/senegal/thies/thies-5116. 2018

### 4.2.2 Moisture content

The first step to determine the moisture content is to prepare the analytical/analysis sample of the material by crushing it using the knife mill Retsch Grindomix GM 100 (Figure 4.3) in order to obtain a completely homogeneous material with a size lower than 1 mm, which is required by the standard BS EN ISO 14780:2017. The process took place in the laboratory of biofuels of the Faculty of Tropical AgriSciences at CULS. No other compounds were added to the raw biomass.


*Figure 4.3 Retsch Grindomix GM 100 Grinding knife mill*

Source: Author, 2017

Once the grinding process finished (see Figure 4.4), the sample was ready for the measurement of the moisture content, which also took place at the biofuel laboratory at CULS. As by the standard EN ISO 18134-3 (2015) Determination of moisture content in general analysis sample , the procedure started by taking 1 g (approximately) of the sample, which was weighted using the KERN digital laboratory scale (model ABJ 120-4NM), with a readout of 0.1 mg (see Figure 4.5). Then, as it is shown in the Figure 4.6 the sample was dried under controlled temperature of 105 ±2 °C for about 3 hours using a MEMMERT oven (model UFE 500), untill a constant weight of the sample. Once the drying process finished, the sample was cooled down using a desiccator for around 15 minutes, afterwards the samples were weighted ones more. To calculate the moisture content the following equation was used:

$$MC = \frac{m_w - m_d}{m_w} * 100$$

Where:

- MC: Moisture content (%)
- $m_w$: Mass of the sample before drying (g)
- $m_d$: Mass of the sample before drying (g)


*Figure 4.4 Analytical sample*
Source: Author, 2017


*Figure 4.5 KERN laboratory scale (model ABJ 120-4NM)*
*Source: Author, 2017*

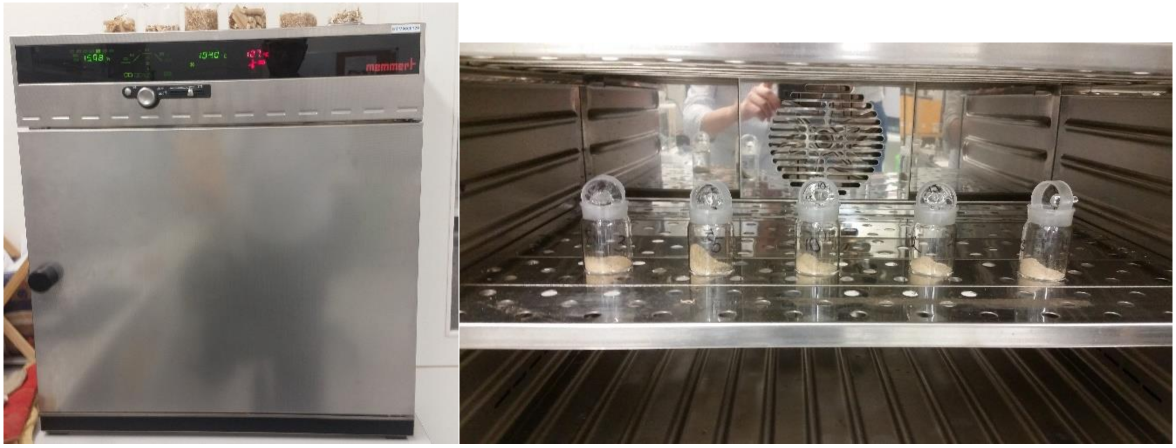


*Figure 4.6 MEMMERT drying oven (model UFE 500) with samples*
Source: Author, 2017

The measured moisture in analysis sample was later used in calculations of other parameters, e.g. NCV a.r. The moisture content for the three forms of peanut shells' solid biofuels (loose shells, pellets and briquettes), that are illustrated in the Figure 4.7, was measured in accordance to the standard EN ISO 18134-2 (2015) Solid biofuels - Total moisture - Simplified method. The same drying oven was used and the samples were dried until the constant weight was achieved (about 5-8 hours); scale KERN (model EW 3000-2M) with the readout of 0.01 g was used.

*Figure 4.7 Forms of material*
Source: Author, 2017

### 4.2.3 Calorific value

In concordance with the standard BS EN ISO 18125 (2017) for the measurement of calorific value, the same previously ground sample was used. Then using the KERN Laboratory scale a portion of approximately 0.7 g was wrapped and weighted in a combustion paper, then placed in the crucible with an ignition wire between the electrodes, after it was covered by the high-pressure vessel bomb (see Figure 4.9), in order to charge it with oxygen to a pressure of 3.0 ± 2 MPa. Subsequently, the charged vessel bomb was inserted into the MS-10A calorimeter can (Figure 4.8), to start the full combustion of the sample. When the process finishes the calorimeter shows a jump of temperature, which is used to calculate the Gross Calorific Value by the following equation:

$$GCV = \frac{(dTK * TK)}{m} - Qw - Qp$$

Where:

- GVC: Gross Calorific Value (J/g)
- TK: Constant of calorimeter calibration (9,051 J/°C)
- dTK: Temperature jump after burning (°C)
- m: Weight of the sample (g)
- Qw: Calorific capacity of the wire (50 J/g)
- Qp: Adjusted calorific capacity of the paper (1,462.86 J/g)

Once the Gross Calorific Value, the content of Hydrogen and the moisture content are known, it is possible to calculate the Net Calorific Value using the following equation:

$$NCV = GCV - 24.42 * (8.9\mathrm{H} + \mathrm{W})$$

Where:

- NCV: Net Calorific Value (J/g)
- H: Hydrogen content (%)

- W: moisture content (%)


*Figure 4.8 MS-10A calorimeter*
Source: Author, 2017

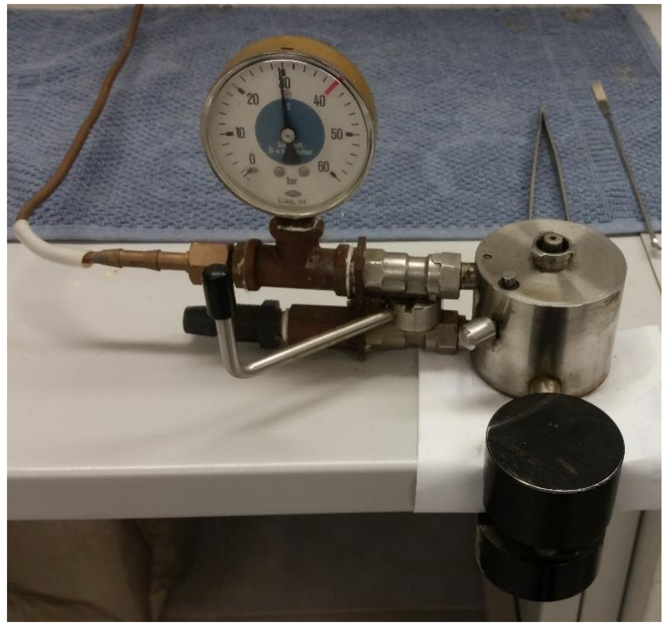


Figure 4.9 High-pressure vessel bomb

Source: Author, 2017

### 4.2.4 Ash properties

In this section, two properties of the ash were determined: the ash content and the ash melting behavior, which methodology of measurements is explained bellow.

#### 4.2.4.1 Ash Content

The ash content was determined following the standard BS EN ISO 18122 (2015), in the laboratory of solid biofuels at CULS. The calculation of ash content is performed by using the weight of the inorganic residue after a full combustion under controlled temperature. The process stared by placing approximately 1 g of previously dried sample (105° C) in a crucible heated up to 500 °C for 60 min prior the test, then the samples and the plates were put in the muffle furnace (see Figure 4.10) for 30 min raising the temperature uniformly until 250° C, whence for another 60 min conserving the same temperature. Later, the muffler was heated up uniformly until 550° C for 30 min to finally keep this temperature for 120 min more. Once the process finished, the content of the residue (ash) was weighted. Is important to mention, that all of the measurements of weight were done using the laboratory scale KERN. Bellow, the equation to calculate the ash content of the sample is described:

$$A_d = \frac{m_3 - m_1}{m_2 - m_1} * 100$$

Where:

$A_d$: Ash content (%)

$m_1$: Mass of the crucible (g)

$m_2$: Mass of the crucible plus sample before drying (g)

$m_3$: Mass of the crucible plus sample after drying (g)


*Figure 4.10 Muffle furnace*
Source: Author, 2017

4.2.4.2 Ash melting behavior

In accordance to the standard DD CEN/TS 15370-1 (2006) Solid biofuels — Method for the determination of ash melting behavior, the first step of the procedure was the preparation of the test piece by burning the material in the previously mentioned muffle furnace, then the ash residue was grinded until a maximum particle size of 0.075 mm and moisten with demineralized water to make it into a paste, placed in a stainless steel mould and hand-pressed with a spring press until a consistent cylindrical shape with a height and diameter of approximately 3 mm. Later, the test piece was dried under the room temperature and placed in the top of a mullite material as it is shown in the Figure 4.11; in order to be introduced into the furnace, in which the temperature was raised until 550° C point of Shrinkage Staring Temperature (SST). Then, the temperature was raised uniformly within a rate of 3 – 10 ° C/min recording the temperature at which the characteristics changes in shape occur (see Figure 4.12), until the last phase in the ash melting process described in the Figure 4.13. The process was made for three samples (repetitions).

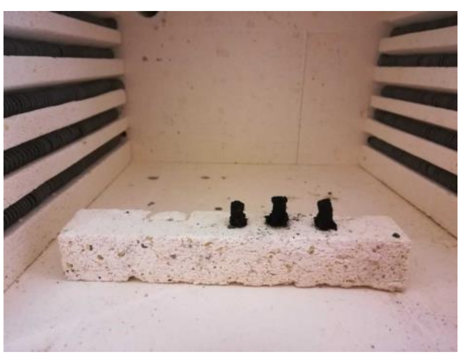


*Figure 4.11 Test piece on the top of the mullite*
Source: Author, 2017

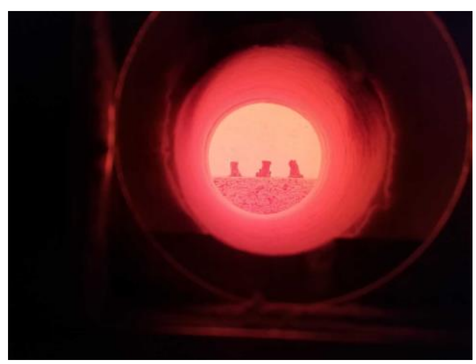


*Figure 4.12 Ash melting process*
Source: Author, 2017

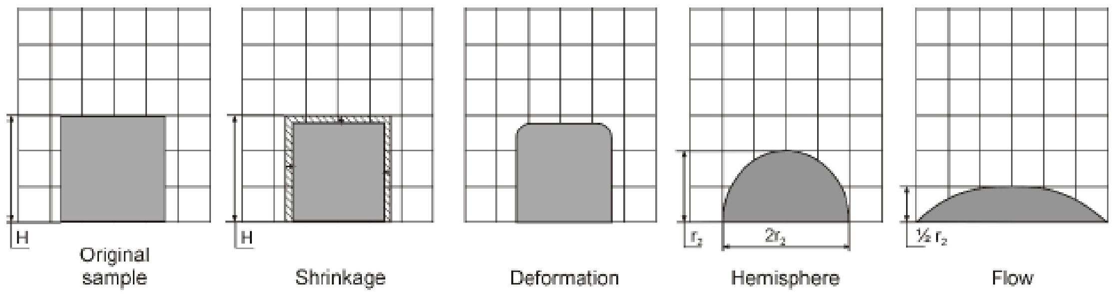



*Figure 4.13 Phases in the ash melting process*
Source: CEN/TS 15370-1, 2006

### 4.2.5 Mechanical durability

The test of mechanical durability was done for pellets and briquettes as it will be explained bellow:

#### 4.2.5.1 Pellets

According to the standard BS EN ISO 17831-1 (2015) for the determination of the mechanical durability of the pellets, was used the pellet durability tester (see Figure 4.14) available at the laboratory of the RIAE in Prague.

First a sample of approximately 500 g was weighted and prepared by using a sieve of 40 cm of diameter with holes of 3.15 mm, in order to separate the small particles of the pellets by hand-shaking the sample in circular movements (10 times). Then, the remaining pellets were weighted again and placed into the pellet durability tester for 10 minutes with a speed of 50 rpm (500 rotations), subsequently the pellets were taken, sieved and weighted again using a digital laboratory scale. It is important to mention that the whole procedure was repeated 4 times. The formula to calculate the mechanical durability was:

$$D_U = \frac{m_1}{m_2} * 100$$

Where:

- $D_U$: Mechanical durability (%)
- $m_1$: Mass of the pellets before the process (g)
- $m_2$: Mass of the pellets after the process (g)


*Figure 4.14 Pellet durability tester*

Source: Author, 2017

### 4.2.5.2 Briquettes

To calculate the mechanical durability of the briquettes, the standard BS EN ISO 17831-2 (2015) was followed, using the briquette durability drum available at the engineering laboratory of CULS.

The process started by measuring approximately 2 Kg of the material, then the loose small particles were removed by using a sieve with the holes' diameter of 16 mm in which the briquettes were hand-shaken in circular movements 10 times. After this, the sample was introduced into the briquettes' durability drum for a tumble procedure at 21 rpm for 5 min

(105 rotations), subsequently the sample was removed manually from the machine in order to sieve it and be weighted again. The calculation of the mechanical durability was done by using the same equation as in the case of the pellet test. The procedure was repeated 3 times.

*Figure 4.15 Briquette durability drum*

Source: Author, 2017

### 4.2.6 Pelletizing

The process of pelletizing started by grinding part of the material using the 9FQ-40C hammer mill, available in the Research Institute of Agricultural Engineering (RIAE) in Prague with a screen hole diameter of 6 mm. Subsequently, the ground material was pressed to the shape of solid pellets at RIAE using the MGL200 pelletizing machine manufactured by the Czech company Kovo Novák (see Figure 4.16), with a diameter of matrix holes' of 6 mm. Is important to mention that no additives were added to the raw material.

*Figure 4.16 Pelletizing machine MGL200*
Source: Author, 2017

### 4.2.7 Briquetting

The briquetting process was performed in the RIAE using the hydraulic briquetting press Brikstar model CS 50-12 made by the Czech company Briklis under a working pressure of 18 MPa. The raw material was placed in the machine without any binding agent nor different biomass, as it is shown in the Figure 4.17. Whole process was conducted under the room temperature and humidity. Produced briquettes had a cylindrical shape, with an approximate length of 42.73 mm and a diameter of 65 mm.


*Figure 4.17 Hydraulic briquetting press Brikstar CS 50-12*
Source: Author, 2017

### 4.2.8 Measurement of dimensions

The diameter and length of the raw material, pellets and briquettes were determined following the standard BS EN ISO 17829 (2015), using the digital caliper shown in the Figure 4.18. For the pellets 8 samples/pieces were used to determine the diameter and 98 pieces (80 g) to measure the length. In the case of briquettes 15 pieces were used to measure the diameter and length. Finally, due to the shape of the shells the determination of the dimensions was made differently; length, height and 3 measurements of width as is shown in the Figure 4.19.

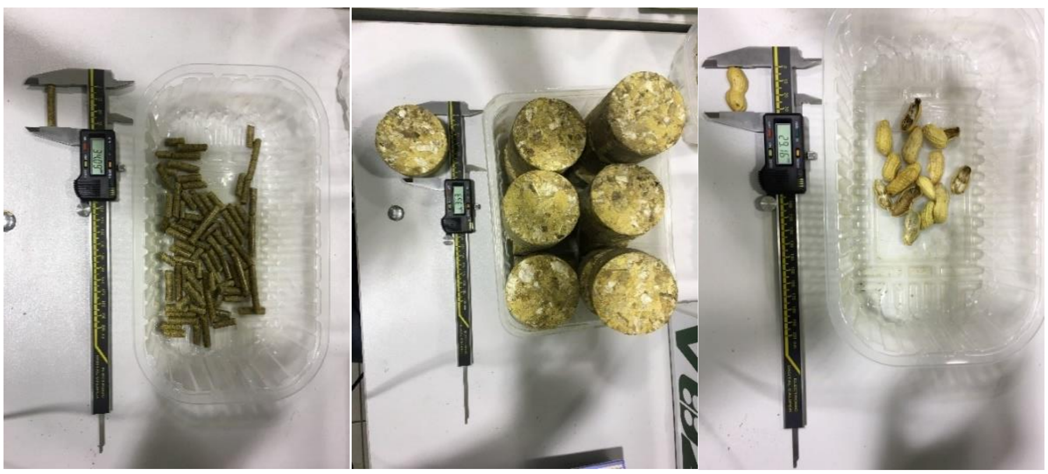


*Figure 4.18 Measurement of dimensions using the digital caliper*
Source: Author, 2017

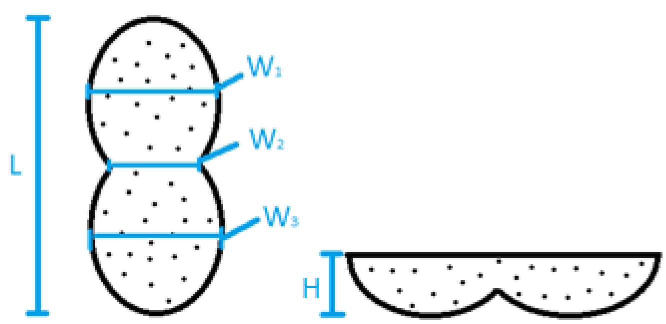



*Figure 4.19 Points of dimensions' measurements on peanut shell*
Source: Author, 2017

### 4.2.9 Bulk density

The calculation of bulk density was done for the three forms of the material: loose raw shells, briquettes and pellets. As per the standard procedure BS EN ISO 17828 (2015) Solid biofuels — Determination of bulk density, the process started by selecting the appropriate measuring container (large for the peanuts shells and briquettes, small for the pellets– see Figure 4.20). Then, the containers were filled by pouring the sample material from a height of 200 to 300 mm above the upper edge forming a cone shape, then the samples were settled by dropping the container from 150 mm onto a wooden board, action which was repeated 3 times. Afterwards, the container was refilled and adjusted until the rim level using a scantling. After this, the container filled with the material was weighted. The whole procedure was repeated 3 three times for each material. The volume of both containers was 50.07 L for the big one and 20.63 L for the small one.

The bulk density as received was calculated using the following equation:

$$BD = \frac{(m_1 - m_2)}{V} * 100$$

Where:

- BD: Bulk density (Kg/m$^3$)
- $m_1$: Mass of the empty container (Kg)
- $m_2$: Mass of the full container (Kg)
- V: Volume of the container (m$^3$)

*Figure 4.20 Measurement containers*

Source: Author, 2017

### 4.2.10 Elemental analysis

The elemental analysis test determines the content of Nitrogen, Carbon, Hydrogen (C, H, N) and Sulfur (S) in the material, which were measured according to the standard BS EN ISO 16948 (2015) and the EN ISO 16994 (2015), respectively. The test was made by using the apparatus LECO CHN628+S Series Elemental Determinator. The process started by weighting approximately 1 g of previously dried material which was enveloped into aluminum foils and placed into the equipment. The LECO CHN628+S measures the content of Nitrogen, Carbon, Hydrogen and Sulphur by burning the material under pure oxygen conditions within the furnace, which ensure a complete combustion of all the organic samples, then the compounds are measured by analyzing the gas from the combustion.

It is important to mention that the test was repeated 3 times in accordance to the standard. The equipment was previously calibrated, following the procedure written in the apparatus manual.


*Figure 4.21 LECO CHN628+S Series*

Source: Author, 2017

4.2.11 Emission analysis

The procedure of measuring the emissions from the combustion of the pellets was done by the RIAE in Prague, within the framework of the project “Central Bohemian Innovative Vouchers Program” in 2017, measuring the emissions of CO, $CO_2$, $NO_x$ and coarse particulate matter PM10. The analysis was done for the peanut shell pellets, as well as pellets from other materials such as unbaked wood (with soil remnants), wheat (cereal) straw pellets and residues from mustard.

The first step of the process was to burn the pellets using the Petrojet Biorobot *15* combustion boiler with the revolving grate (see Figure 4.22), built by the Czech manufacturers Systémy Ltd. and Petrojet Trade Ltd. under the technical parameters described in the Table 4.1. During the combustion, the concentration of gaseous emissions were measured by the device Testo 350 whereas the concentration of particulate matter was stated using the Testo 380 apparatus. Both of devices were manufactured by the Testo SE & Co.KGaA (see Figure 4.23). The whole process was conducted under the room temperature and humidity, for 8 hours. It is relevant to mention that no additives were added to the peanut pellets, however a calcium-based additive was added to the pellets made from wheat straw to increase the ash melting temperatures.

*Table 4.1 Combustion technical parameters*

| Parameter | Unit | Value |
|---|---|---|
| **Power output (nominal/minimal)** | kW | 15/4.5 |
| **Efficiency** | % | 89 |
| **Operational chimney draft (nom./min.)** | Pa | 13/5 |
| **Exhaust mass rate (nom./min.)** | Kg/s | 0.008/0.004 |
| **Fuel input (nom./min.)** | Kg/h | 3.3/1.1 |
| **Flue gas temperature (nom./min.)** | ° C | 147/105 |

Source: Research Institute of Agricultural Engineering, 2017.

*Figure 4.22 Petrojet Biorobot 15*
Source: Research Institute of Agricultural Engineering, 2017.

*Figure 4.23 Devices for combustion analysis: Testo 350 (left), Testo 380 (right)*
Source: Research Institute of Agricultural Engineering, 2017.

## 4.3 Potential of peanut shell as an energy source

To calculate the energy potential, a linear regression statistical analysis was used trough historical groundnut production in Senegal reported by the FAO from 1996 until 2017, necessary data adopted from other authors (see Chapter 5.10) as well as the Net Calorific value obtained in the present study by the author. The equation to calculate the potential, will be the one reported by Perea-Moreno et al. (2018) explained bellow:

$$E_c = RH * P_c * NCV * f_s * U_c$$

Where:

Ec: Potential of energy production (MWh);

RH: Relative air humidity (%)

Pc: Peanut production per year (Kg);

NCV: Net Calorific Value d.b. (MJ/Kg);

Fs: Factor of shell (share) in a whole peanut (%);

Uc: Unit of conversion (0.000277778 Wh/J)

# 5 RESULTS AND DISCUSSION

In this chapter the results from the research part are described, in accordance to the objectives, and comparing the outcomes with the values obtained from relevant studies and international standards. The results were obtained from the experiments performed by the author described in the chapter 4.

The analysis of the results starts with the physical properties related to the raw material which are directly linked to the combustion performance of the biomass; such as moisture content, calorific value (G.C.V. and N.C.V.) and ash properties. Later, in the chapter are described the physical/mechanical properties of all three forms of the material (raw shells, briquettes and pellets); such as dimensions, mechanical durability and bulk density. Finally, the chemical characteristics are discussed, including the elemental analysis (content of C, H, N) and emissions.

At the end of the chapter the previously mentioned properties were compared with the minimum requires of the standard EN ISO 17225 (2014) Solid biofuels - Fuel specifications and classes, parts 6 and 7 for the categorization of graded non-woody pellets and briquettes, respectively.

## 5.1 Moisture content

As it was mentioned before, the measurement of moisture content was done in accordance to the EN ISO 18134-2 (2017) for the three forms of material (loose peanut shells, pellets and briquettes), which results are shown in the Table 5.1. The obtained value fulfills the requirements of the standard EN ISO 17225 (2015) parts 6 and 7, which establishes that the moisture content of quality solid fuels (category "A") should not exceed 12% for pellets and briquettes. The value obtained is comparable with the 5.79% for peanut shell reported by (Perea et al,.2018) and the values reported by FAO (2001) of 3 – 10%. The moisture content is one of the key parameters to determine the Net Calorific Value, thus it is directly correlated to the combustion potential of the material.

*Table 5.1 Moisture content Peanut shells (Arachis hypogea)*

| Form of material | Moisture content (%) |
|---|---|
| Uncompacted shells (a.r.) | 7.20 |
| Pellets (a.r.) | 2.5 |
| Briquettes (a.r.) | 6.92 |

Source: Author, 2019

The Figure 5.1 shows a comparison of the moisture content between different materials commonly used for energy purposes. According to the information reported from different authors (Spilacek et al., 2014, Zhang et al., 2012, Brunerová et al., 2017) the peanuts shells have lower MC than the sawdust, wood chips and jatropha shell, but higher MC in comparison of the cocoa, wheat straws, rice waste and date pits. Also, it is important to mention that as after the compaction process the MC decreased (especially in the pellets) and due to convenient MC of initial shells, thus no additional drying process is necessary to fulfill the EN ISO 17225 (2015) requirements.

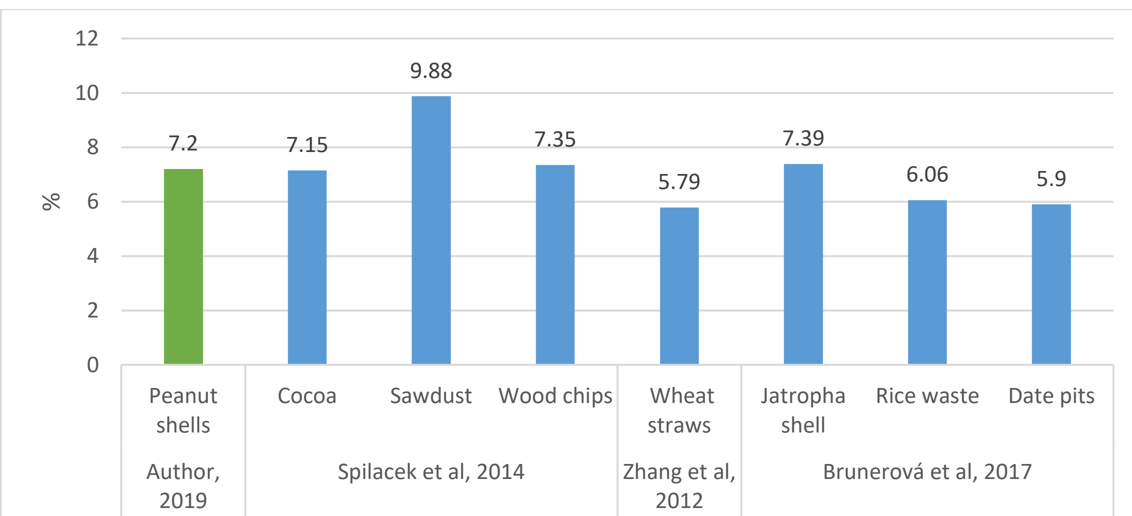



*Figure 5.1 Comparison of moisture content between different sources*

Source: Autor based on the shown references, 2019

The measured moisture content in prepared analysis sample, used for calculation of NCV a.r. was 4.08%.

## 5.2 Calorific value

The Gross Calorific Value was determined following the procedures established in the standard BS EN ISO 18125 (2017), whereas the Net Calorific Value was calculated following the formula described in the section 4.2.3 using the moisture content expressed in the section 5.1. The results for both properties are shown in the Table 5.2. Both parameters were measured in wet (as received – a.r.) and dry basis (d.b.). According to the standard EN ISO 17225 (2014) parts 6 and 7 the material can be classified as “A” class for both pellets and briquettes (respectively) due to the fact that the measured Net Calorific Value is higher than 14.5 MJ/kg.

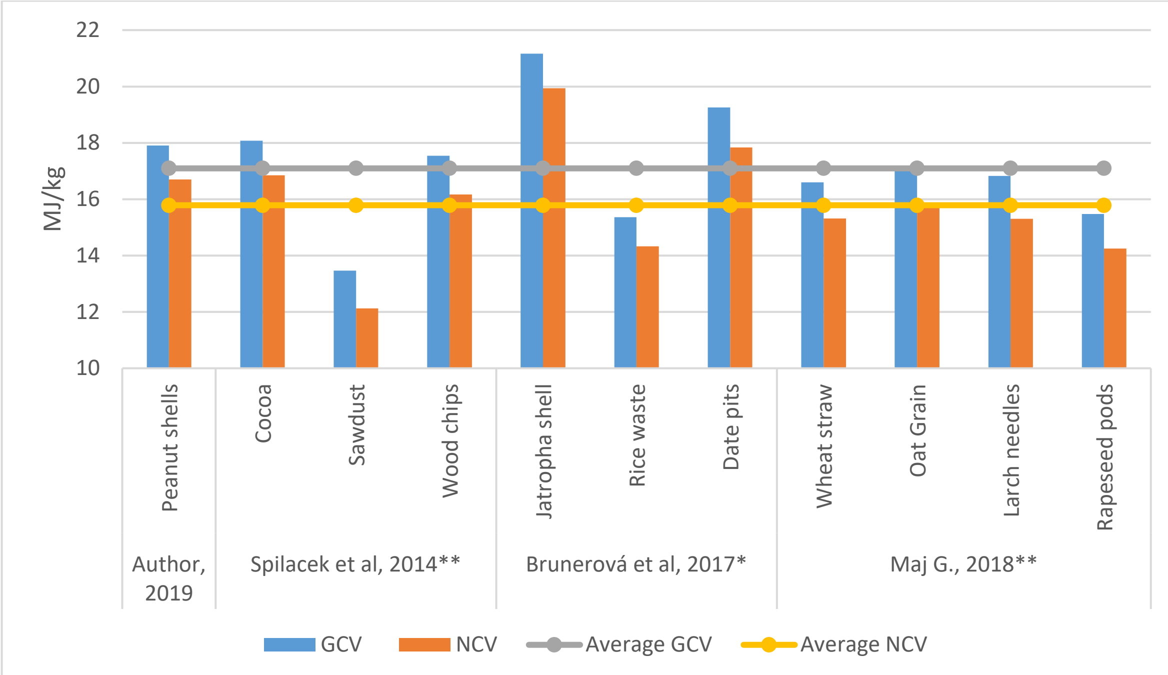
The GCV and NCV obtained are lower than the value reported by (Perea et al., 2018) who obtained a GCV of 18.547 MJ/Kg and a NCV of 17.111 MJ/Kg. In addition, the FAO (2004) reported a NCV of 16.7 MJ/Kg, which is similar to the measured NCV d.b., but higher than NCV a.r.

*Table 5.2 Gross and Net Calorific Value for peanut shells*

| Material | GCV (MJ/Kg) | | NCV (MJ/Kg) | |
|---|---|---|---|---|
| | a.r. | d.b. | a.r. | d.b. |
| Peanut shells (*Arachis hypogea*) | 17.154 | 17.910 | 15.950 | 16.705 |

Source: Author, 2019

The Figure 5.2 shows the comparison between the measured values* and different calorific values** of other materials with possible use for energy purposes. As per the results obtained from different authors, the GCV and NCV of the peanut shells are above the average value; 17.094 MJ/kg and 15.786 MJ/kg, respectively.




* Dry basis (d.b.)

** Condition (d.b./a.r.) not specified

*Figure 5.2 Comparison of GCV and NCV between different sources*

Source: Author based on the shown references, 2019

## 5.3 <u>Ash properties</u>

The results for the analysis of ash content and ash melting behavior are described in the following sections.

### 5.3.1 Ash content

The ash content of the peanut shells was measured according to the standard BS EN ISO 18122 (2015). The result of the ash content is shown in the Table 5.3, which is far above from the limit established by the standard BS EN ISO 17225 (2014) parts 6 and 7 which demands an ash content lower than 6% for the category “A”, and 10% for the category “B”.

*Table 5.3 Ash content of peanut shells*

| Material | Ash content (%) |
|---|---|
| Peanut shells (*Arachis hypogea*) | 16.51 |

Source: Author, 2019

As the Figure 5.3 shows, the ash content of the peanut shells is significantly higher than the value reported by Vassilev et al. (2017) of 5.4%; as well as the AC obtained by Perea-Moreno et al. (2018) of 4.26% (for peanut shells from Andalusia, Spain). The difference could be possibly related to the soil conditions of the location or presence of impurities in the shells like soil or dust. In addition, according to Nunes et al. (2016) the concentrations of Al, Ca, Cl, Fe, K, Mg, P, Na, S, Mn, Si, and Ti are directly related to the ash content of the solid biomass. In addition, Vassilev et al. (2013) reveals that there is a positive correlation between detrital sand or soil in the samples and the ash content, as well as mineral and metallic pollutants in the biomass. Hence a deep chemical analysis of the biomass, soil and ashes should be done to fully understand the correlation between the mentioned elements and compounds to the ash content of the peanut shells.

In comparison with other materials, the obtained value is considerable higher than the AC reported by Brunerova et al. (2017) for the date pits and the jatropha shell, but lower than the rice waste. In addition, Maj (2018) also reported lower values of ash for the wheat straw, oat grain, larch needles and rapeseed pods, as well as Spilacek et al. (2014) obtained lower content of ash especially for the sawdust and the woodchips. In the Figure 5.3 , the results from the mentioned authors are shown.

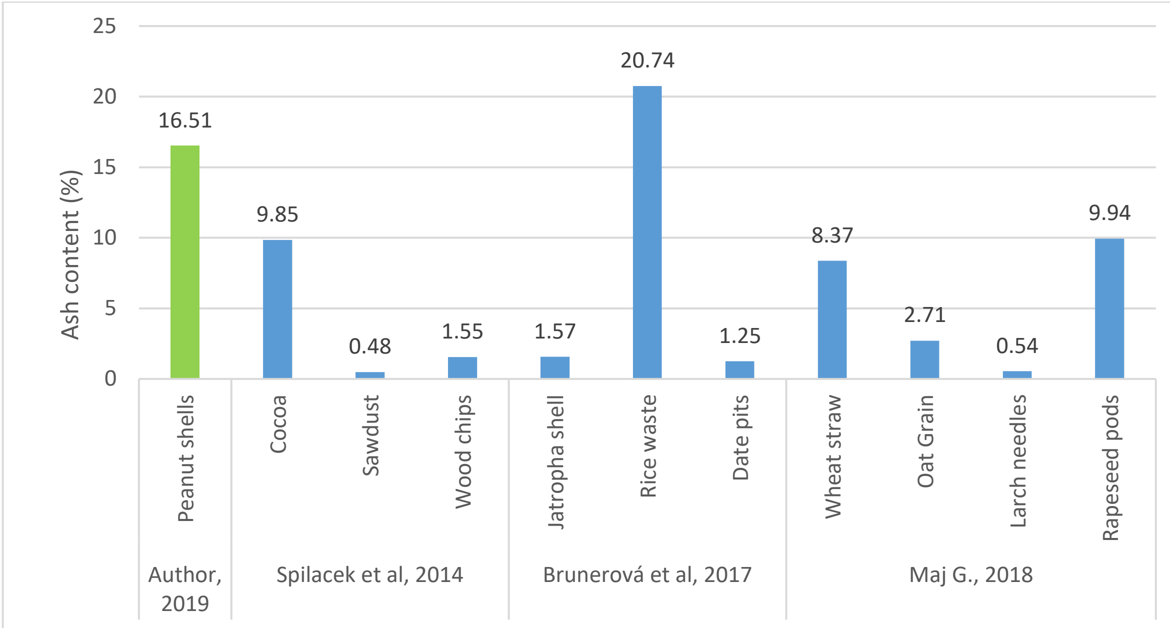



*Figure 5.3 Comparison of ash content between different sources*

Source: Autor based on the mentioned references, 2019

### 5.3.2 Ash melting behavior

The temperatures of the 3 stages for the ash melting behavior were measured following the CEN/TS 15370-1 (2006) technical specification. As it was explained in the section 4.2.4.2 a sample of ash was exposed to high temperatures to determine under which temperatures the ash changes its shape. The results are shown in the Table 5.4, from which it is possible to assure that the deformation process starts at 860-890 °C, followed by the hemisphere under 925-965 °C and finally the flowing of the ash starts at 1,140-1,170 °C.

*Table 5.4 Ash melting behavior of peanut shells*

| Melting Stage | Temperature (°C) |
|---|---|
| Deformation | 860-890 |
| Hemisphere | 925-965 |
| Flow | 1,140-1,170 |

Source: Author, 2019

Similar studies were conducted by Cioabla et al. (2015) for different agricultural waste, as the Figure 5.4 shows, the cereal mix has a similar ash melting behavior comparable with the peanut shells, whereas the wheat and the corn stalk have a considerably lower flowing temperature. According to Konttinen et al. (2013), the modern fluidized bed furnaces for biomass can have a low bed temperature of 650-850 °C, which means that pellets and briquettes from peanut shells can be burned in the mentioned furnaces without any sintering problems.

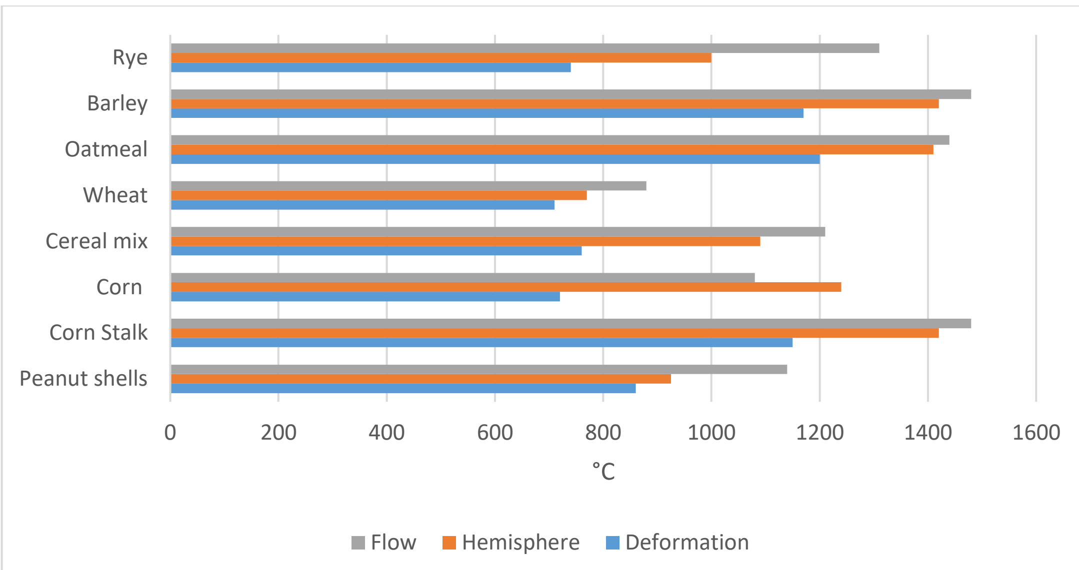



*Figure 5.4 Comparison of ash melting behavior between different sources*

Source: Cioabla et al. (2015); Author, 2019.

## 5.4 <u>Dimensions</u>

As it was mentioned in the section 4.2.8, the dimensions were measured for each form of the material (pellets, briquettes and raw shells) according to the standard BS EN ISO 17829 (2015). The diameter and width of the briquettes and pellets are given/influenced by the pelletizer and the briquetting press, whereas the peanut shells dimensions depends on the variety of the plant as well as the climate conditions (Rami, 2013). The dimensions of each type of material are shown in the Table 5.5.

*Table 5.5 Dimensions of the peanut shells, pellets and briquettes.*

| | Diameter (mm) | | | Length (mm) | | | Width (mm) | | | Height (mm) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Shells | - | | - | 24.28 | ± | 6.11 | 8.48 | ± | 0.94 | 3.05 | ± | 0.39 |
| Pellets | 6.05 | ± | 0.04 | 23.22 | ± | 6.62 | - | | - | - | | - |
| Briquettes | 66.41 | ± | 0.32 | 42.73 | ± | 6.11 | - | | - | - | | - |

Source: Author, 2019

## 5.5 Mechanical durability

The mechanical durability (MD) of pellets and briquettes from the peanut shells were measured according to the standard BS EN ISO 17831 (2015) parts 1 and 2, respectively. The results shown in the Table 5.6 were compared to the standard EN ISO 17225-6 (2014), from which it is possible to confirm that the pellets just slightly did not achieved the value for "B" categorization, which demands a MD above 96%. Nevertheless, due to the proximity of the results with the specification, it can be recommended to evaluate this parameter with additives to increase the rate of compaction, therefore the MD. Regarding the briquettes, the EN ISO 17225-7 (2014) does not include a specification for the mechanical durability. It is also important to mention that the MD could be affected by impurities in the sample, so for future analysis it is recommended to remove them (if present).

*Table 5.6 Mechanical durability of pellets and briquettes from peanut shells*

| Type | Mechanical durability |
|---|---|
| Pellets | 95.86 |
| Briquettes | 95.11 |

Source: Author, 2019

Nevertheless, when the obtained values are compared with the results from another authors (see Figure 5.5), the mechanical durability of both pellets and briquettes presents values above of the average. In case of briquettes, Ivanova et al. (2014) analyzed the MD for the giant reed, giant knotweed, sweet sorghum and hemp where the first 3 presents values under 90.8% whereas the hemp is the only material with a higher MD than the peanut shells. In addition, Brunerová et al (2017) studied the MD for wheat and poppy, from which both of them presented values under the result obtained for the peanut shells.

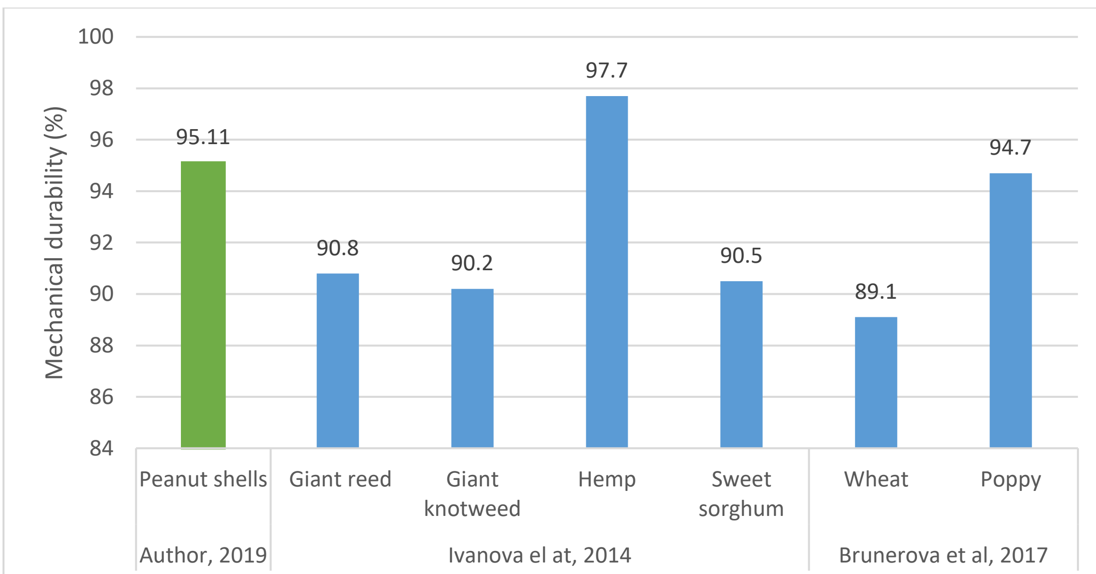



*Figure 5.5 Comparison of mechanical durability of biomass briquettes*

Source: Author based on the shown references, 2019

Regarding the pellets, Ungureanu et al (2016) studied the MD of pellets made from different biomass types (see Figure 5.6) from which the olive pomace and grape pomace were the only samples with a MD significantly lower than the peanut shells, whereas the wheat straw, barley stray and Pyrenean oak presented values slightly lower than the peanut shells. The rest of the samples accomplished the specification for the standard 17225-6 (2014) of >96% for categorization “B” and >97% for categorization “A”.

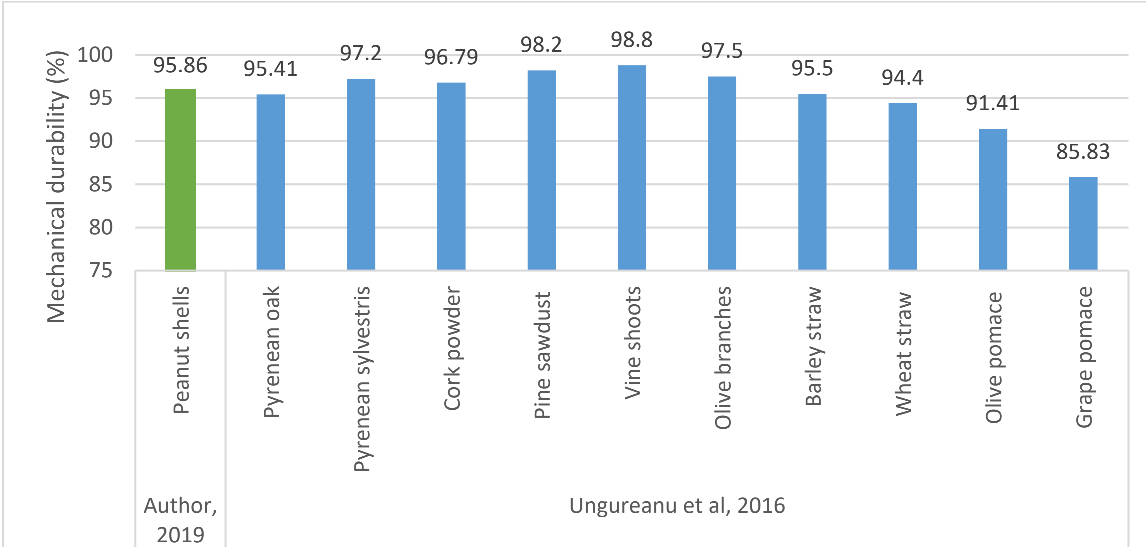



*Figure 5.6 Comparison of mechanical durability of biomass pellets*

Source: Author based on the shown references, 2019

## 5.6 <u>Bulk density</u>

The measurement of the bulk density (BD) was done following the standard BS EN ISO 17828 (2015). The results are presented in the Table 5.7 for the pellets, briquettes and raw material. The obtained values show that the pellets have the highest result, complying with the specification of the standard 14225-6 (2014) which establishes a minimum BD of 600 kg/m$^3$ for categories "A" and "B". Regarding the briquettes, the standard 17225-7 (2014) does not include a specification for the bulk density. The results indicate that the B.D. of the pellets allows to storage more material per cubic meter in comparison to the raw material and briquettes, this due to the shape and dimensions of the pellets.

*Table 5.7 Bulk density of pallets, briquettes and raw peanut shells*

| Type | Bulk density (Kg/m$^3$) |
|---|---|
| Pellets | 698.4 |
| Briquettes | 270.5 |
| Peanut shells | 107.6 |

Source: Author, 2019

The Figure 5.7 shows the comparison between the bulk density of peanuts pellets with different materials. As reported by Ungureanu et al. (2016) the olive and grape pomace present a considerably higher BD, whereas the olive branches and wheat straw shows a lower value, for the rest of the materials (Pyrenean oak, pyrenean sylvestris, cork powder and vine shoots) the BD is similar to the peanut shell pellets. In addition, Liu et al. (2016) analyzed the BD for the bamboo and pine, from which the first one has considerably lower BD than the reported in the present research, however the B.D. of the pine is similar to the mentioned.

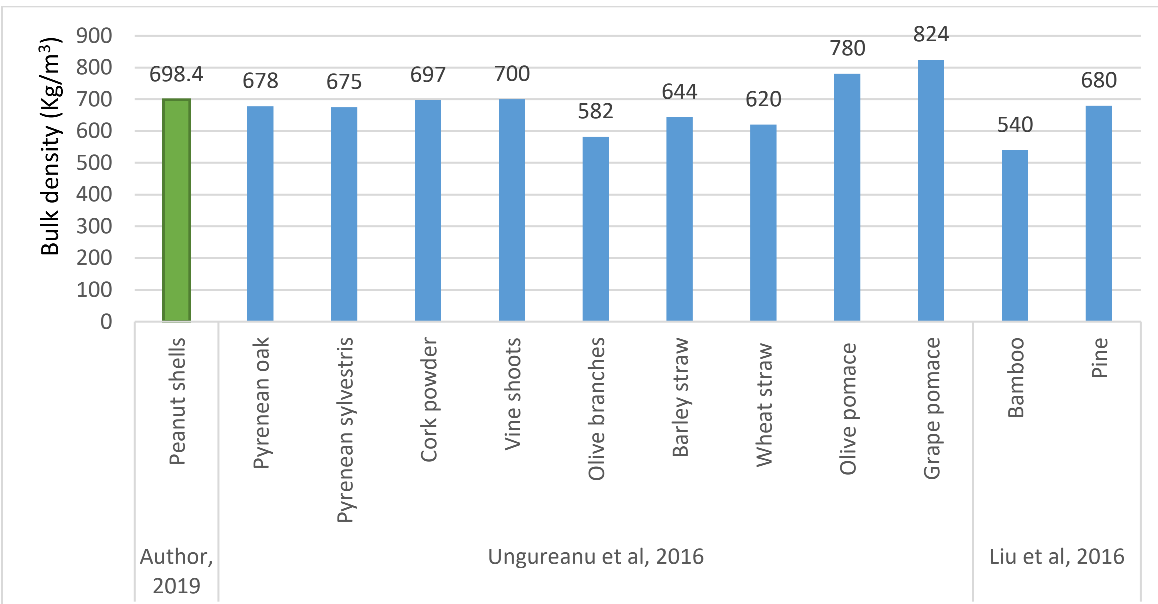



*Figure 5.7 Comparison of bulk density of biomass pellets*

Source: Author based on the shown references, 2019

## 5.7 Elemental analysis

The content of Nitrogen, Carbon and Hydrogen (C, H, N) and Sulphur of the peanut shells was measured following the procedure of the standard BS EN ISO 16948 (2015) for C, H, N and the EN ISO 16994 (2015) for S, which results are presented in the Table 5.8. The content of Nitrogen fulfils the specification in the standard EN ISO 17225 (2014) parts 6 and 7 which demands a content of Nitrogen lower than 1.5% for categorization “A” in both non-wooden pellets and briquettes. The value of the Sulphur also fulfills the limits required by the standard EN ISO 17225 (2014) part 6 and 7, which demands a S percentage bellow or equal than 0.2% for categorization “A”. The content of Carbon and Hydrogen are not included in the mentioned standard; however, both were measured to understand the results of the emission analysis and the NCV calculation.

*Table 5.8 Content of nitrogen, carbon and hydrogen in peanut shells*

| **Element** | **%** |
|---|---|
| Nitrogen | 1.02 |
| Carbon | 43.16 |
| Hydrogen | 5.08 |
| Sulphur | 0.05 |

Source: Author, 2019

A similar analysis was made by Perea-Moreno et al. (2018) for the peanut shells, reporting, however, significantly higher value of S, a slightly higher content of C and H, but a lower content of N (see Table 5.9). As it is shown in the Table 5.9, the results for the peanut shells were also compared with other sources of biomass, from which it is possible to observe a non-significantly variations in the contents of C, H and S (except for the S content of rapeseed pods), however the percentage of N reveals considerably variation on the reported values: as high as 2.64% for the sawdust or lower than 0.4% for wood chips and rice waste (Spilacek et al, 2017, Brunerová et al, 2017).

The Nitrogen and Sulfur content are two of the most important chemical parameters since high values will represent emissions of NOx and $SO_2$, therefore incompliance of the emission allowances (Splilacek et al, 2014), that will be analyzed in the section 5.8. The amount of Carbon has a positive correlation to GCV, hence a higher carbon content is associated with a higher calorific value, explaining why the GCV is higher in traditional sources of energy (fossil fuels) when is compared to biomass sources (Fernández et al., 2012). In addition, the measurement of C, H, N content is important to calculate the GCV theoretically using correlation equations, formulated by different authors (Perea-Moreno et al., 2018).

*Table 5.9 Comparison of C, H, N content with other sources of biomass*

| Material | C | H | N | S | Source |
|---|---|---|---|---|---|
| Peanut shells (d.b.) | 43.16 | 5.08 | 1.02 | 0.05 | Author, 2019 |
| | 46.42 | 6.61 | 0.5 | 0.54 | Perea-Moreno et al., 2018 |
| Cocoa (unk) | 42.98 | 4.85 | 2.64 | 0.2 | Spilacek et al., 2014 |
| Sawdust (unk) | 47.29 | 5.05 | 0.16 | 0.15 | |
| Wood chips (unk) | 47.09 | 5.46 | 0.38 | 0.2 | |
| Jatropha shell (d.b.) | 49.77 | 5.15 | 0.49 | 0.05 | Brunerová et al., 2017 |
| Rice waste (d.b.) | 37.28 | 4.43 | 0.38 | 0.06 | |
| Date pits (d.b.) | 44.24 | 6.13 | 1.04 | 0.10 | |
| Wheat straw (unk) | 41.04 | 5.59 | 0.52 | 0.07 | Maj, 2018 |
| Oat Grain (unk) | 41.86 | 6.53 | 1.53 | 0.11 | |
| Larch needles (unk) | 45.73 | 5.81 | 0.91 | 0.09 | |
| Rapeseed pods (unk) | 39.23 | 5.62 | 0.61 | 0.54 | |
| **Min** | 37.28 | 4.43 | 0.38 | 0.05 | |
| **Max** | 49.77 | 6.53 | 5.46 | 0.54 | |
| **Average** | 43.65 | 5.46 | 1.40 | 0.16 | |

d.b.: dry basis
unk: unknown

Source: Autor based on the shown references, 2019

## 5.8 Emission analysis

As it was mentioned in the section 4.2.11 the emission analysis was conducted by the RIAE in Prague, measuring the emission of CO, $CO_2$, $NO_x$ and coarse particulate matter PM10 for different materials, including the peanut shells pellets. The results for the peanut shells pellets emission are shown in the Table 5.10.

*Table 5.10 Concentration of emissions from peanut shell pellets*

| Pollutant | Unit | Value |
|---|---|---|
| CO | ppm | 33 |
| $CO_2$ | % | 11 |
| $NO_x$ | ppm | 360 |
| PM10 | $mg/m^3$ | 800 |

Source: Author, 2019

The Table 5.11 presents the comparison between all materials. The concentration of CO is the lowest in all of the materials analyzed, however the percentage of $CO_2$ is higher than the wood and cereal pellets, but lower than the mustard residues. On the another hand the concentration of NOx is lower than the straw and mustard pellets but higher than the wood pellets, the same as the coarse particulate matter PM10. The former, indicates that the wood pellets represents the lowest source of emissions, followed by the peanut shells.

*Table 5.11 Emission comparison between biomass sources*

| Material | CO ppm | $CO_2$ % | $NO_x$ ppm | PM10 $mg/m^3$ |
|---|---|---|---|---|
| Peanut shells pellets | 33 | 11 | 360 | 800 |
| Wood pellets | 50 | 7 | 64 | 170 |
| Cereal straw pellets | 230 | 7 | 390 | 1,700 |
| Cereal straw pellets + 5% lime | 220 | 7 | 410 | 2,500 |
| Residues of mustard | 50 | 14 | 550 | 1,400 |

Source: Author, 2019

In addition to the above, a comparison was done between obtained values and the maximum emission allowance standards, established by the Ministry of Environment and Sustainable Development of Senegal and formulated by the Senegal Normalization Association (ASN): Standard NS 05-062 (2013) Atmospheric Pollution: regulation standards appendix 2: Limit values for Emissions for special installations. The Table 5.12, shows that the concentration of CO is far below the emission limit established, nevertheless the values obtained for the $NO_x$ and PM10 shows an incompliance of the law. The above indicates the necessity of implement treatment systems in the boilers for the particulate matter and $NO_x$ control. Higher PM10 results could be also affected by content of impurities in the sample material.

*Table 5.12 Evaluation of NS 05-062 (2003) compliance*

| Pollutant | Peanut shell Value ppm | Peanut shell Value mg/m$^3$ | NS 05-062 Limit mg/m$^3$ | Compliance |
|---|---|---|---|---|
| CO | 33 | 41.25 | 200 | Yes |
| $NO_x$ | 360 | 738 ($NO_2$) | 600 | No |
| PM10 | - | 800 | 50 | No |

Source: Author, 2019

## 5.9 Evaluation of standard BS EN ISO 17225 (2014) compliance

All of the previously mentioned parameters were compared to the values established in the standard BS EN 17225 (2014) parts 6 and 7, in order to determine the classification of the material. As the Table 5.13 shows, the parameters diameter, moisture, Net Calorific Value, Nitrogen, Sulphur and bulk density compliance with the specification, classing the material in an “A” category (the best quality class). However, the values reported for ash content and mechanical durability surpass the values established. The above shows the necessity to include additives (or possibly to remove impurities) to reduce the amount of ash after the combustions, as well as to improve mechanical durability (durability could be also enhanced by applying higher compression pressure).

It is relevant to mention that according to the standards, the parameters such as moisture, ash, Net Calorific Value, and Nitrogen content share the same specification for pellets and briquettes, whereas the diameter, mechanical durability and bulk density are parameters exclusively regulated for the pellets.

*Table 5.13 Compliance evaluation with the standard EN ISO 17225 (2014) part 6 and 7*

| **Parameter** | **Unit** | **Type of biofuel** | **Result** | **Specification** | | | |
|---|---|---|---|---|---|---|---|
| | | | | "A" class | **Ev.** | "B" class | **Ev.** |
| Diameter | mm | P. | D: 6.050 ± 0.04 L: 23.216 ± 6.62 | 06 < D < 25 3.15 < L ≤ 40 | Yes | 06 < D < 25 3.15 < L ≤ 40 | Yes |
| Moisture (a.r.) | w-% | P. | 2.50 | M ≤ 12 | Yes | M ≤ 15 | Yes |
| | | B. | 6.92 | M ≤ 12 | Yes | M ≤ 15 | Yes |
| Ash content (d.b.) | w-% | P.S. (P., B.) | 16.51 | A ≤ 6 | No | A ≤ 10 | No |
| Mechanical durability | w-% | P. | 95.86 | DU ≥ 97.5 | No | DU ≥ 96 | No |
| NCV (a.r.) | MJ/Kg | P.S. | 15.95 | NCV ≥ 14.5 | Yes | NCV ≥ 14.5 | Yes |
| Nitrogen (d.b.) | w-% | P.S. (P., B.) | 1.02 | N ≤ 1.5 | Yes | N ≤ 2.0 | Yes |
| Sulphur (d.b.) | w-% | P.S. (P., B.) | 0.05 | S ≤ 0.2 | Yes | S ≤ 0.3 | Yes |
| Bulk density | Kg/m$^3$ | P. | 698.4 | BD ≥ 600 | Yes | BD ≥ 600 | Yes |
| P.S. = Peanut Shells | | | | | | | |
| P. = Pellets, B. = Briquettes | | | | | | | |

Source: Author, 2019

## 5.10 Potential of peanut shell as an energy source

As it was mention in the section 4.3, the potential of peanut shells as an energy source (Ec) was calculated using the equation reported by Perea-Moreno et al. (2018). The Table 5.14 shows the parameters used for the calculation.

*Table 5.14 Values used to calculate the Ec*

| **Parameter** | **Value** | **Unit** | **Source** |
|---|---|---|---|
| RH (Thiès) | 0.62 | % | Les Ateliers, 2012 |
| Fs | 0.3 | % | Perea-Moreno et al., 2018 |
| Uc | 0.000277778 | - | Perea-Moreno et al., 2018 |
| NCV | 16.70 | MJ/Kg | Author, 2019 |

Source: Author based on the shown references, 2019

As the Figure 5.8 shows, due to the considerable variation between the production of peanuts over the years 1996 and 2017, the linear regression shows a gradual increasement in the production of the peanuts, therefore a slight grow in the potential of energy generation. According to the prediction, by 2035 Senegal would be able to generate 847.55 MWh of electricity from peanut shells which would be enough to feed the basic electricity necessities of 462.06 households in Senegal (102,114.46 inhabitants), according to the energy consumption per capita in Senegal (221 kWh) reported by the World Bank (2018) and the average size of a household (8.3 inhabitants per household) reported by United Nations (2018).

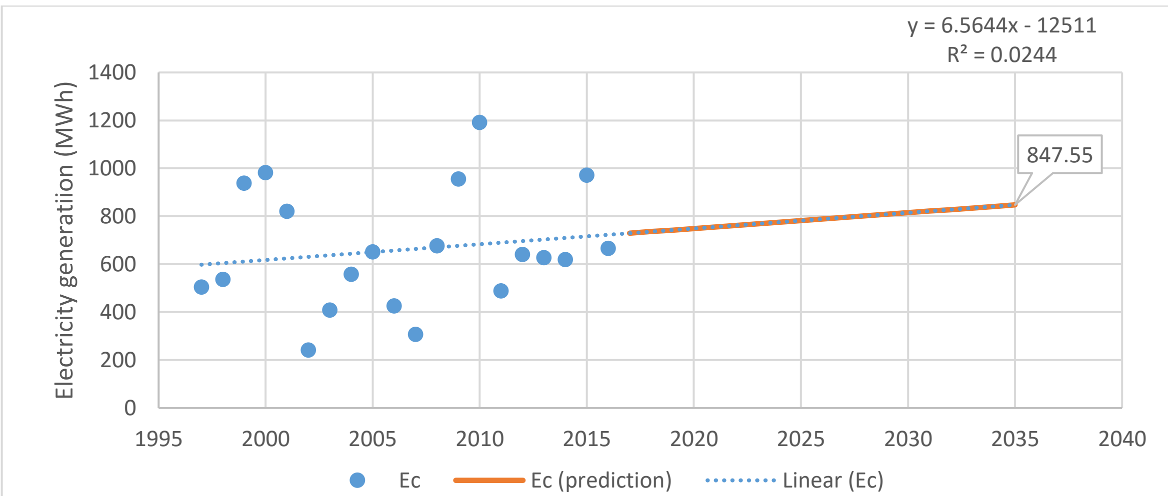



*Figure 5.8 Potential of peanut shells' energy generation in Senegal*

Source: Author, 2019

## 6 CONCLUSIONS

The generation of waste from the worldwide production of agricultural commodities such as peanuts, rice, wheat, soybeans, jatropha, among others, could be an important source of bioenergy. If it is properly treated (e.g. compacted), has suitable properties and availability of biomass it could contribute to reduce the dependency of conventional fuels by reusing the waste in a sustainable way.

According to the results, it is possible to confirm that the peanut shells could represent a feasible source of energy due to its high production in developing countries such as China, India, Senegal, and others. In addition, due to the poor nutritional value of the shells, there is no potential application for livestock's feeding purposes. The research showed that the production of densified biofuels from both pellets and briquettes made from peanut shells is possible. For production of briquettes grinding of the shells was not required, meaning that the briquettes production could be a cheaper option, since there is no necessity of machinery to grind the material. The compacted material, as well as the loose shells are characterized by a high calorific value (G.C.V. and N.C.V.) presenting similar values to e.g. cocoa, wood chips, oat grains reported by other authors. The obtained calorific value as received is directly related to the moisture content of the fuels. The moisture content of peanut shell biomass was considerably lower in comparison with the standard requirements, thus it was indicated that no additional drying process is required in order to fulfill the EN ISO 17225 (2015) requirements for solid biofuels. Additionally, the results showed that the moisture content of the peanut shells decreased by 65% after the compaction process for the pellets and 3.88% for the briquettes.

The mechanical durability of biofuels produced from peanut shells was slightly lower than the strict values required for standardized traded biofuels, although this parameter can be improved by optimization of input composition (additives, regulation of particle size of the material or regulation of a moisture content), use of other type of briquetting or pelletizing machine or simply a higher compaction pressure. Regarding the bulk density, after the densification process, the value for briquettes was almost 3 times (251.4 %) higher comparing to the loose material form, in the case of pellets the bulk density increased more than 6 times (649.07 %). This is a big advantage of compacted biofuels, which positively affect transportation, storage and manipulation operations. It is also important to mention, that the content of Nitrogen and Sulphur in the shells is lower than the requirements established in the EN ISO 17225 (2015), however during the combustion analysis the emissions of $NO_X$ and PM10 did not fulfill the requirements established by the Ministry of Environment and Sustainable Development of Senegal NS 05-062 (2013) Atmospheric Pollution: regulation standards appendix 2: Limit values for Emissions for special installations, which could be related to the combustion equipment, device used to measure the emissions or possible impurities in produced biofuels, thus a deep analysis of combustion properties, behavior in the fuel boiler as well as detailed chemical analysis of input material is recommended.

The main disadvantage of fuels based on peanut shells obtained from Senegal is the high ash content (16.51% d.b.), which is several times higher than the values published by other authors as well as the standard requirement on ash content in pellets/briquettes. This fact can be explained either by different chemical composition of peanut shells affected by the soil conditions (even the content of heavy metals) or by the presence of impurities in the peanut shell sample. Thus, the recommended chemical analysis of the biomass sample will also help to make a conclusion whether the ash produced after the combustion is suitable as a fertilizer. After understanding the root cause of the high ash content, it could be recommended to conduct a research evaluating different additives to reduce the ash in the material, as well as evaluate the effect of selected additives on the rest of the parameters. All the results (except for the ash content) confirm that peanut shells could be suitable source of biofuel in Senegal. According to the linear regression, the projected production of peanuts (981 tons by 2035) represents a potential energy generation of 847.55 MWh which is enough to satisfy the energy needs of more than 100,000 inhabitants in Senegal.

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