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FACULTY OF TROPICAL AGRISCIENCES

Department of Sustainable Technologies

Energy use of solid biofuels made of *Jatropha curcas* L. seed cake

Diploma Thesis

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Declaration

I hereby declare that the Diploma Thesis "Energy use of solid biofuels made of Jatropha curcas L. seed cake" is my own work and effort. It has been written and developed individually under the control of thesis supervisor and with using of cited sources.

Date ………………………… Signature…………………………

Christina Vlachosová

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Abstract

Fossil fuels cover a substantial part of the worldwide energy consumption and due to their exhaustion, looking for an alternative resource is becoming a today´s priority.

The diploma Thesis deals with energy utilization of waste biomass from the seeds of Jatropha curcas L. In the last decades, the development of the plant has been increasing in trend significantly. Jatropha is planted in many tropical countries due to its high content of oil, which is predominantly used for biodiesel production. During the oil pressing process, huge amount of waste seed cake biomass is produced. The objective of the present Thesis was to evaluate the possibility of utilizing the seed cakes from Jatropha curcas L. in the form of solid biofuels based on determination of physical, chemical and mechanical properties; production of briquettes and pellets; evaluation of combustion and emissions characteristics.

The Thesis was divided into two parts. The purpose of theoretical part was to summarize scientific information about biomass, solid biofuels as well as about the energy crop Jatropha curcas L., especially its usage and previous studies focused on waste seed cakes. The purpose of the practical part was to bring assessment of energy utilization of the plant seed cake biomass in different forms of solid biofuel.

Analysis showed that in case of initial form of Jatropha seed cakes production of briquettes was not feasible. The dependence between compressive forces, needed for production of quality briquette and moisture content was found by the preliminary compression test. Although the seed cakes in initial form have suitable physical and chemical properties, it is not efficient to burn them in automatic pellet boilers. Despite of the fact, that mechanical durability of pellets was low, the present research concluded that produced pellets are the most promising alternative possibility compared to other forms of solid fuels. Pellet´s combustion process was fluent in automatic pellet boiler and they fulfilled the limitations of CO concentrations as well.

Keywords: seed cake, waste biomass, standards, combustion, energy utilization, pellets, briquettes, emissions

Table of content

List of tables

List of figures

List of graphs

List of abbreviations

CO	Carbon monoxide
CO_2	Carbon dioxide
CULS	Czech University of Life Sciences Prague
e.g.	For example (exemplī grātia)
ECs	Energy crops
EC	European Commission
EU	European Union
FAFNR	Faculty of Agrobiology, Food and Natural Resources
FE	Faculty of Engineering
FTA	Faculty of Tropical AgriSciences
GCV	Gross calorific value
GHGs	Greenhouse gases
MC	Moisture content
NCV	Net calorific value
NO	Nitrogen oxide
NO_2	Nitrogen dioxide
O_2	Oxygen
RES	Renewable energy sources
RIAE	Research Institute of Agricultural Engineering in Prague

List of symbols

°C	Degree Celsius
a.r.	As received
cm	Centimetre
d.b.	Dry basis
g	Gram (unit of weight)
$J.g^{-1}$	Joule per gram
$kg.m^{-3}$	Kilogram per cubic metre
kN	Kilonewton
$l.ha^{-1}.year^{-1}$	Litre per hectare per year
mg	Milligram
$mg.m^{-3}$	Milligram per cubic meter
$MJ.kg^{-1}$	Megajoule per kilogram
mm	Millimetre
$mm.min^{-1}$	Millimetre per minute
$mm.year^{-1}$	Millimetre per year
ml	Millilitre
MPa	Megapascal
ppm	Parts per million
$t.ha^{-1}.year^{-1}$	Ton per hectare per year
W	Watt

1 Introduction

Increase in energy demand is mainly caused by constant population growth, increasing of living standards and persistent urbanization. The world needs an enormous amount of energy to maintain the future economic development. In these days development of alternative energy sources is urgent due to exhaustibility of world´s oil reserves and other fossil fuels; and also due to the fact of significant environment pollution. Biomass, including agricultural and wood residues, solid municipal wastes as well as energy crops, is a renewable source with a perspective potential to substitute a part of conventional fossil fuels. Solid biofuels made of biomass are used with increasing interest as a renewable and environmentally friendly energy source. Nowadays, production of high quality solid biofuels, is strongly desired.

The plant *Jatropha curcas* L. from Euphorbiaceae family is often called by scientist as "Celebrity of renewable energy" and is originated in Central America (Valíček, 2002). Nowadays it is grown in most tropical countries. The plant is known for its ability to survive in the toughest conditions because of low demand for irrigation and pest's control. *Jatropha curcas* L. has a high economic potential and its popularity is permanently increasing due to minimal quality of soil requirements and high oil content in seeds (Janick and Paull, 2008).

The main production factor of the plant is seed which is providing oil used for production of biodiesel. Waste seed cake produced by oil pressing forms kind of biomass, which cannot be used as an animal feed for its high toxicity. The biomass can be used as fertilizer in low quantities. Jatropha plantations expand at a fast pace and a constant waste biomass is produced, therefore remains the question how to utilize the biomass in best way. Using waste biomass for energy purposes can reduce amount of fossil fuels consumption and thus reduce pollution, even the waste management problems.

Since the plant is grown for oil production in principle and since the waste seed cakes have high energy potential the main objective of the thesis is to assess possible energy utilization of *Jatropha curcas* L. seed cakes in the form of solid biofuels.

2 Literature review

The literature review, part of this work, is a fundamental insight into the whole issue- "Energy use of solid biofuels made of *Jatropha curcas* L. seed cake" and it is divided into two main parts. First one briefly describes division of renewable energy sources and is primarily focusing on biomass energy, especially on energy crops and biofuels. The second part is dedicated to *Jatropha curcas* L. background, whole plant utilization and known utilization of *Jatropha curcas* L. seed cake.

Part I.

2.1 Renewable energy sources

Traditionally used fossil fuels are in critical threat of fast depletion as the world's population is still growing and the demand for energy is continuously increasing. Fossil fuels cover about four fifth of the energy consumption in these days (Brožek *et al*., 2012).

The Directive 2009/28/EC defined renewable energy as: "*energy from renewable non-fossil sources, namely wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases*". Renewable energy includes energy derived from natural processes that do not involve the consumption of exhaustible resources such as fossil fuels and uranium (BP Global, 2015). RES[1] handle various advantages over the fossil fuels such as reduction of GHGs[2] emissions (through moderation of CO_2[3] emissions), sustainability of production, an independence from volatile global market, etc.

The Renewable energy directive establishes policy for the production of energy from renewable sources in EU. It requires covering at least 20 % of EU total energy consumption with renewables by 2020 (EC, 2015). In 2013 the consumption of renewable energy reached

[1] Renewable energy sources
[2] Greenhouse gases consists of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), hydro fluorocarbons (HFCs) and per fluorocarbons (PFC) (Remuzgo *et al.*, 2015)
[3] Carbon dioxide

19.1 % share while the modern renewable energy (hydropower, wind, solar geothermal, biofuels and modern biomass) contributed with 10.1 % and traditional biomass used for cooking and heating in rural areas in developing countries contributed with 9 % (REN21, 2015).

2.1.1 **Biomass energy**

According to many sources there is an increasing worldwide interest in the use of biomass as a perspective, sustainable and especially renewable source of energy which can contribute to social and economic development (Pambudi *et al*., 2010; Tumuluru *et al*., 2010; Carels 2011; Pothula *et al*., 2014). According to REPP (2005) biomass is any organic matter, which is available on a renewable or recurring basis. In accordance with the Directive 2009/28/EC of European Commission defining biomass as: "*the biodegradable fraction of products, waste and residues from biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste*". Biomass from plants can serve as an alternative renewable and carbon-neutral raw material for the energy production (Tumuluru *et al*., 2010). Generally, according to McKendry (2002) and Faik (2013), the dry biomass is composed from 40-50 % cellulose, 20-25 % lignin, 15-25 % hemicellulose and 5-10 % by other components; however the components content always depends on plant species. The relative share of these main elements is the important determinants in establishing the suitability of plant species for subsequent conversion to an energy source (McKendry, 2002).

In recent years biomassit has become a popular source of various renewable energy, fuel and product applications due its local availability and environmental benefits. Biomass can be converted into energy by **thermochemical** (pyrolysis, gasification, and combustion), **biochemical** (anaerobic digestion, fermentation), and **physicochemical** (transesterification) or by **mechanical** (briquetting, pelleting, crushing) way (McKendry 2002; Celjak 2008; Perďochová 2010). Due to those mentioned methods, sources of biomass are used particularly to produce **solid fuels** (pellets, briquettes, chips and logs), **gaseous fuels** (syngas and biogas),

liquid fuels (bio alcohols and biodiesel) and **heat** (Sims *et al.*, 2006). Ferry and Cabraal (2006) mention that the most commonly used, technically feasible and economically efficient method for obtaining energy from biomass is direct combustion to produce heat, providing space and water heat or generate electricity through steam turbine used.

The European commission (not dated) has stated that about two-thirds of all renewable energy consumption in the EU in 2012 was created by biomass. It also has issued non-binding recommendations on sustainable criteria for biomass and biofuels: "*Forbid the use of biomass from land converted from forest; ensure that biofuels emit at least 50 % less GHGs over their lifecycle in comparison with fossil fuels in 2017 and 60 % in 2018; ensure monitoring of biomass origin and prefer national biofuels".*

2.1.2 **Waste biomass and energy crops**

As it was already mentioned before, biomass could be purposely cultivated (energy crops) or waste products could be used for energy purposes. Waste biomass includes agricultural crop and livestock residues, forest residues, urban wood waste, municipal solid waste and as well industrial wastes. Waste products from wood or from other agricultural harvesting and processing operations are the least costly biomass. This include wood and material from processing of wood such as wood shavings, barks, sawdust, as well as agricultural wastes, which include residues from harvesting and processing of agricultural product (e.g. husks, stalks, leaves and seed cakes) (Grover and Mishra, 1996). However not all residues are available and suitable for bioenergy production.

Nevertheless, the reserves of these waste resources are limited. Purposely cultivated crops- high yielding plants mainly cultivated for energy purposes are more and more planted for use in energy production to overcome this obstacle and to utilize biomass more efficiently (Tumuluru *et al.*, 2010). According to Prade (2011) the advantages of ECs[4] are characterized by landscape maintenance and protection of soil erosion, by providing new job opportunities in rural areas and deliberate cultivation of energy crops on soil unsuitable for plant production leads to the revitalization of these soils. Sladký *et al*. (2002) refers main specific requirement

[4] Energy crops; purposely cultivated biomass

of ECs as fast growing plants with very high yield; resistance to weeds, pests and diseases; low demand of water and fertilizers; easy harvesting and low economical capital. Division of particular categories and types of EC is shown in Table 1.

Alakangas and Virkkunen (2007) have estimated that approximately 30 million hectares of arable land could be available for energy crops production, whereas the total area under energy crops in the EU is about 2.5 million hectares.

Table 1. Categories and types of energy crops.

Plants	Examples
Yielding starch and sugar	Sugar cane, Sugar beet, Sweet sorghum, Corn, Wheat, Barley, Potatoes, Cassava
Yielding oil	Rapeseed, Sunflower, Soybean, Oil palm, *Jatropha curcas* L., Chinese tallow tree, Copaiba, Algae
Lignocelluloses	Woody plants (willow, acacias), Cereals, Grass (elephant grass), Other plants (hemp, sorghum, knotweed)

Source: Petříková *et al*., 2006; Prade 2011

2.1.3 **Solid biofuels**

Due to the increased demand for energy and also limited fossil fuels reserves there is high interest in biomass based biofuels. Biomass for energy production includes a wide range of materials which can be classified according to many criteria such as sources or type of conversion process (Tumuluru *et al*., 2010). Solid biofuels are fuels predominantly produced from lignocellulosic commonly waste biomass by following processes:

by ***grinding, chipping, cutting*** are produced ***woodchips, shavings, logs***;
by ***pressing*** are produced ***briquettes, pellets, straw bales***;
by ***slow pyrolysis***[5] is produced ***charcoal*** *;*
by ***torrefaction***[6] are produced ***torrefied fuels***.

[5] Thermochemical decomposition of organic material by burning without oxygen (Lehmann and Joseph, 2009)
[6] Mild pyrolysis process carried out at temperatures ranging from 225 to 300 °C (Prins *et al*., 2006)

The whole process of thermal utilisation of solid biofuels is affected by the type of used solid biofuel, its chemical composition and its physical characteristics such as bulk density, moisture content, and particle size distribution, gross and net calorific value (Van Loo and Koppejan, 2002). Each type of source has a different composition but oxygen, carbon, and hydrogen ratio is fundamental for all types of solid biomass. In accordance with Obernberger *et al*. (2006) from the ratio of elements could be basically stated that herbaceous biomass has higher share of nitrogen, while woody biomass has higher ratio of carbon. Hydrogen and carbon react with oxygen during the combustion and create carbon dioxide and water. These elements also positively correlate with increasing gross calorific value while higher amount of oxygen decreases GCV[7] (Picchi, 2013). Solid biofuels produced from renewable resources could help to minimize the fossil fuel burning and CO_2 production through the biomass carbon cycle (Naik *et al*., 2010).

2.1.3.1 Mechanical densification

Biomass in its original form is very difficult and inefficient to handle, transport, store and also utilize because of high moisture content of material, it ranges from 10 % up to 70 %, irregular sizes and shapes, and low bulk density[8]. One of the possible solutions to overcome mentioned limitations of raw material is biomass densification process into pellets, briquettes or cubes. Densified biofuel is defined by standard EN ISO 16559 (2014) as "*solid biofuel made by mechanically compressing biomass or thermally treated biomass to mould the solid biofuel into a specific size and shape such as cubes, pressed logs, biofuel pellets or biofuel briquettes*". The process increases the bulk density values from initial 40-200 $kg.m^{-3}$ up to a final 600-800 $kg.m^{-3}$ (Mani *et al*., 2003; McMullen *et al*., 2005; Kaliyan and More, 2009). According to Tumuluru *et al.* (2011) the densification process is critical for producing a feedstock material. The crucial factor of biomass utilization and fuel deliveries is bulk density, which together with the net calorific value determines energy density. The material bulk density is in direct relationship with transport and storage costs. The density of the processed product impacts on fuel storage requirements, the sizing of the materials handling system and

[7] Gross calorific value
[8] Bulk density is defined as "ratio of the mass and the volume of a sample including pore volume" (Rabier *et al*., 2006)

how the material is likely to behave during subsequent thermo-chemical or biological processing as a fuel. McKendry (2002) claims that the loose straw has bulk density about 20-40 kg.m^{-3}, while pressed pellets can reach bulk density of 560-700 kg.m^{-3}. Pellets, one of the most densified forms of solid biofuels, can reach 600-1,200 kg.m^{-3} in maximum.

2.1.3.2 Briquettes

Briquetting is a compaction process where structural, elastic and plastic phases of deformation take place. Briquettes are a compressed blocks of organic materials with a diameter range from 40 to 100 mm and a length of 300 mm; primarily used to generate thermal energy for heating and cooking (Shaw, 2008). The Standard EN ISO 16559 (2014) defines briquette as "*densified biofuel made with or without additives in the form of cubiform, polyhedral, polyhydric or cylindrical units with a diameter of more than 25 mm, produced by compressing biomass*". The briquettes are often used as an ecological substitute to replace fossil fuel as coal or firewood. Their use is time saving, money saving, also can decrease local deforestation and provide opportunity for generating family income. Agricultural or other waste residues are permanently difficult to use as solid biofuels because of their volume and high moisture content. The main aim of biomass compaction is to achieve desired shape, volume and consistency of the material (Pambudi *et al.*, 2010). Process of briquetting remains the most applied technology of fuel compression (Ivanova, 2012). In accordance with Tumuluru *et al*. (2010) major factors affecting the briquettes properties are: shape and size of briquette, surface area, particle size distribution, bulk density, porosity, moisture content, and last but not least strength. Van Look and Koppejan (2002) claim, that briquettes can be burned in any wood boilers, fireplaces and central heating boilers.

2.1.3.3 Pellets

According to Stupavský (2010) pellets are generally highly compressed cylindrical extrusions often produced with various length of 5 to 40 mm and diameter of 6 mm. Andert *et al*. (2006) claim that ratio between length and diameter of pellet should not be higher than 1:3. The Standard EN ISO 17225-6 (2014) defines non-woody pellets as "*densified biofuel made from grinded or milled biomass with or without additives and unitized as cylinders with* *usually diameter less than 25 mm, random length and typically 3.15 mm to 40 mm with broken ends, obtain by mechanical compression".* The raw material for non-woody pellets production is mainly herbaceous, fruit or aquatic biomass or biomass blends and mixtures. The mixtures can also contain woody biomass as a bark, shavings, chips or sawdust. This kind of pellet is usually manufactured in a die with total moisture content less than 15 % of their mass. In accordance with Kott (2010) in case that input material contains low amount of water, additionally is wetted just before pressing. It releases adhesive substances from surface of the material and hold particles together.

2.1.3.4 Direct combustion

Combustion is a chemical reaction between chosen fuel and oxygen available from air. Carbon dioxide and water vapor are produced during the combustion processes together with releasing of heat (Stupavský and Holý, 2010). Process of combustion is formed by four phases: drying of fuel, pyrolysis, combustion of gaseous components and combustion of solid components (Pastorek, 2004). Naik *et al*. (2010) state that biomass can be used as substitute of conventional fossil fuels in case of well venting during its combustion in domestic stoves or boilers. According to Van Look and Koppejan (2002) low bulk density, net calorific value, ash melting point and high volatile mass content contrarily are properties defining the biomass biofuels and have to be taken into account within the boilers are designed. Woody pellets are known for low ash content of 0.5-2.5 % and net calorific value ranges between 17.5-19.5 $MJ.kg^{-1}$, whereas alternative biomass pellets reach value of ash content between 1-9 % and 15-18 $MJ.kg^{-1}$of net calorific value (Carrol and Finnan, 2012).

One of the most monitored properties in the biofuel sector are emissions, released during combustion. The regulation 201/2012 Sb. (MZP, 2012) defines emissions as the *"introduction of one or more pollutants into the air*." Simultaneously describes *"air pollutant as any substance which is present in the atmosphere in the certain percentage it may have harmful effects on human health or environment odors.*" According to Havrland *et al*. (2011) since CO_2 released during combustion of biomass is comparable with the fixed CO_2 during growing plants, biomass does not contribute to a build of CO_2 in the atmosphere. Main gas pollutants produced during the biomass combustion processes due to the release of heat contained in the chosen fuel are: Carbon monoxide (CO), Sulfur dioxide (SO_2), Nitrogen oxides (NOx), Solid polluting matter and Total organic carbon (TOC) (MZP, 2012). The high mass concentrations were recorded during combustion of wood logs in uncontrolled combustion devices as fireplaces or wood stove. It was found that emissions of agricultural biomass pellets burned in controlled conditions are much higher in comparison with woody pellets (Johansson *et al*., 2003).

Part II.

2.2 Background of *Jatropha curcas* L.

The chapter engages on origin and botanical description of *Jatropha curcas* L. plant and describes factors influencing its production. Furthermore mentions still unclear yield issue.

2.2.1 Origin and botanical description

The term Jatropha is originated from Greek word iatrós (doctor) and trophé (food or nourishment), which shows the historical uses in medicine (Kumar and Sharma, 2008). *Jatropha curcas* L. in English is commonly known as Jatropha, pig nut, physic nut, Barbados nut or purging nut. The plant belongs to the Euphorbiceae family (Janick and Paull, 2008). According to Valíček (2002) and Carels (2009) this family contains approximately 175 known species. *Jatropha curcas* L. is historically worldwide known as a tropical medicinal plant. In recent years the plant gets to the forefront of interest due to its significance in the energy sector.

A number of authors consider the centre of Jatropha origin to the north-eastern part of South America and Central America (Jongschaap *et al.*, 2007; Janick and Paull, 2008; Abdelgadir and Staden, 2013). The plant was probably distributed by Portuguese sailors during the 16th century via the Cape Verde Islands and Guineu Bissau to other Asian and African countries, where was also expanded later (Heller, 1996).

The plant is a perennial and multipurpose large shrub or tropical tree which grows up to six meters in height under the normal conditions (Heller, 1996). However under the significantly convenient conditions a height of eight to ten meters can be reached (Abdelgadir and Staden, 2013). Its life span is up to 50 years (Achten *et al.*, 2008). Smooth grey bark of the plant exudes pink latex, which has got medicinal effects as other parts of the plant. Fruit of Jatropha is a small yellow capsule which includes two or three black long seeds inside (Figure 1, Figure 2 below). These seeds are popular for high oil content (Janick and Paull, 2008).

Jatropha is widely grown in most of tropical and some subtropical areas of all continents nowadays. It is currently being promoted in southern Africa, Mali, Nepal and Brazil, but especially China, India, Malaysia and Indonesia represent almost 91 % of the global production (Openshaw, 2000; Valíček, 2002; GreenOdin, 2014).

Figure 1. Jatropha fruits (Source: Jatropha curcas Plantations, 2013).

Figure 2. Jatropha seeds (Source: DEGJSP, 2012).

2.2.2 **Factors affecting production**

Jatropha curcas L. is known for its ability to survive even in the toughest conditions. However, there are some certain factors which are influencing plant productivity.

2.2.2.1 Climate conditions

Jatropha curcas L. is specie of succulent plant which is adapted to arid climate. We may see this plant in the dry and even in the humid, tropical or subtropical climate. According to Jongschaap *et al.* (2007) the most suitable place for growing is climatic belt, called *Jatropha curcas* L. belt, which contains the area between 30° north and 35° south latitude, shown in Figure 3 below. Authors also refer that the plant is grown in lower altitudes of 0 – 500 meters above the sea level.

The plant is tolerated to variable rainfalls (200-2,380 mm.year^{-1}). Janick and Paull (2008) argue that the plant can survive at minimal rainfalls of 200 mm.year^{-1} and only 800 mm.year^{-1} is needed for seed production. However, another source says that the minimum of annual rainfall for surviving is 300 mm.year^{-1} and optimal amount of rainfall needed for the production is 1,000-1,500 mm.year^{-1} (FACT, 2007). Immoderate humidity (3,000 mm.year^{-1}) has definitely damaging effect for that plant.

The optimal growing temperature is between 20 °C and 28 °C. Too high temperatures may lead to decrease of yields (Gour, 2006). The plant is intolerant toward frost and also reacts badly to shady places. However, it is not sensitive to the day length therefore can bloom at any time during the whole year.

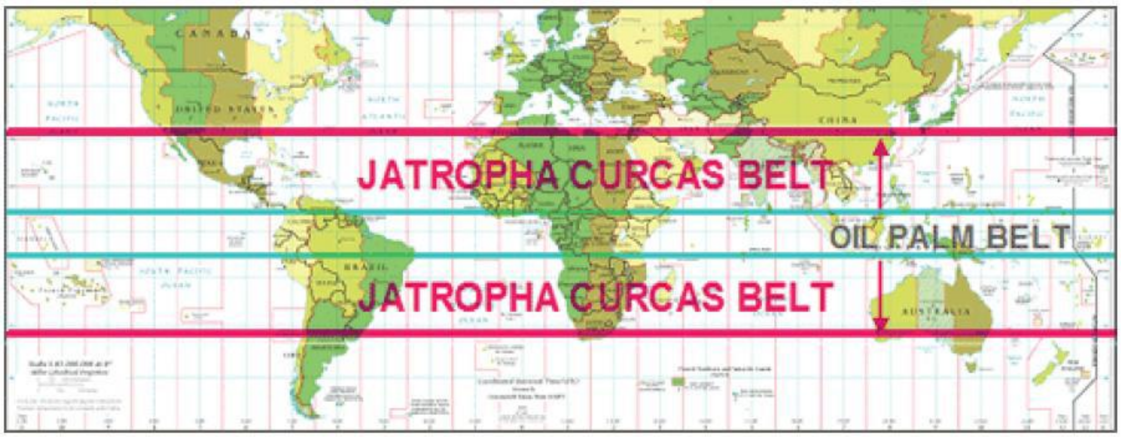


Figure 3. Climatic belt of *Jatropha curcas* L. in comparison with Oil palm belt (Source: Joil, 2014).

According to FACT (2010) beginning of the rain period when the soil has adopted to the initial soil moisture is the most suitable season for planting of *Jatropha curcas* L.

2.2.2.2 Soil conditions and fertilizer requirements

Jatropha is known for its ability to survive even in very poor and arid soils. It is also able to take root in rocky rifts. Mostly is grown on agriculturally unsuitable land; however growing under these conditions does not suggest high productivity (Jongshaap *et al*., 2007). Plant can be grown on all types of soil, except for waterlogged soils. The most suitable are aerated soils, thus sandy and loamy soil of at least 45 cm depth (Gour, 2006).

The plant is described as a plant with low nutritional requirements due to the fact of growing on poor quality soils. But increasing of productivity certainly involves proper fertilization and appropriate watering (Jongshaap *et al*., 2007). Achten *et al.* (2008) mention, that optimum concentration of inorganic fertilizers is changing with the plant age. Yong *et al.* (2010) in their study claim that there is no significant difference in seed oil content among the fertilizer treatment, on the other hand they refer the fruit yield is higher.

2.2.2.3 Pests and diseases

The crop is highly resistant to pests or diseases due to its toxic character. However, the tolerance has been demonstrated only in cultivating of plant individually, because according to Jongschaap *et al.* (2007) the incidence of diseases and pests is widely announced under monoculture plantation. However, observed diseases such as collar rot, leaf spots, root rot and damping-off could be under the control with use of suitable combination of planting techniques (for example avoiding waterlogged conditions on plantation).

2.2.3 **Yield**

The Jatropha cultivation is still in an experimental phase. FACT Foundation and some other organisations have been documenting current best practices in detail, but only selected issues are covered. The issues that are often misunderstood and urgently require further research still exist (Nielsen *et al*., 2013). Also Achten *et al*. (2008) refer that seed yield is still difficult issue and the mature seed yield is still not known, since systematic yield monitoring only started recently.

Generally, the plant starts to produce fruits already in first year, but harvested yields are stabilized usually in about five years. Stable harvest means seeds production of 0.3-12 $tons.ha^{-1}.year^{-1}$, depending on rainfall, soil nutrients and on the whole conditions of growing (IEEJ, 2009). Likewise Openshaw (2000) reported a similar wide range of yield (0.4-12 $tons.ha^{-1}.year^{-1}$). Thus it is not coherent with another source which states that maximum possible range of yield could be 1.5-2 $tons.ha^{-1}.year^{-1}$ (Biomuber, 2015). Tewari (2007) claimed that under the good conditions and sites or under the optimal management practise 5 $tons.ha^{-1}.year^{-1}$ can be achieved. Jongschaap *et al.* (2007) conclude to a potential yield range of 1.5–7.8 $tons.ha^{-1}.year^{-1}$.

According to Heller (1996) for the best oil yields, the seeds have to be harvested at maturity. Seeds are mature if the colour of the fruits has changed from green to yellow or brown.

2.3 Utilization of *Jatropha curcas* L.

Jatropha curcas L. is a plant with many attributes, many uses and significant potential. The whole plant can be used for multiple purposes.

2.3.1 **Medicinal purposes**

Extract from all parts of the plant (seeds, leaves, bark) has been used in traditional medicine as well as for veterinary purposes for a long time. Heller (1996) refers the antitumor effects of Jatropha extract. Curcas oil contains ***Curcin***, which is strongly irritant, even toxic, protein, which makes it unsuitable for animals and humans. That is also why the oil has laxative effects and is used as a strong purgative. The oil could be also applied for the skin injuries treatment or diseases (eczema, ulcers and moulds) as well as pain absorption, for example rheumatic pain. Leaves infusion is used for cough or as an antiseptic after childbirth. The latex is characterized by antimicrobial properties.

2.3.2 **Source of food**

Generally, the consumption of *Jatropha curcas* L. as a source of food is very limited due to its high toxicity. Janick and Paull (2008) argue that four up to five fresh uncooked seeds could cause a person´s death. However Makkar *et al*. (1998) observed non-toxic variety of *Jatropha curcas* L. in some provinces of Mexico and Central America. The existence of non-toxic curcas oil could mean a potential source of oil for human consumption. Similarly the seed cakes could be suitable source of protein for livestock as well as for human.

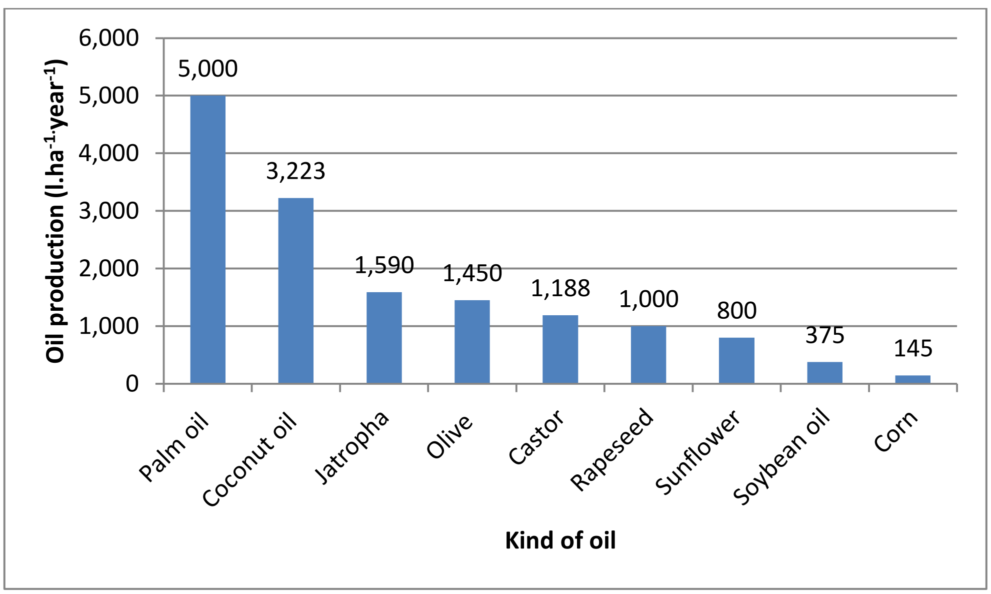
2.3.3 **Biological protection**

There are references to the fact that the extract of any part of *Jatropha curcas* L. has insecticidal properties (Heller, 1996). Even it was established that the seed oil may be used to protect cotton, potato or corn against insects or other pests (Sharma and Kumar, 2008).

Exactly due to the bitter of Jatropha oil and its toxic character, the plant is growing as a living fence around agriculture areas or around the plots. The fence serves protection against cattle or unwelcome wild game (Achten *et al*., 2008).

2.3.4 **Source of energy**

The plant is well known as high oil yielding crop. Graph 1 below represents comparison of oil production of the main high yielding food and energy crops mostly used for energy purposes. The crude oil may be obtained by pressing of whole seed or even the kernel. The oil has a high oxidative stability, low acidity, high saturated fatty acid content and low temperature variability in comparison with other non-edible oils (IEEJ, 2009). The curcas oil is mainly used for biodiesel production and also to provide light and heat for cooking commonly in remote areas, where is usually attained by simple mechanical presses.



Graph 1. Comparison of oil production of some oil crops (Source: Koh and Ghazi, 2011; Jansen 2013).

2.3.4.1 Biodiesel production

Jatropha curcas L. is planted in huge amount for a biodiesel production; a lot of money and research is going into these projects. Jatropha biodiesel is presented as of the best alternative sources of energy for the global lack of traditional energy sources (Jansen, 2013). Due to the fact that oil cannot be used for nutritional purposes without detoxification and also due to possibility of cultivation in dry and marginal lands, it makes its use as biodiesel very attractive. However, the exact oil content in seeds is not quite clear, authors diverge in their arguments. Valíček (2002) mentions 37 %, Janick (2008) 60-68 % and Mofijur *et al*. (2012) refers 50-55 %- outputs from all authors talk about high yields.

Seed oil can be extracted either hydraulically using a press or chemically using solvents. Chemical extraction can only be achieved in large industrial plants. In developing world, simple manual press for pressing the oil from the seeds by traditional way is mainly used which still inefficient and its maintenance is difficult (Brittaine and Lutaladio, 2010). The maximum quantity and quality of pressed oil depends on the method of extraction.

Biodiesel from oil could be produced by several ways; however the most widespread is the process of transesterification. During the reaction, alcohol and oils in the presence of catalyst produce esters and glycerol, which is widely used in cosmetics industry. Jatropha crude oil produced by transesterification has a relatively high viscosity, but in areas with higher temperature can be used directly as diesel engine fuel (IEEJ, 2009).

According to Nyer (2011) *Jatropha curcas* L. planting is not in direct competition with food crops based agriculture because it is grown on marginal land and it is not suitable for human consumption due to toxic compounds. On the other hand avoiding of large-scale production is very required and intercropping with food crops is recommended. However, fact remains that the plant is mainly grown in large-scale on agricultural lands because of high crop yields (Edrisi *et al*., 2015).

Gexsi (2008) published a study with view on all of the Jatropha projects developed between year 2008 and 2015. Figure 4 (below) shows that interest about Jatropha rapidly growing and its plantations are expanding year to year. From 900,000 ha planted worldwide in 2008, enormous growth of 5 million hectares is to be recorded in 2010 and already 13 million hectares were expected in 2015.

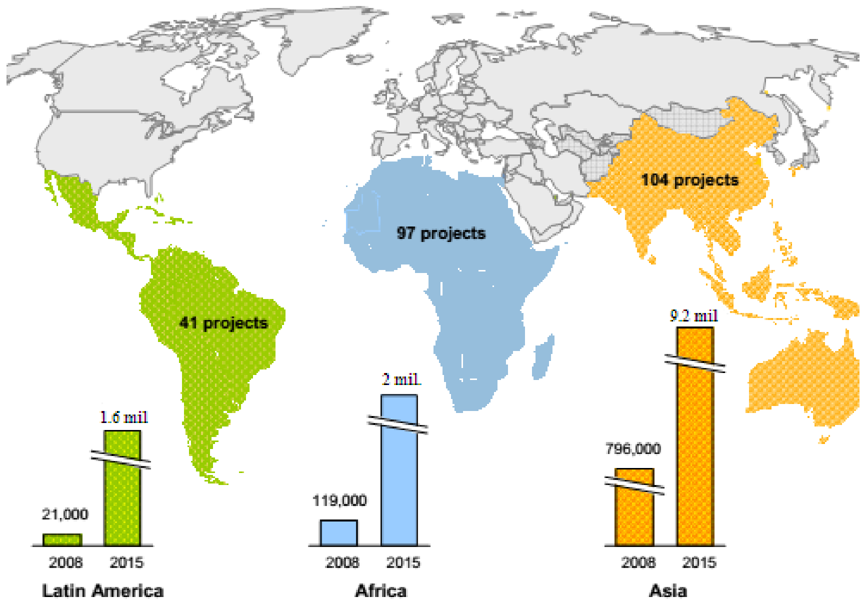


Figure 4. Comparison of Jatropha projects and plantations size (in ha) in 2008 and 2015 (Source: GEXSI, 2008).

2.4 Utilization of Jatropha seed cake

Seed cake or press cake is the valuable by-products of whole seed processing of oil, which represent by far the largest part of plant seed (Figure 5 below). With every tone of *Jatropha curcas* L. oil there are produced generally three tons of waste seed cakes during the oil extraction (Sricharoenchaikul *et al.*, 2011). The seed cakes are very rich in proteins; however they contain highly toxic protein-curcin, so they cannot be used as a stock feed without treatment (Heller, 1996; GTZ, 2009).

Figure 5. Jatropha press cakes (Source: FACT, 2010).

Nevertheless, material may be used for various applications; especially it has a potential as fertilizer, feed for biogas production and also as a source of solid biofuel. The conversion of the seed cakes into value added products is possible by three main processes: biochemical, physicochemical and thermochemical processes.

2.4.1 **Fertilizer**

Jatropha seed cakes are excellent organic source of nutrients for plants, because of high nitrogen ratio content. Achten *et al*. (2008) state, that seed cakes contain even more nutrients in comparison with manure. According to Mavankeni (2007) the cakes can be directly applied or can be used in production of compost to increase the effect of fertilizer. On the other hand Heller (1996) warns about a potential phytotoxicity in applying of large seed cakes quantities into the soil. According to Prakash (2012) in Peru show the problems with using of press cakes, because of its toxicity, applied directly into the soil as fertilizer, which killed the beneficial earth worms. However, Devappa *et al.* (2010) argue that the main toxin- phorbol ester, takes about few days to completely break down in the soil, which does not cause any long-term environmental problem.

Waste seed cakes or other waste material of the plant may serve as a source for biogas production by anaerobic digestion. According to Pandey *et al*. (2012) the material provides almost 60 % more biogas in comparison with manure. Together with producing of biogas by fermentation, at the same time is formed digestate. The slurry, the by-product of seed cake fermentation is mainly used as a natural fertilizer due to its high nutrient content (Contran *et al*., 2013).

Dimpl (2011) refers in his study that average calorific value of seed cakes biogas can achieve more than 20 $MJ.kg^{-1}$ and it could be used for heating / cooking, lightening and also for burning in engines or to generate electricity. This technology is primarily used in China, Vietnam and Nepal for household consumption, where biogas is produced for lightening or cooking (FAO, 2009).

2.4.2 **Potential as a solid biofuels**

FACT Foundation (2010) claims, that the best utilization of the press cakes is for energy purposes and also for fertilizing. In accordance with Dorp (2013) Jatropha press cakes have an energy content of around 25 $MJ.kg^{-1}$. FAO (2010) states that energy content of remaining parts of the fruit after oil extraction exceeds the oil energy content, means that more energy could be generated from seed cakes in comparison with the oil.

2.4.2.1 Briquettes and pellets production

The press cakes are used for making briquettes to substitute the firewood, and these briquettes can be burned similarly like wood in industrial boilers. Briquettes generally require a high content of a combustible material and an additional material using as a binder to hold the briquette together.

In Guatemala, an organization called TechnoServe has identified press cakes as an interesting source for briquettes production. The objective of its study was to determine feasibility of Jatropha seed cakes briquettes in combination with locally available organic waste materials. During the materials assessment was shown, that corn stalks, corn husks, cow dung, coffee husks and also Jatropha fruit shells are optimal waste materials for mixing with press cakes because of their local availability. As potential waste materials were identified banana peels or orange rinds, but in the project they were not investigated. Experiment was performed by using a manual screw press (Figure 6). The only suitable materials such as cow dung and corn husks were established for mixing with seed cakes.

Figure 6. Manual Screw press (Source: Nyer, 2011).

TechnoServe has investigated briquettes production project in Honduras as well. Briquettes were made from Jatropha seed cakes and woody sawdust, which could be the most promising material for stirring. Unfortunately there have not been available project findings (Nyer, 2011).

Research by Pambudi *et al*. was done in 2010 where seed cakes powder was mixed with starch binder for pellet making. The ratio was 10 % of binder and 90 % of seed cakes powder and binder consists of 70 % of water and rest of cassava starch. Low amount of binder means, that it might be ignored as they also reported. Another project was focused on mixing of one part of Jatropha press cakes together with two parts of rice husk. Because the seed cakes content high amount of residual oil, Lautsen (2010) has developed the Jiko MBono stove (Jatropha stove) for the Jatropha seed cakes pellets combustion. It is a gasification cook stove mainly used and widespread in African countries

2.4.2.2 Charcoal briquettes production

The seed cakes briquettes are producing a lot of smoke while burning. To solve this problem and also to increase the energy content of the briquettes and to reduce the weight, the Jatropha seed cakes briquettes can be “charcoalized” by pyrolysis or by torrefaction. The smoke emission from burning these charcoal briquettes is much lower, than from the briquettes and they burn more easily.

Figure 7. Production of charcoal briquettes in Tanzania: Briquetting machine, Jatropha seed cakes briquettes and Charcoal kiln (Source: Raghavan, 2013).

Seed cakes could be turned into charcoal before or after pressing into briquettes, the process is based on similar principle, where is a binder necessary. It is possible to make charcoal in an oven (Figure 7 above) or by traditional way with soil covering. About 60 % of press cakes briquettes weight will remain after the process of charcoal production. According to this fact Dorp (2013) claims that there is a high potential of *Jatropha curcas* L. seed cakes in combination with other agro-residues as rice husks, corn stoves, coffee husks, cotton stalks or cow dung in charcoal briquettes production.

Dorp (2013) in his report mentions a project at Diligent Tanzania, where a testing facility has been set up for Jatropha press cakes briquettes production. The project was focused on production of alternative ‘green charcoal’ made by seed cakes without any other raw materials for household cooking use. The briquettes were made by compaction of seed cakes plant after the oil extraction. Capacity of the production was 1,500 tons.year^{-1}. However, Diligent has reported that the results are insufficient, primarily because higher temperature for production is required, the burning time is shorter and charcoal briquettes produce high amount of smoke while they are burning.

Another project has been taken place in the Philippines, where the Department of Environment and Natural Resources (DENR) was experimenting with the production of charcoal briquettes made of Jatropha and other agro-residues. DENR was comparing three types of raw materials, namely 100 % Jatropha seed cakes, 100 % Jatropha husk and 50 % husk and 50 % seed cakes which were carbonized. Materials were bonded by binders such as corn or cassava starch at different binder level based on weight of feedstock to charcoal briquettes formation. For the most appropriate charcoal briquettes were selected briquettes from 100 % *Jatropha curcas* L. seed cakes; evaluations were based on charcoal yield, carbonization time, crushing strength, proximate analysis and heating value (Cuaresma *et al*., 2015).

3 Objectives and hypothesis

3.1 Overall objective

The main thesis objective was to assess the possibilities of *Jatropha curcas* L. seed cakes for energy utilization in the form of solid biofuels.

3.2 Specific objectives

The overall objective of the thesis is supported and supplemented by the specific objectives, which are set to help to fulfil the main objective. The specific objectives had been defined as following:

- **i.** to determine physical, chemical and mechanical properties of *Jatropha curcas* L. seed cake according to EN and ISO standards;
- **ii.** to process *Jatropha curcas* L. seed cake into the form of solid biofuel (briquettes, pellets);
- **iii.** to compare utilization of Jatropha seed cake and Jatropha pellets based on combustion and emission properties.

3.3 Hypotheses

- **i.** *Jatropha curcas* L. seed cake can be transformed into pellets, which can meet the international standard for graded non-woody pellets ISO 17225-6 (2014).
- **ii.** *Jatropha curcas* L. seed cake can be transformed into quality briquettes without any additives.
- **iii.** Emissions released during *Jatropha curcas L*. seed cake combustion are higher in comparison with emissions released by combustion of pellets made of *Jatropha curcas* L. seed cake.

4 Methodology

The methodology is divided into two parts. First part describes methodology of writing of literature review and the second part is focused on practical research.

4.1 Literature review

For establishing theoretical part of the thesis, literature review, available literature and sources of Czech and also mainly foreign authors of books and scientific articles were used. The articles were found on scientific databases, primarily from Scopus, Science Direct and Web of Science. The articles were searched based on combination of keywords: Jatropha seed cake, waste biomass, solid biofuels, pellets, briquettes, combustion, emissions etc.

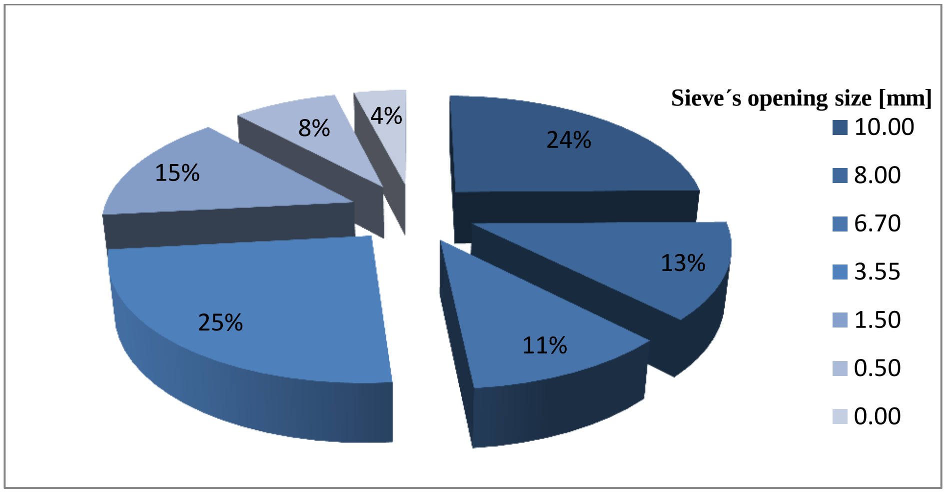
4.2 Practical research

Practical research was based on qualitative and quantitative methods of research and included these parts:

4.2.1 **Material**

In the practical part, waste seed cakes of *Jatropha curcas* L. plant were used. Material was originated from North Sumatra, Indonesia and was provided by **Farmet a.s.** company within Czech University of Life Sciences Prague cooperation. Farmet a.s. is the dynamically developing Czech company involved in the development, production, sale and service of agricultural machines for soil processing, sowing and technologies for processing of oilseeds, vegetable oils and feed production.

Material is characterized by very low moisture content of 7.76 % and particle size distribution was as shown in Graph 2. It is obvious, that material was mainly represented by larger parts; almost 74 % of seed cakes account particles with size range of 10 – 3.5 mm and rest 26 % of the mass represents particles lower than 1.5 mm.



Graph 2. Pie chart of particle size distribution of *Jatropha curcas* L. seed cakes (Source: Author, 2016).

4.2.2 **Methods**

Particular parts of the research were done in Laboratory of biofuels in FTA[9], CULS[10]; Laboratory of Environmental Chemistry in the Interfaculty Centre of Environmental Sciences, CULS; Department of chemistry in FAFNR[11], CULS; Faculty of Engineering, CULS and also in Research Institute of Agricultural Engineering in Prague.

Firstly were determined physical, mechanical and chemical properties of raw *Jatropha curcas* L. seed cake according to methodology of European Technical Committee for Solid Biofuels. Secondly, solid biofuels such as pellets and briquettes from the seed cake were tested. Finally was done determination of emissions released during the combustion of pellets and initial material under specific condition.

4.2.2.1 Classification according to origin and source

Classification of the material is based on origin and source of biofuel. Source of biofuel was determined according to standard ISO 17225-1 (2014): Solid biofuels- Fuel specifications and classes- Part 1: General requirements.

[9] Faculty of Tropical AgriSciences
[10] Czech University of Life Sciences Prague
[11] Faculty of Agrobiology, Food and Natural resources

4.2.2.2 Analytical sample preparation

Raw material was crushed to the particle size lower than one mm by using of Grinding knife mill Retsch Grindomix GM 100 in Laboratory of biofuels, FTA (Figure 8). The device ensured completely homogenized correct size analytical sample according to standard EN 14780 (2011): Solid biofuels- Sample preparation.

Figure 8. Grinding knife mill Retsch Grindomix GM 100 (Author, 2016).

4.2.2.3 Determination of ash content

Ash content was determined according to standard EN 14775 (2009): Solid biofuels-Determination of ash content in Muffle furnace (Figure 9). Samples were analysed in Laboratory of solid biofuels, FTA. Ash content was defined by calculation of weight of the inorganic residue after combustion of sample in the controlled temperature. Measured ash content was calculated according to formula (1) below. All weightings were performed on the digital laboratory scale KERN (model EW 3000-2M) with readout 0.1 mg.

Figure 9. Muffle furnace LAC (Source: Author, 2015).

Figure 10. Analytical samples after ash content determination (Source: Author, 2015).

During the first stage the empty porcelain crucibles in furnace were heated up to 550 °C for at least 60 minutes. Then the crucibles were cooled on a heat resistant plate for 10 minutes and then transferred to a desiccator without desiccant to ambient temperature cool. One gram of material (analytical sample) was weighed out into the cold crucibles. In the second stage the crucibles were placed into the cold furnace and temperature was continually raised up to 250 °C over a period of 30 minutes. The temperature was maintained for 60 minutes to allow the volatiles to leave the sample before ignition. During next 30 minutes temperature was increased up to 550 °C and maintained at this level for 120 minutes to achieve absolute combustion (Figure 10). Samples were determined triple and as result was considered arithmetic mean of two nearest measurements, whereas the difference between two did not exceed 0.2 %.

$$\boldsymbol{A_d} = \frac{(\boldsymbol{m_3} - \boldsymbol{m_1})}{(\boldsymbol{m_2} - \boldsymbol{m_1})} \cdot \mathbf{100} \cdot \frac{\mathbf{100}}{\mathbf{100} - \boldsymbol{M_{ad}}} [\%] \tag{1}$$

$\mathbf{A_d}$ – ash content [%]

$\mathbf{m_1}$ – weight of the empty porcelain crucible [g]

$\mathbf{m_2}$ – weight of porcelain crucible with wet sample[g]

$\mathbf{m_3}$ – weight of porcelain crucible with ash [g]

$\mathbf{M_{ad}}$ – average moisture content of used sample [%]

4.2.2.4 Determination of Nitrogen, Carbon and Hydrogen content

Nitrogen, Carbon and Hydrogen contents were determined according to standard EN 15104 (2011): Solid biofuels- Determination of total content of carbon, hydrogen and nitrogen-Instrumental method. Element analysis was done by automatic device LECO CHN628 Series Elemental Determinator in the Laboratory of RIAE[12], Prague. The reliable determination of these CHN[13] elements is important for quality control and the results can be used as input parameters for calculations applied to the combustion of solid biofuels.

Figure 11. Determiantor CHN LECO (Source: Author, 2016).

Figure 12. Autoloader CHN (Source: Author, 2016).

Principle of the method is that into the aluminium foil was weighed 0.1 g of dried material (analytical sample) and were made small globule. The sample was loaded into an autoloader and put into the purge chamber to remove atmospheric gas. Further the sample moved to the dual- stage furnace system operated at temperatures up to 1,050 °C with pure

[12] Research Institute of Agricultural Engineering in Prague
[13] Carbon, Hydrogen, Nitrogen

oxygen to ensure complete combustion of all samples. The results were automatically calculated and shown in the computer.

4.2.2.5 Determination of volatile matter content

Content of volatile matter was determined in accordance with standard EN 15148 (2009): Solid biofuels- Determination of the content of volatile matter. It was determined as the loss in mass, less that due to moisture, when a solid biofuel was heated out of contact with air under standardized conditions. Dried analytical sample was burned for seven minutes at 900 °C in oxygen free environment in Muffle furnace ELSKLO MP5 in the Laboratory of RIAE (Figure 13, Figure 14).

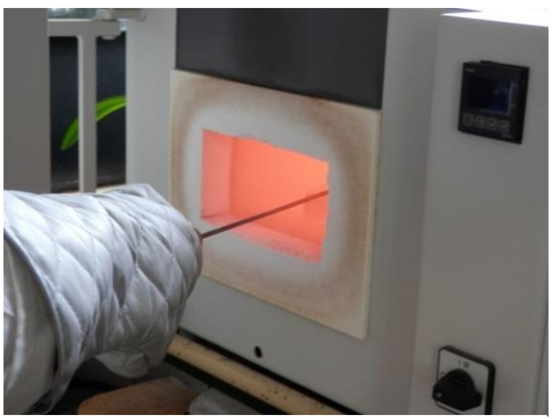


Figure 13. Heated muffle furnace (Source: Author, 2015).

Figure 14. Analytical samples after volatile matter content determination (Source: Author, 2015).

Volatile matter contents under anhydrous conditions are expressed by following formula (2).

$$\boldsymbol{V_d} = \left[\frac{\mathbf{100} \cdot (\boldsymbol{m_2} - \boldsymbol{m_3})}{(\boldsymbol{m_2} - \boldsymbol{m_1})} - \boldsymbol{M_{ad}}\right] \cdot \left(\frac{\mathbf{100}}{\mathbf{100} - \boldsymbol{M_{ad}}}\right) \ [\%] \tag{2}$$

$\boldsymbol{V_d}$ – volatile matter content [%]

$\mathbf{m_1}$ – weight of empty vessel [g]

$\mathbf{m_2}$ − weight of the vessel with sample before heating [g]

$\mathbf{m_3}$ − weight of the vessel with sample after heating [g]

$\mathbf{M_{ad}}$ − average moisture content of used sample [%]

4.2.2.6 Determination of gross calorific value

Gross calorific value was determined according to standard EN 14918 (2009): Solid biofuels- Determination of calorific value in the Laboratory of RIAE, Prague by automatic Calorimetr IKA 6000 (Figure 15). For determination, small pellet with weight about one gram was made from analytical sample by manual press (Figure 16). The amount of heat per unit of weight was released by the complete combustion of the small pellet in the pressure vessel in the calorimeter under compressed oxygen at temperature 22 °C. The results of gross calorific value were automatically calculated and shown on the display of calorimeter after entering the sample weigh.

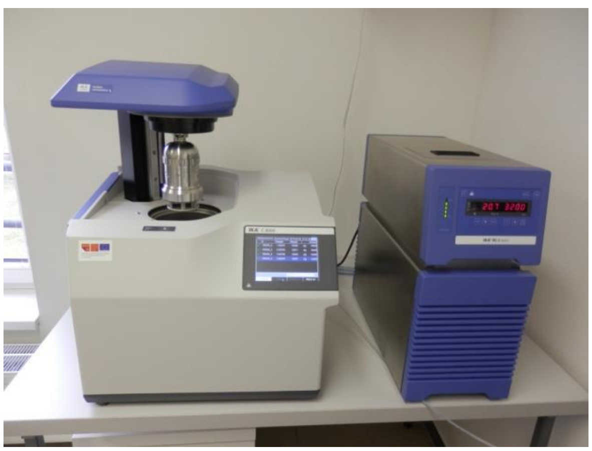


Figure 15. Calorimeter IKA 6000 (Source: Author, 2016).

Figure 16. Prepared pellet in oxygen bomb (Source: Author, 2016).

4.2.2.7 Calculation of net calorific value

The net calorific value was obtained by calculation from the gross calorific value determined on analytical sample by following equation (3) according to standard EN 14918 (2009): Solid biofuels- Determination of calorific value.

$$\boldsymbol{Q_i = Q_{gr} - 24.42 \cdot (M_{ad} + 8.94H)}\ [\mathbf{J}.\boldsymbol{g^{-1}}] \qquad \mathbf{(3)}$$

$\mathbf{Q_i}$ **−** net calorific value $[\mathrm{J.g^{-1}}]$

$\mathbf{Q_{gr}}$ **−** gross calorific value $[\mathrm{J.g^{-1}}]$

$\mathbf{24.42}$ **−** heat of water evaporation

$\mathbf{M_{ad}}$ **−** moisture content [%]

$\mathbf{8.94}$ **−** coefficient for conversion of hydrogen to water

$\mathbf{H}$ **−** hydrogen content [%]

4.2.2.8 Determination of Co, Ni, Cu, Zn, As, Cd, Hg, Pb content

All contents of minor elements were determined according to EN ISO 16968 (2015): Solid biofuels- Determination of minor elements in the Laboratory of Environmental Chemistry in the Interfaculty Centre of Environmental Sciences, CULS.

The freeze-dried and homogenized samples were decomposed in a microwave-assisted wet digestion system with focused microwave heating (Discover SPD-Plus, CEM Inc.). An aliquot (~0.3 g of dry matter, in 3 replicates) of the sample was weighed in a quartz-glass digestion vessel (volume 35 ml) and 6.0 ml of concentrated nitric acid (Analytika Ltd.) was added; the mixture was heated at maximum power 300 W, temperature 180 °C and maximum pressure 21 bar for 12 minutes. After cooling, the solution was quantitatively transferred to plastic polyethylene tubes, filled to 30 ml with MilliQ water and kept at laboratory temperature until measurement. Element contents in the digests were measured by inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7700x, Agilent Technologies Inc.) using no gas mode or a collision cell mode to reduce potential interferences.

4.2.2.9 Determination of residual oil

Residual oil of *Jatropha curcas* L. seed cake was determined according to Classic Soxhlet extraction method in the Department of chemistry, FAFNR. Into the extraction thimble was weighed 10 g of grinded material (analytical sample) with accuracy of 10 mg. The extraction thimble was blocked by cotton (pre-extracted by petroleum ether) and was put into the Soxhlet extractor. Flask with ground glass 250 ml (pre-dried, weighed with accuracy of one milligram) was joint to extractor and was connected with condenser by a few pieces of pumice. 150 ml of petroleum ether was poured into the extractor. Extraction was carried out during four hours and then the device was allowed to cool. The solvent was distilled out from the flask by electric water bath. Flask was put into the preheated oven for 20 minutes then it was cooled in a desiccator and weighed. This procedure was repeated until the difference between two weightings was less than 10 mg.

4.2.2.10 Briquetting process

Briquettes were made using the hydraulic piston briquetting press Brikstar model CS 50-12 made by Briklis Company (Czech Republic) and applied pressure was 18 MPa (Figure 17). Briquetting was carried out at the FE[14], CULS. Briquettes were prepared without any additional binding agents, in original form without grinding and with initial moisture content at the room temperature. Briquettes were done with cylindrical shape length of 30-50 mm and diameter of 65 mm.

Figure 17. Hydraulic piston press Brikstar (Source: Author, 2016).

[14] Faculty of engineering, CULS

4.2.2.11 Compression test

For the determination of the required force to produce compacted briquettes from *Jatropha curcas* L. seed cake, the Universal Testing Machine (Tempos ZDM 50, Czech Republic) and pressing vessel diameter (D) of 60 mm shown in Figure 18 and Figure 19 were used. The preliminary experiment was carried out in the laboratory of Department of Mechanical Engineering, FE1, CULS.

Different compressive forces from 50, 100, 150, 200, 250 and 300 kN were applied at speed of 10 mm·min-1 onto Jatropha seed cake with sample weight of 100 g, measured at initial pressing height (H) of 70 mm in the pressing vessel diameter (D) of 60 mm. The raw material (Jatropha seed cake) had initial moisture content of 7.76 % (a. r.). For comparison, the moisture content of the raw material was increased to 14 % (a. r.) with an addition of water. Experimental data were processed and analyzed by Microsoft Office Excel software (2007).

Figure 18. Universal compression device Tempos ZDM 50 (Source: Kabutey *et al.*, 2015).

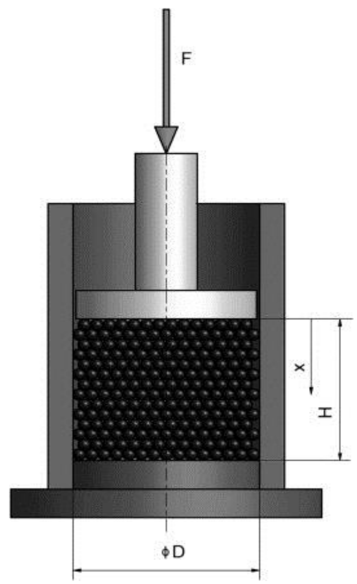


Figure 19. Schematic of pressing vessel (Source: Kabutey *et al.*, 2015).

4.2.2.12 Grinding of the raw material

Jatropha seed cakes for pelletizing were grinded by Hammer mill 9FQ-40C (Pest Control Corporation Company, Czech Republic) containing sieve with holes of 6 mm in diameter.

4.2.2.13 Pelletizing process

For pellets production was used line MGL 200 made by company Kovo Novák (Czech Republic) in the Laboratory of RIAE, Prague (Figure 20). Grinded seed cakes without additives were used as the feed material for pelletizing. Water for pelletizing was added by automatic line mixing device. Pelletizing press consists of flat die with 6 mm hole openings and rollers.

Figure 20. Pelletizing line MGL 200 (Source: KovoNovák, 2016)

4.2.2.14 Determination of dimensions

The length and diameter of pellets were determined according to standard EN 16127 (2012): Solid biofuels- Determination of length and diameter of pellets. The dimensions of representative fuel pellets were measured by using a digital caliper (Figure 21). The length was always measured along the axis of the cylinder and the diameter was measured perpendicularly to the axis. Test portion of 40 pellets was selected with respect to pellet diameter group of 6 mm. The tested portion of pellets was firstly sieved by using a sieve with hole´s diameter of 3.15 mm. As a result was calculated arithmetic mean value expressed to the nearest 0.1 mm.

Figure 21. Length determination of pellet by automatic caliper (Source: Author, 2016).

4.2.2.15 Determination of bulk density

Bulk density was determined according to standard EN 15103 (2009): Solid biofuels-Determination of bulk density in the Laboratory of RIAE, Prague. For solid biofuels with a nominal top size up to 12 mm and for pellets is used small container with height 228 mm and inner dimeter 167 mm. The small container was filled with tested pellets from a height of 200 mm to 300 mm. The filled container was shocked exposed to allow settling by dropping from 150 mm three times. After the container was completely filled to the brim it was weighted. Immediately after determination of bulk density, moisture content was determined according to EN 14774-2 (2009): Solid biofuels- Determination of moisture content- Oven dry method-Total moisture-Simplified method. The result for each determination was calculated to 0.1 $kg.m^{-3}$ and mean value of the results was calculated and rounded to the nearest 10 $kg.m^{-3}$. Samples were determined twice and as result was considered arithmetic mean, whereas the maximum acceptable difference of two measurements for sample with bulk density above 300 $kg.m^{-3}$, did not exceed 2 %.

Bulk density of the sample in original state is calculated according to following formula (4).

$$\boldsymbol{BD_{ar} = \frac{m_2 - m_1}{V}\ [kg.m^{-3}]} \tag{4}$$

$\mathbf{BD_{ar}}$ − bulk density in original state $[\mathrm{kg.m^{-3}}]$
$\mathbf{m_1}$ − mass of empty container [kg]
$\mathbf{m_2}$ − mass of full container [kg]
$\mathbf{V}$ − volume of the container $[m^3]$

Bulk density of the sample in anhydrous state is calculated according to following formula (5).

$$\boldsymbol{BD_d = BD_{ar} \cdot \frac{(100 - M_{ar})}{100}\ [kg.m^{-3}]} \tag{5}$$

$\mathbf{BD_d}$ − bulk density in dry state $[\mathrm{kg.m^{-3}}]$
$\mathbf{BD_{ar}}$ − bulk density in original state $[\mathrm{kg.m^{-3}}]$
$\mathbf{M_{ar}}$ − water content [%]

4.2.2.16 Determination of moisture content

The moisture content of the pellets was determined according to valid standard EN 14774-2 (2009): Solid biofuels- Determination of moisture content- Oven dry method- Total moisture- Simplified method in Laboratory of biofuels, FTA. All weightings were performed on the digital laboratory balance Kern (model EW 3000-2M) with readout 0.1 mg and for determination was used drying oven Memmert (model 100-800).

The oven was heated up to 105 ºC together with empty containers. After the constant temperature was achieved in oven, containers were removed out, cooled in the desiccator with desiccant about 15 minutes to room temperature and weighed. Samples (minimum 300 g of pellets) were put into the weighed containers, weighed together and were dried in the oven at 105 ºC until the weight is constant in mass. After the drying process, the filled containers were removed out, cooled in desiccator and reweighed. The moisture content of samples was calculated by using the following formula (6). Samples were determined twice and arithmetic mean was considered as result.

$$\boldsymbol{M_{ad}} = \frac{(\boldsymbol{m_2} - \boldsymbol{m_3})}{(\boldsymbol{m_2} - \boldsymbol{m_1})} \cdot \mathbf{100}\ [\%] \tag{6}$$

$\mathbf{M_{ad}}$ – moisture content [%]
$\mathbf{m_1}$ – the mass of the empty container[g]
$\mathbf{m_2}$ – the mass of the container plus sample before drying [g]
$\mathbf{m_3}$ – the mass of tcontainer lid plus sample after drying [g]

4.2.2.17 Determination of mechanical durability

Mechanical durability determination of produced pellets was done according to standard EN 15210 - 1 (2009): Solid biofuels- Determination of mechanical durability of pellets by Pellet durability tester in the Laboratory of RIAE, Prague.

For determination mechanical durability was used Pellet tester with rotating steel drum and with speed of 50 revolution per minute (Figure 22). Pellets samples were weighed to reach the total mass of 2.5 kg. The mass of pellets were divided into the four pieces and two of them were sieved through the sieve with size of 3.15 mm (Figure 23). Then there was weighed , two times, 500±10 g of sieved pellets, which were put into the tester for 10 minutes. After the process finished, pellets were weighed again. The mechanical durability was then calculated according to following formula (7).

$$\boldsymbol{DU} = \frac{\boldsymbol{m_A}}{\boldsymbol{m_E}} \cdot \mathbf{100}\ [\%] \tag{7}$$

$\mathbf{DU}$ – mechanical durability[%]
$\mathbf{m_A}$ – weight of pellets after durability testing [g]

$\mathbf{m_E}$ – weight of pellets before durability testing [g]

Figure 22. Pellet durability tester for mechanical durability determination (Source: Author, 2016).

Figure 23. Pellets in sieve of 3.15 mm (Source: Author, 2016).

4.2.2.18 Combustion and thermal emission analysis

Determination of the thermal emission analysis was obtained by combusting of two forms of solid biofuel. Produced Jatropha pellets and *Jatropha curcas* L. seed cakes in initial form were analysed. For comparison of emission concentrations woody pellets were also examined. Research was done in the laboratory on FE, CULS. Selected fuel materials were burned in an automatic pellet boiler, Hot-air boiler KNP-18 made by company Kovo Novák (Czech Republic) with nominal heat output of 18 kW, specifically designed for combustion of pelletized fuels (Figure 24).

Gaseous compounds were measured continuously during the combustion at the flue gas analysis extraction point by Emission Analyzer Madur GA–60 in all experiments (Figure 25). Value of the ambient temperature, flue gas temperature and chemical composition of gases in the range of CO, NO and NO_2 were measured. Experimental data were processed and analyzed by Microsoft Office Excel software. Values were measured in volume fraction concentration (ppm) and were converted to mass concentrations ($mg.m^{-3}$) and also to reference oxygen content O_r= 10 %, that are related to dry flue gas at normal pressure of 101.325 kPa and temperature 0 °C (Malaťák *et al*., 2010). Each fuel was tested for minimally one hour according to regulation. Regression statistical analysis of relationships between variables was used to evaluate of measurements.

Figure 24. Automatic pellet boiler KNP-18 (Source: Author, 2016).

Figure 25. Emission Analyzer Madur GA-60 (Source: Author, 2016).

Based on the values from the direct measurement and from the characteristics of the fuel, the analyzer calculated these following gas components:

$$CO_2 = CO_{2max} \cdot \left(1 - \frac{O_2}{20.95}\right) [\%]$$

(8)

$\mathbf{CO_2}$ – measured carbon dioxide content [%]

$\mathbf{CO_{2max}}$ – maximum content of carbon dioxide measured for given fuel, based on elemental analysis [%]

$\mathbf{O_2}$ – measured oxygen content in volume [%]

$\mathbf{20.95}$ – content of oxygen in air [%]

$$\boldsymbol{NO_x = NO + NO_2} \tag{9}$$

$\mathbf{NO}$ **and** $\mathbf{NO_x}$ − values directly measured in ppm

For correct interpretation of stoichiometric analysis was necessary to use data from complex elemental analysis.

5 Results and discussion

This chapter provides findings from the practical research according to objectives and hypothesis of the thesis and compares it with the relevant findings of other authors. In the first place, results of input properties of the *Jatropha curcas* L. seed cake, ash content, gross and net calorific value, content of minor elements and residual oil content, which highly affect burning behaviour, are presented, followed by main results from briquetting and pelleting processes. Last but not least evaluation of emissions produced during combustion of pellets and the raw material is presented. Majority of results were noted as arithmetic means according to repeatability limit of the current standards for solid biofuels and all values from measurements are available for viewing in Annex 1.

5.1 Properties of *Jatropha curcas* L. seed cake

Physical and chemical properties of initial material were determined and assessed according to EN ISO 17225-6 (2014): Solid biofuels- Fuel specifications and classes, Part 6: Graded non-woody pellets.

5.1.1 Origin and source

According to standard ISO 17225-1 (2014) the raw material was categorized as a Fruit biomass; biomass from the parts of a plant which are from or hold the seeds. *Jatropha curcas* L. seed cake was classed as graded non-woody pellets under the standard.

5.1.2 Ash content

Content of ash of *Jatropha curcas* L. seed cakes was determined according to standard EN 14775 (2009).

Table 2. Ash content of *Jatropha curcas* L.

Material	Ash content d.b.[%]
Jatropha curcas L. seed cakes	6.43

Source: Author, 2016

Table 2 shows measured ash content, which classed the material to the category B according to EN ISO 17225-6 (2014). In accordance with the standard ash content of non-woody pellets may achieve up to 10 %.

In comparison with Hidayat (2014) who presented ash content value 6.1 %, is the value found in the present research comparable. However, is not comparable with the value of 5.48 % which was determined by Kaválek *et al.* (2013) neither with value 4.98 % determined by Sricharoenchaikul *et al*. (2011). In accordance with standard ISO 17225-1 the average ash content of woody biomass, varies between 0.7-3 %, which is much lower than ash content of herbaceous biomass reaches value up to 10 %. Werther *et al*. (2000) reported that woody residues achieve about 0.5 %, coal 4.9 % and in case of agricultural wastes: cotton husk 3.2 %, soya husk 5.1 or pepper wastes 7.4 %.

5.1.3 **Carbon, Hydrogen and Nitrogen content**

Determination of Carbon, Hydrogen and Nitrogen content were done according to EN 15104 (2011). Results are shown in Table 3.

Table 3. Content of C, H, N elements in *Jatropha curcas* L. seed cakes.

Material	N d.b.[%]	C d.b. [%]	H d.b. [%]
Jatropha curcas L. seed cakes	4.08	48.50	6.40

Source: Author, 2016

The effect of nitrogen and carbon content in the fuel is crucial from the viewpoint of emissions which are released during combustion. The material is characterized by high amount of carbon content. Among other things, nitrogen content did not fulfil the requirement of ISO 17225-6 (2014) reported content of nitrogen up to 2 %. Sricharoenchaikul *et al*. (2011) presented similar values of CHN in their study. Carbon content reached up the value of 46.5 %, hydrogen content of 6.04 % and the value of nitrogen content achieved 3.12 %.

5.1.4 **Volatile matter content**

Determination of volatile matter content was done according to EN 15148 (2009). Loo and Koppejan (2008) reported that high volatile matter ranges from 70 to 86 % in case of biomass, which improves the combustion rate of the material. According to Kotlánová (2010) this parameter is important for construction of combustion facilities. Author also claim that volatile matter may create up to 80 % of fuel weight on dry basis and high proportion of the parameter may influence the value of emissions. According to Bridgwater (1991) one of the typical attributes of biomass is high content of volatile matter. Agricultural wastes are characterized by higher contents of the volatile matter. It indicates easier ignition and burning of residues; however, it is expected that combustion will be rapid and difficult to control (Werther *et al.*, 2000). Lower volatile matter causes high smoke and releases toxic gases (Loo and Koppejan, 2008).

Table 4. Volatile mater content of *Jatropha curcas* L.

Material	Volatile matter content d.b.[%]
Jatropha curcas L. seed cakes	72.6

Source: Author, 2016

Table 4 shows that result of volatile matter was 72.6 % in this case. The value is comparable with volatile matter content of 73.0 % for cotton husk, 72 % for coffee husks and 70.5 % for coconut shell (McKendry, 2002). While, in case of wood there is the value of volatile matter about 47 %, fossil fuels reach the lower value, e.g. coal 34 % (Werther *et al.*, 2000).

5.1.5 **Gross and net calorific value**

Calorific value is the main energy parameter of biofuels. The net calorific value (NCV) was calculated on the basis of gross calorific value (GCV) and moisture content according to Formula (3). The results of GCV and NCV of Jatropha seed cakes as received and in dry basis are presented in the Table 5.

Table 5. Average gross and net calorific value.

Material	GCV [MJ.kg^{-1}**]**		NCV [MJ.kg^{-1}**]**	
	a.r.	d.b.	a.r.	d.b.
Jatropha curcas L. seed cakes	19.0	20.5	17.5	19.1

Source: Author, 2016

Gross and net calorific values for several kind of plants are available for viewing in Table 6.

Table 6. GCV and NCV for selected plants in dry basis.

Plant	GCV d.b. [MJ.kg^{-1}]	NCV d.b. [MJ.kg^{-1}]	Source
Hemp	19.6	18.6	Havrland *et al*. (2013)
Sweet sorghum	19.1	17.1	
Miscanthus giganteus L.	19.3	-	
Cotton plant	19.0	-	Stavjarská (2013)
Safflower	17.0	15.5	VEC (2011)
Straw	18.8	14.0	Gabrielová (2007)
Woody biomass	20.1-22.0	19.4-20.8	Jevič *el al*. (2008)

It can be concluded, that Jatropha seed cake is the material with very high gross and net calorific values, which are very close to values of woody biomass. The presented results have reached similar values which noted Kaválek *et al*. (2013). The author stated GCV 19.11 MJ.kg^{-1} and NCV 17.56 MJ.kg^{-1} as received.

Gross and net calorific values of Jatropha pellets correspond to GCV and NCV of Jatropha seed cakes in dry basis. According to EN ISO 17225-6 (2014) produced pellets fulfil NCV requirements of category A of graded non-woody pellets which is given by NCV higher than 14.5 MJ.kg^{-1} on dry basis. NCV of Jatropha pellets is comparable with woody pellets where NCV ranges between 16 to 19 MJ.kg^{-1}.

5.1.6 **Minor elements content**

Chemical analysis of minor elements was determined according to EN ISO 16968 (2015). Results from determination of minor elements are shown in Table 7.

Table 7. Content of minor elements in Jatropha seed cakes.

Element	Content d.b.[$mg.kg^{-1}$]
Co	0.135
Ni	0.307
Cu	7.601
Zn	17.150
As	0.030
Cd	0.004
Hg	0.010
Pb	0.147

Source: Author, 2016

All of studied minor elements were in the limits given by standard ISO 17225-6 (2014) for graded non-woody pellets thus the material is classed into the category A. Therefore, could be *Jatropha curcas* L. seed cake safely used as a biofuel in common combustion facilities. Baernthaller *et al*. (2006) state that content of minor elements influences concentration of particular emissions produced during combustion, and content of ash which is used as a fertilizer. Generally, sources of minor elements in the biomass are related to way of primary treating and manipulating with the material (Kotlánová, 2010).

5.1.7 **Residual oil content**

Research of residual oil content was done by Classic Soxhlet extraction method and the result is reported in Table 8.

Table 8. Residual oil content of *Jatropha curcas* L.

Material	Residual oil d.b.[%]
Jatropha curcas L. seed cakes	5.5

Source: Author, 2016

The residual oil content was found of 5.5 %. The residual oil content does not tend to seed cake water intake and also increases the calorific value (Pambudi *et al*., 2012; Kaválek *et al*., 2013). The founded value is not comparable with value of Hidayat (2014) study, where 12.0 % of residual oil was reported or with value of 17 % noted by NIIR Board (2008). Generally, seed cakes contain residual oil up to 12 % of the weight.

5.2 Processing of Jatropha seed cakes to solid biofuel

An attractive way of biomass utilization for energy purposes is solid biofuel production through the briquetting or pelleting process. Biomass produced according to this process gets added value and provides unsophisticated transportation and storage.

5.2.1 **Briquettes production**

As shown in Figure 26, it was founded that the raw material without any additives could not join together and production of compatible briquettes was not feasible under the given conditions with the pressure of 18 MPa. This fact could be probably caused by low initial moisture content which was 7.76 % or by lower pressure. Commonly moisture content of the feedstock material for briquetting below 15 % is recommended. However according to Kers *et al.* (2010) the optimum moisture content of briquetting material should be between 10-18 %. Authors claim that MC above 18 % and below 10 % causes inconsistent briquette particles and briquettes are falling to pieces.

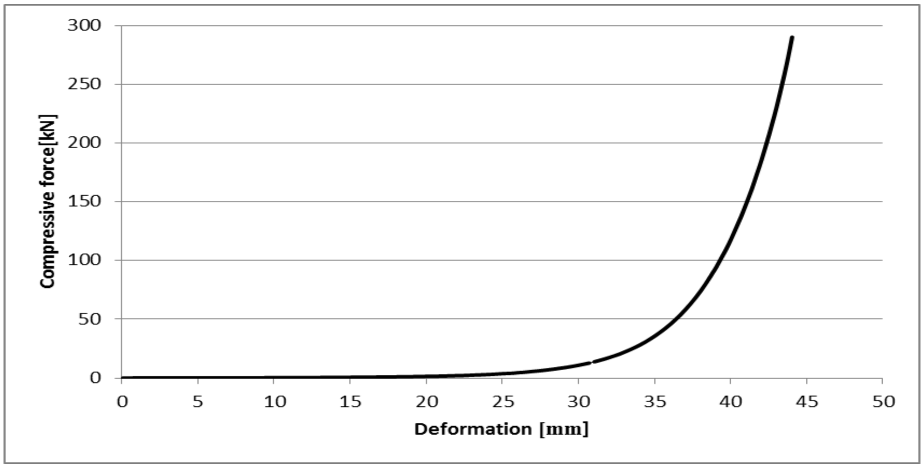
Figure 26. Unfeasible Jatropha briquettes production (Source: Author, 2016).

5.2.1.1 Compression testing

Due to the fact that Jatropha seed cake with the initial moisture content of 7.76 % (a.r.) could not be compacted to produce briquettes without additives under hydraulic piston briquetting press Brikstar (model CS 50-12, Briklis Company, Czech Republic) with an applied pressure of 18 MPa, the material was tested under compression loading. It was proved to be the dependency between compressive force needed for production of briquette quality and moisture content.

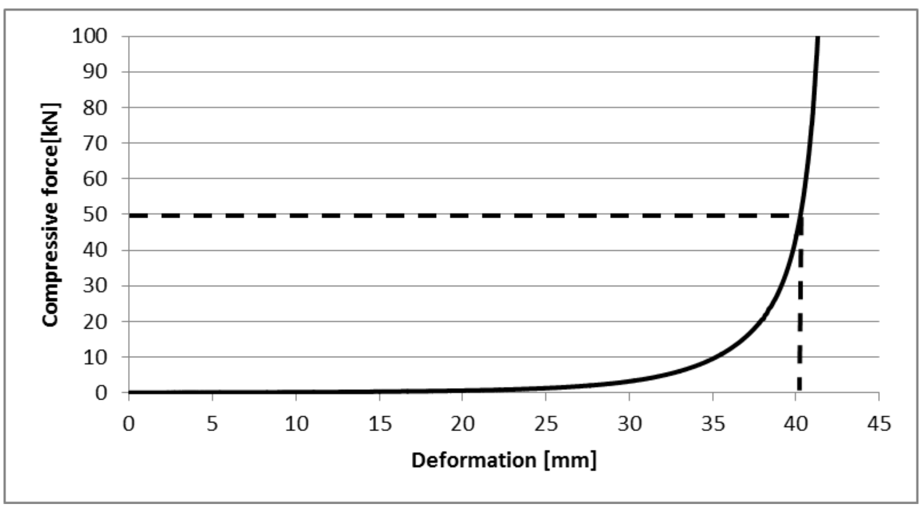
Figure 27. Briquette produced by applying compressive force of 300 kN (Source: Author, 2016).

Using a compressive force of **300 kN** produced a compacted form of briquette. Application of any other lower forces did not allow compatible briquette. Although, the briquette was obviously compatible, with mere touched of the hand, it was easily crumbled. This effect can be observed in Figure 27 above. Graph 3 below, represents behaviour of seed cake at force 300 kN. Based on the area under the graph, it is clear that the process of briquette production under compression loading is economically and energetically demanding.



Graph 3. Deformation curve at compressive force of 300 kN (Source: Author, 2016).

Applying a compressive force of 50 kN on the moistened material also produced compacted briquette. To improve the briquette quality or better compaction, a compressive force of 100 kN was also applied on the moistened material. The deformation curve, Graph 4, suggests that if the moisture content of the material is increased, then the energy demand for the compaction process will reduce.



Graph 4. Deformation curve at compressive force of 100 kN similar to 50 kN (Source: Author, 2016).

The preliminary compression test showed that the production of briquettes with high compressive forces is feasible, but it is economically and energetically demanding and inefficient. Increasing moisture content of initial material can improve feasibility of the production and quality of the briquettes. However, repeated or further research is needed to confirm the findings provided herein. The procedure has to be done carefully, because of briquettes susceptibility to mould inclination during storage. Kers et al. (2010) found that optimum MC of material for briquetting should be between 10 and 18 % (a.r.) as was mentioned in previous chapter. For production of compacted briquette, application of lower force could be sufficient depending on the quality and moisture content of the material.

5.2.2 **Pellets production**

Produced pellets were tested according to specifications given by international standard for Graded non-woody pellets ISO 17225-6 (2014). The comparison of tested specifications and specifications given by standard are shown in the Table 13 (chapter 5.2.2.5 below). *Jatropha curcas* L. pellets were made from grinded residual seed cakes. Majority of physical and chemical tests of produced pellets were determined on analytical sample, due to the identical internal characteristic of produced pellets and used seed cakes

5.2.2.1 Dimensions and shape

The shape of produced pellets shown in Figure 28 was specified in accordance with ISO 17225-1 (2014). The length and diameter dimensions were determined according to standard EN 16127 (2012). The results are shown in Table 9.

Table 9. Diameter and length of pellets made of *Jatropha curcas* L. seed cakes.

Material	Length [mm]	Diameter [mm]
Jatropha curcas L. pellets	23.4	6.3

Source: Author, 2016

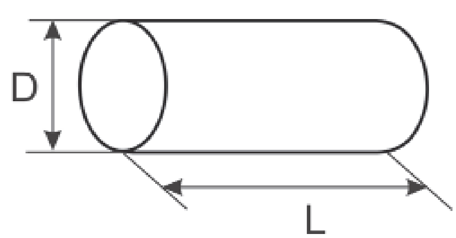


Figure 28. Shape of produced pellets (Source: ISO 17225-1, 2014).

The diameter of produced pellets was on average 6.3 mm. Generally it is more or less given by diameter of flat die which was 6 mm in this study. Therefore diameter of produced pellets varied around this value and was affected by adhesion properties of material and storage of pellets after pelleting. Slight expansion was observed during measuring and final pellets had diameter dimensions up to 0.4 mm larger. The length of the pellets was on average 23.4 mm. Brožek *et al*. (2012) state that the length of fuel is influenced by particle size of used material. Authors reported that finer crushed material is better feed to the chamber than coarse one. The cylindrical shape of pellets was given by the shape of matrix.

According to ISO 17225-6 (2014) non-woody pellets may reach values of 6-10±1 or 12-25±1mm in diameter and 3.15-50 mm in length thus the produced Jatropha pellets were categorized into the class A. Similarly in comparison with woody pellets, for non-industrial use, it may achieve values of 6±1 or 8±1 mm in diameter and 3.15-50 mm in length.

5.2.2.2 Bulk density

The bulk density assessment was done according to standard EN 15103 (2009). The low densities of the residues complicate their processing, transportation, storage and efficiency of burning (Werther *et al*., 2000). Table 10 shows average bulk density as received and also bulk density on dry basis of Jatropha pellets.

Table 10. Bulk density of *Jatropha curcas* L. pellets.

Material	Bulk density a.r. [$kg.m^{-3}$]	Bulk density d.b. [$kg.m^{-3}$]
Jatropha curcas L. pellets	623	559

Source: Author, 2016

According to EN ISO 17225-6 (2014) pellets fulfil limitations for category A, where bulk density is required higher than 600 $kg.m^{-3}$ as received. The performed results indicate that Jatropha pellets reach high values which encourage transporting and storage. Bulk density of Jatropha pellets is comparable with the bulk density of brown coals ranges from 560-600 $kg.m^{-3}$. While most agricultural wastes have very low bulk densities; for example chopped straw 50-120 kg.m^{-3} and rice husks 122 kg.m^{-3}, the woody pellets ranges between 560-630 kg.m^{-3} as well as values founded in the present research (McKendry, 2002).

5.2.2.3 Moisture content

Moisture content of pellets produced from Jatropha seed cakes is presented in the Table 11. According to the technical standard ISO 17225-1 (2015) moisture content of quality solid biofuels should not exceeds 15 %(a.r.) The moisture content of solid biofuels is one of the most important parameters that affect mainly net calorific value of fuel and transport or storage properties. According to EN ISO 17225-6 (2014) pellets fulfil limitations for category A, where required moisture content is below 12 % (a.r.). Therefore pellets could be classified into the category M12.

Table 11. Moisture content of Jatropha pellets.

Material	Moisture content a.r. [%]
Jatropha curcas L. pellets	10.26

Source: Author, 2016

Moisture content of the Jatropha pellets shown in Table 11 is slightly above to the moisture content of woody pellets with diameter of 6 mm, which ranges between 3-10 % (a.r.). According to McKendry (2002) the presented value is comparable with 11 % (a.r) MC of coal.

5.2.2.4 Mechanical durability

The mechanical durability was determined according to EN 15210 - 1 (2009). The results are presented in Table 12 and calculated by using Formula (7). Mechanical durability is one of the most important parameter of solid biofuel due to their storage, transportation as well as commercialization. The parameter is especially important for those pellets, which are manipulated and fed into the combustion facilities (Kotlánová, 2010).

Table 12. Mechanical durability of Jatropha pellets.

Material	Mechanical durability a.r. [%]
Jatropha curcas L. pellets	70.28

Source: Author, 2016

Durability is the main parameter used to describe the physical quality of densified solid biofuels. As Carroll and Finnan (2012) claim, pellets are very susceptible to physical wear and tear which leads to the production of fine particles or dust during transport and storage. According to EN ISO 17225-6 (2014) pellets did not fulfil limitations for category A neither for category B, where is required mechanical durability more than 96 %. The requirements for woody pellets according to standard ISO 17225-1 (201) range from 97.5-96.5 %.

5.2.2.5 Summary and comparison of pellets properties

The comparison of tested specifications and specifications given by standard are shown in the Table 13.

Table 13. Properties of Jatropha pellets evaluated according to ISO 17225-6:2014.

Property class	Unit	Result	Limitation	Evaluation
Origin and source		Fruit biomass	Herbaceous biomass Fruit biomass Aquatic biomass Blends and mixtures	fulfilled
Dimension Diameter, Length	mm	6.31 (D) 23.39 (L)	D06 to D25 $3.15 < L \leq 50$	fulfilled
Moisture	w-% a.r.	10.26	$M \leq 15$	fulfilled
Ash	w-% d.b.	6.43	$A \leq 10$	fulfilled
Mechanical durability	w-% a.r.	70.28	$DU \geq 96.0$	**unfulfilled**
Additives	w-% a.r.	0	≤ 5	fulfilled
Bulk density	$kg.m^{-3}$a.r.	623	$BD \geq 600$	fulfilled
Net calorific value,	$MJ.kg^{-1}$ d.b.	19.1	$Q \geq 14.5$	fulfilled
Nitrogen, N	w-% d.b.	4.8	$N \leq 2.0$	**unfulfilled**
Arsenic, As	mg. kg^{-1} d.b.	0.031	$As \leq 1$	fulfilled
Cadmium, Cd	mg. kg^{-1} d.b.	0.004	$Cd \leq 0.5$	fulfilled

Copper, Cu	mg. kg^{-1} d.b.	0.135	Cu ≤ 20	fulfilled
Lead, Pb	mg. kg^{-1} d.b.	0.147	Pb ≤ 10	fulfilled
Mercury, Hg	mg. kg^{-1} d.b.	0.010	Hg ≤ 0.1	fulfilled
Nickel, Ni	mg. kg^{-1} d.b.	0.307	Ni ≤ 10	fulfilled
Zinc, Zn	mg. kg^{-1} d.b.	17.150	Zn ≤ 100	fulfilled

Source: Author, 2016

From Table 13 is evident, that pellets without any additives fulfilled most of the standard properties except mechanical durability and nitrogen content. While mechanical durability has impact on manipulation entirely (chapter 4.2.2.17), nitrogen content influences emission concertation of NO and NO_2 (chapter 4.2.2.18).

5.3 Evaluation of combustion process and emission concentrations

Determination of emissions concentration was compared to burning of Jatropha pellets, Jatropha seed cakes in initial form and in form of woody pellets. Biofuels were combusted in Hot-air boiler with nominal heat output of 18 kW. Table 14 noted selected final values of analysis, which were indicated for the normal conditions, i.e. at a temperature T= 0 ° C, pressure p= 101.325 kPa and reference oxygen content in the flue gas O_r= 10 %. Results at Table 14 were found out based on complex stoichiometric analysis located in Annex 2, Annex 3 and Annex 4.

5.3.1 **Evaluation of combustion process**

During combustion process was found out, that in the current state is possible to burn seed cakes in automatic pellet boiler. However, the process of combustion of this material was not fluent. The seed cakes were constantly blocking the fuel feeder and constant intake of fuel to combustion chamber was significantly limited. When dosing was possible, the flame was strongly suffocated by intake of fuel. Therefore the fuel was completely burnt, which is related to high concentration of flue gas and high amount of ash. According to Černý (2013) energetically feasible biomass is not possible to use directly in combustion facilities. Although during burning of Jatropha pellets, there were no visible problems during combustion. The burning was continual without any signs of interruption. Ash content also reaches higher values, but still fulfils limitations for biomass combustion.

5.3.2 Evaluation of emission concentration

The results of emissions concentration measured in this research are presented in the Table 14.

Table 14. Concentration of emissions in produced solid biofuel.

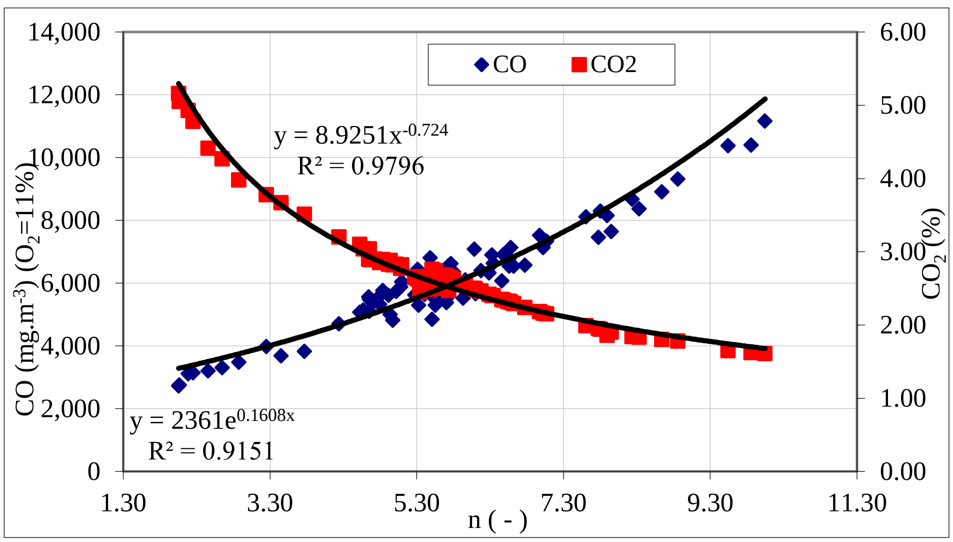
Type of biofuel	CO [mg.m^{-3}]	CO_2 [%]	NO_x [mg.m^{-3}]
Jatropha seed cakes	6,109.7	2.7	857.0
Jatropha pellets	2,923.3	2.8	1,312.4
Woody pellets	624.8	3.0	328.4

Source: Author, 2016

Several authors published studies about influences of different kinds of fuels on emissions quantities (Olsson, 2006; Trozzi, 2006; Rabaçal *et al*., 2013). Kaválek (2015) reported that also power input of stove significantly influenced emission factor. Author claimed that with power input increasing, amount of emissions is lower.

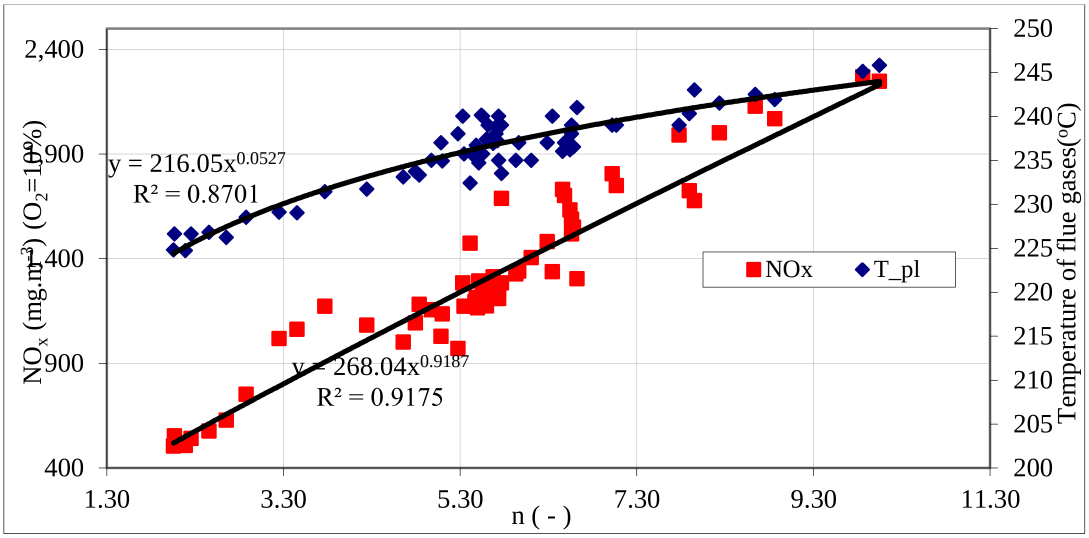
According to standard EN 303-5 (2012), only the **CO** emission limit is defined for biomass combustion in a boiler with automatic fuel feeder of maximum rated capacity 50kW and the value is 3,000 mg.m^{-3}. Carbon oxide is formed during the incomplete burning. Despite of the fact, that CO contributes twice more to global warming, compared with carbon dioxide, is not included between the major greenhouse gases (Malaťák *et al*., 2010). Research showed that, by combustion of Jatropha pellets the CO emissions were on the border with standard limit. In case of initial material (Jatropha seed cake) burning, limits were exceeded more than two times. In the comparison with woody pellets, which achieved value of almost 625 mg.m^{-3}, used alternatives have significantly higher concentrations (Table 14). As results from CHN analysis (chapter 5.1.3) show, Jatropha seed cakes are material with very high carbon content, which influenced the concentration of carbon oxides during combustion.

CO_2 is a significant greenhouse gas, with a long atmospheric lifetime. No specific lifetime for carbon dioxide can be determined because it is continuously cycled between the atmosphere, oceans and land biosphere and its net removal from the atmosphere involves a range of processes with different time scales (Alakoski *et al*., 2016). Quantity of CO_2 emission from fossil fuels combustion creates only about 4 % of the total amount of CO_2 coming into the atmosphere (Malaťák *et al*., 2010). Comparison of CO_2 expressed as a percentage in Table 14 claimed, that values for all these three materials are very similar. Graph 5 below graphical represents of the course of CO and CO_2 concentrations depending on the excess air coefficient (n) during the combustion of Jatropha seed cakes. Dependencies during the other fuel combustion you can see in referred annexes.



Graph 5. Dependency of CO and CO_2 on the excess air coefficient in Jatropha seed cake (Source: Author, 2016).

Emissions **NO_x** indicate harmful substances NO and NO_2. As it can be seen in Table 14 the woody pellets creates the lowest produced NO_x values. The highest concentration of NO_x emissions was produced by Jatropha pellets. The value exceeded the concentration produced by Jatropha seed cakes. According to CHN analysis, Jatropha material reached high concentrations of nitrogen content thereby did not fulfil standard limitations (see Table 13). This fact has impact on high concentrations of NOx emissions. According to Kaválek *et al.* (2013) the abundance is caused by residual oil presence, too. Malaťák *et al*. (2010) claimed that quantity of NOx formation increases with the increasing combustion temperature (T_pl), with increasing excess air ratio (n) and also with longer residence time of flue gases in the combustion chamber. The effect is preferably observable during the Jatropha pellets combustion (Graph 6). Effects on the combustion of other two kinds of fuel are available for viewing in Annex 3 and Annex 4.



Graph 6. Dependency NO_x on temperature and excess air ratio in Jatropha pellets (Source: Author, 2016).

6 Conclusion

Solid biofuels made of waste biomass are suitable alternative sources of energy that have many benefits comparing to fossil energy sources.

Presented diploma thesis was focused on the above topics, especially on searching for appropriate methods of *Jatropha curcas* L. seed cake for energy purposes. Results from research as well as the relevant findings of other authors were formulated. Lastly, the recommendation for future research is presented. The research results demonstrated the suitability of the *Jatropha curcas* L. seed cakes for energy purposes, primarily due to its physical, mechanical and chemical properties. The material is distinguished by very low initial moisture content and it is characterized by high net calorific value.

Research partly confirmed the **first hypothesis**. Experiment founded, that *Jatropha curcas* L. seed cakes is the material suitable for pellets production without any additives. Produced pellets fulfill almost every limitation of standard ISO 17225-6, especially bulk density and calorific value. Mechanical durability was found as the weakest property, which negatively affects the manipulating with material. Also Nitrogen content did not fulfil the requirements. The higher Nitrogen content caused the higher concentration of NO_x during released combustion.

Research partly confirmed the **second hypothesis**. It was founded, that from *Jatropha curcas* L. seed cake in initial form without any kind of additives or water, was not feasible to produce briquettes during applying common pressure of 18 MPa. Nevertheless, the research identified feasibility of experiment, in case of high compression forces (300 kN) application, for briquette production. Such kind of production process is completely ineffective, due to high energetic and economic demands. On the other hand, preliminary compression test shown the dependence between compressive force, needed for compatibility of the briquette and moisture content. It was found that with additional moistening, the lower compressive forces could be used to produce quality and compactable briquettes

Research partly confirmed the **third hypothesis.** During thermal emission analysis was found out, that it is possible to burn seed cakes in automatic pellet boilers, but the combustion is not stable a fluent, because the fuel is blocking the fuel feeder. During the combustion, excessive concentrations of CO are released, which are many times over the limitations; however, in comparison to Jatropha pellets, concentrations of NO_x are lower. Based on the research results the pellets showed themselves as a better fuel in comparison with seed cakes, especially due to much lower concentrations of CO, which fulfils standard emission limit.

6.1 Recommendation for further research

Jatropha seed cakes in initial form could be used as a local fuel in classic stoves without any adjustments, which is a big advantage due to decreasing costs comparing to compacted biofuels. The present research proved that combustion of seed cakes in automatic boilers is problematic, what is why it is recommended to focus further research on selection of an appropriate fraction of the seed cake material for automatic combustion equipment.

Further improvement of pellet´s mechanical durability is needed for better and comfortable manipulation. It is suggested to mix the Jatropha seed cake biomass with another material for higher durability; for example woody sawdust, limestone, corn or cassava starch and other Jatropha wastes could be tasted. Mixing with another material is recommended also due to the question of NO_x emission decreasing.

Economical study of the whole pelletizing process is recommended due to the fact, that pellets made of *Jatropha curcas* L. seed cakes have generally positive properties.

It is advisable to perform a detailed further research of the water addition influence on quality and compatibility of Jatropha briquettes.

7 References

Abdelgadir HA, Van Staden J. 2013. Ethnobotany, ethnopharmacology and toxicity of Jatropha curcas L. (Euphorbiaceae): A review. South African Journal of Botany 88: 204–218.

Achten WMJ, Verchot L, Franken YJ, Mathijs E, Singh VP, Aerts R, Muys B. 2008. Jatropha bio-diesel production and use. Biomass and bioenergy 32: 1063–1084.

Alakangas E, Virkkunen M. 2007. Biomass fuel supply chains for solid biofuels: From small to large scale. Eubionet. 32p.

Alakoski E., Jamsen M, Agar D, Tampio E, Wihersaari M. 2016. From wood pellets to wood chips, risks of degradation and emissions from the storage of woody biomass: A short review. Renewable and Sustainable Energy Reviews 54: 376-383.

Andert D, Sladký V, Abrham Z. 2006. Energetické využití pevné biomasy. Praha. Výzkumný ústav zemědělské techniky Praha. 59 p.

Baernthaler G, Zischka M, Haraldsson C, Obernberger I. 2006. Determination of major and minor ash-forming elements in solid biofuels. Biomass and Bioenergy 30 (11): 983-997.

Biomuber.2015. Oil from Jatropha curcas. Available at http://biomuber.com/services--products.html: Accessed 2016-01-29.

BP Global. 2015. Renewable energy. Available at http://www.bp.com/en/global/corporate/search.html?q=renewable+energy&_charset_=UTF-8: Accessed 2016-02-01.

Bridgwater, A.V. 1991. An Overview of Thermochemical Biomass Conversion Technologies. Bristol : Fuel for Thought Conference.

Brittaine R, Lutaladio N. 2010. Jatropha: A Smallholder Bioenergy Crop, The Potential for Pro-Poor Development. Roma: FAO. 97p.

Brožek M, Nováková A, Kolářová M. 2012. Quality evaluation of briquettes made from wood waste. Journal of Agricultural Engineering Research 58: 30–35.

Carels N. 2011. The Challenge of Bioenergies: An Overview. dos Santos Bernardes MA editor. Biofuel’s Engineering Process Technology: 23–64.

Carroll JP, Finnan J. 2012. Physical and chemical properties of pellets from energy crops and cereal straws. Biosystems Engineering 112(2): 151-159.

Celjak I. 2008. Biomasa je nezbytná součást lidského života. Biom.cz. Available at http://biom.cz/cz/odborne-clanky/biomasa-je-nezbytna-soucast-lidskeho-zivota: Accessed 2014-04-13.

Contran N, Chessa L, Lubino M, Bellavite D, Roggero PP, Enne G. 2013. State of the art of the Jatropha Curcas Productive Chain: From Sowing to Biodiesel and By-products. Industrial Crops and Products 42: 202–215.

Cuaresma CA, Elauria JC, Suminustrado DC, Elauria MM. Utilization of Jatropha (Jatropha curcas L.) Wastes for Charcoal Briquettes. Journal of the Japan Institute of Energy 94: 1110-1119.

Černý D. 2013. Stanovení tepelně-emisních vlastností malých spalovacích zařízeních při spalování organických odpadů. Závěrečná zpráva o řešení interního grantu TF ČZU za rok 2013. 31p.

DEGJSP. 2012. Farmer´s handbook: Advice on growing Jatropha curcas in East Africa. Nairobi: Pipal Limited. 12p.

Devappa RK, Makkar HPS, and Becker K. 2010. Jatropha Toxicity—A Review. Journal of Toxicology and Environmental Health 13 (6): 476–507.

Dimpl E. 2011. Small-scale Electricity Generation from Biomass Part III: Vegetable Oil. Eschborn: GIZ.

Directive 2009/28/EC. 2009. use of energy from renewable sources. Official Journal of the European Union. 47p.

Dorp M. 2013. Local energy utilization from Jatropha curcas. Global Sustainable Biomass Fund. 40p.

Edrisi SA, Dubey RK, Tripathi V, Bakshi M, Srivastava P, Jamil S, Singh HB, Singh N, Abhilash PC. 2015. Jatropha curcas L.: A crucified plant waiting for resurgence. Renewable and Sustainable Energy Reviews 41: 855–862.

EN 303-5. 2012. Heating boilers – Part 5: Heating boilers for solid fuels, manually and automatically stoked, nominal heat output of up to 500 kW – Terminology, requirements, testing and marking. BSI Standards Publication. 70p.

EN 14774-2. 2009. Solid biofuels- Determination of moisture content- Oven dry method- Total moisture-Simplified method. BSI Standards Publication. 10p.

EN 14775. 2009. Solid biofuels- Determination of ash content. BSI Standards Publication. 12p.

EN 14780. 2011. Solid biofuels- Sample preparation. BSI Standards Publication.28p.

EN 14918. 2009. Solid biofuels- Determination of calorific value. BSI Standards Publication. 64p.

EN 15103. 2009. Solid biofuels- Determination of bulk density. BSI Standards Publication. 16p.

EN 15104. 2011. Solid biofuels- Determination of total content of carbon, hydrogen and nitrogen-Instrumental method. BSI Standards Publication. 18p.

EN 15148. 2009. Solid biofuels- Determination of the content of volatile matter. BSI Standards Publication. 16p.

EN 15210-1. 2009. Solid biofuels- Determination of mechanical durability of pellets. BSI Standards Publication. 14p.

EN 16127. 2012. Solid biofuels- Determination of length and diameter of pellets. BSI Standards Publication. 9p.

EN ISO 16559. 2014. Solid biofuels – Terminology, definitions and descriptions. BSI Standards Publication. 44p.

EN ISO 16968. 2015. Solid biofuels- Determination of minor elements. BSI Standards Publication. 22p.

EN ISO 17225-6. 2014. Solid biofuels- Fuel specifications and classes, Part 6: Graded non-woody pellets. BSI Standards Publication. 18p.

European Commission. 2015. Renewable energy: Moving towards a low carbon economy. Available at https://ec.europa.eu/energy/en/topics/renewable-energy: Accessed 2016-02-01.

European Commission. 2016. Second generation of biofuels ready for roll-out. Available at https://ec.europa.eu/energy/en/news/second-generation-biofuels-ready-roll-out: Accessed 2016-02-02.

FACT. 2007. Position Paper on Jatropha curcas L. State of the artsm, alland large scale project development. Fuels from Agriculture in Communal Technology.

FACT. 2010. The Jatropha Handbook: From Cultivation to Application. Eindhoven: The FACT Foundation. 172p.

FAO. 2009. Small-Scale Bioenergy Initiatives: Brief description and preliminary lessons on livelihood impacts from case studies in Asia, Latin America and Africa. Available at ftp://ftp.fao.org/docrep/fao/011/aj991e/aj991e.pdf: Accessed 2016-01-27.

Faik A. 2013. Plant Cell Wall Structure-Pretreatment, the Critical Relationship in Biomass Conversion to Fermentable Sugars. Tingyue G editor. Green Biomass Pretreatment for Biofuels Production. New York: Springer, p1–30.

FAO. 2010. Jatropha: A Smallholder Bioenergy Crop - The Potential for Pro-Poor Development.

Ferry S, Cabraal A. 2006. Renewable Power in Developing Countries: Winning the War on Global Warming. PennWell Corporation, p42-43.

Gabrielová H. 2007. Nepotravinářské využití zemědělské půdy. České Budějovice: Calla - Sdružení pro záchranu prostředí. 8p.

Gour VK. 2006. Production practices including post-harvest management of Jatropha curcas: Biodiesel Conference Towards Energy Independence: 223-251

GreenOdin. 2014. Biomass feedstock- Jatropha. Available at http://greenodin.com/products/go-biodiesel/go-biomass-feedstock/jatropha/: Accessed 2016-01-25.

Grover PD, Mishra SK. 1996. Regional wood energy development programme in Asia, fild document No. 46: Biomass briquetting: Technology and practices. Bangkok (Thailand): Food and Agriculture Organization of the United Nation. 43p.

GTZ. 2009. Jatropha reality check: a field assessment of the agronomic and economic viability of jatropha and other oilseed crops in Kenya. Nairobi: GTZ – Regional Energy Advisory Platform (East Africa). 158p.

Gui MM, Lee KT, Bhatia S. 2008. Feasibility of edible oil vs. non-edible oil vs. waste edible oil as biodiesel feedstock. Energy 33(11): 1646-1653.

Hammond EG, Lawrence AJ, Caiping S, Tong W, Pamela JW. 2005. Bailey´s Industrial Oil and Fat Products: Soybean oil. Iowa: Iowa State University Ames. 3616p.

Havrland B, Ivanova T, Kordon BL, Kolaříková M. 2013. Comparative analysis of bio-raw materials and biofuels. Jelgava: Engineering for rural development. 541-544.

Hidayat H. 2014. Jatropha Seed Cake Valorization for Non-Food Applications [PhD.]. University of Groningen. 126p.

IEEJ. 2009. Jatropha curcas L.: Development of a new oil crop for biofuel (Summary). New and renewable energy group.

ISO 17225-1. 2014. Solid biofuel-Fuel specifications and classes- Part 1: General requirements. International Organization for Standardization.56p.

Ivanova T. 2012. Research of Energy Plants Processing to Solid Biofuels [PhD.]. Prague: Czech university of life sciences Prague. 142p.

Janick J, Paull RE. 2008. The Encyclopedia of Fruit & Nuts. CABI. 954p.

Jansen RA. 2013. Second generation biofuels and biomass: Assential guide for investors, scientists and decision makers. Weiheim: Wiley-VCH. 261p.

Jatropha Curcas Plantations. 2013. Available at http://www.jatrophacurcasplantations.com/jatropha-curcas-seeds.htm: Accessed 2013-12-10.

Jevič P, Hutla P, Šedivá Z. 2008. Udržitelná výroba a řízeni jakosti tuhých paliv na bázi agrárních bioproduktů: Faktory ovlivňující kvalitu tuhých biopaliv a potenciál biomasy a biopaliv. Metodická příručka Mze ČR. Praha: VÚZT. 124p.

Jevič P, Dubrovin VO, Porev IA, Malaťák J. 2009. Operational parameters of small-capacity biopellets production and mechanization level for their application in heating of houses with energy low consumption. 6th CEE AgEng conference: Institute of Agriculture Engineering LUA: 241-248.

Johasnsson LS, Tullin C, Leckner B, Sjovall P. 2003. Particle emissions from biomass combustion in small combustors. Biomass and Bioenergy 25 (4): 435-446.

Joil. 2014. Bioenergy for a sustainable future. Available at http://www.joil.com.sg/22/map-showing-jatropha-belt: Accessed 2016-02-02.

Jongschaap REE, Corre WJ, Bindraban PS, Brandenburg WA. 2007. Claims and Facts on Jatropha curcas L: Global Jatropha curcas Evaluation, Breeding and Propagation.

Kabutey A, Herák D, Chotěborský R, Sigalingging R, Mizera Č. 2015. Effect of compression speed on energy requirement and oil yield of *Jatropha curcas* L. bulk seeds under linear compression. Biosystems engineering 136: 8-13.

Kaliyan N, Morey RV. 2009. Factors affecting strength and durability of densified biomass products. Biomass and Bioenergy 33: 337–358.

Kaválek M. 2015. Testing possibility of using waste material (Kernel Shells of Oil palm) from palm oil extraction as solid fuel [PhD.]. Prague: Czech University of Life Sciences Prague. 87p.

Kaválek M, Havrland B, Ivanova T, Hutla P, Skopec P. 2013. Utilization of Jatropha curcas L. seed cake for production of solid biofuels. Engineering for rural development: 536-540.

Kers J, Kulu P, Aruniit A, Laurmaa V, Križan P, Šooš L, Kask Ü. 2010. Determination of physical, mechanical and burning characteristics of polymeric waste material briquettes. Estonian Journal of Engineering 16 (4): 307-316.

Koh MY, Ghazi TIM. 2011. A review of biodiesel production from Jatropha curcas L. oil. Renewable and Sustainable Energy Reviews 15: 2240-225.

Kott J. 2010. Výroba pelet z biomasy - technické a ekonomické aspekty. Available at http://biom.cz/cz/odborne-clanky/vyroba-pelet-z-biomasy-technicke-a-ekonomicke-aspekty: Accessed 2016-06-04.

Kotlánová A. 2010. Metody zkoušení fyzikálně-chemických vlastností tuhých biopaliv. Biom.cz. Available at http://biom.cz/cz/odborne-clanky/metody-zkouseni-fyzikalne-chemickych-vlastnosti-tuhych-biopaliv: Accessed 2016-04-09.

KovoNovák. 2016. Pelletizing line MGL 200. Available at http://www.kovonovak.cz/cs/mala-granulacni-linka: Accessed 2016-04-21

Kumar A, Sharma S. 2008. An evaluation of multipurpose oil seed crop for individual uses (Jatropha curcas L): A review. Industrial crops and products 28: 1-10.

Laustsen B. 2010. Jiko Bomba. Improved Biomass Cooking Stoves. Available at http://www.jatropha.pro/PDF%20bestanden/Conference%20Presentations-NJC/Friday%20SESSION%201%20Economics/Presenter%202,%20UDSM%20&%20BJARNE,%20NJC,%202011%2003%2004_2.pdf: Accessed 2016-02-10.

Lehmann J, Joseph S. 2009. Biochar for environmental management: an introduction. Earthscan, UK. 12p.

Loo SV, Koppejan J. 2008.The Handbook of Biomass Combustion and Co-firing. Earthscan. 442p.

Mahanta N, Gupta A, Khare SK. 2008. Production of protease and lipase by solvent tolerant Pseudomonas aeruginosa PseA in solid-state fermentation using Jatropha curcas seed cake as substrate. Bioresource Technology 99: 1729–1735.

Malaťák J, Jevič P, Vaculík P. 2010. Účinné využití tuhých biopaliv v malých spalovacích zařízeních s ohledem na snižování emisí znečišťujících látek. Praha: vědecká monografie. 240p.

Mani S, Tabil LG, Sokhansanj S. 2003. An overview of compaction of biomass grinds. Powder Handling and Processing 15: 160–168.

Mavankeni BO. 2007. Improving maize growth and yield using Jatropha seed cakes under Zimbabwean soil conditions [MSc.]. Zimbabwe: University of Zimbabwe. 84p.

McKendry P. 2002. Energy production from biomass: overview of biomass. Bioresource Technology 83: 37-46.

McMullen J, Fasina OO, Wood CW, Feng Y. 2005. Storage and handling characteristics of pellets from poultry litter. Applied Engineering in Agriculture 21: 645–651.

Mofijur M, Masjuki HH, Kalam MA, Hazrat MA, Liaquat AM, Shahabuddin M. 2012. Prospects of biodiesel from Jatropha in Malaysia. Renewable and Sustainable Energy Reviews 16 (7): 5007-5020.

MPOB. 2014. Malaysian palm oil industry. Available at http://www.palmoilworld.org/about_malaysian-industry.html: Accessed 2015-11-21.

MZP. 2012. Vyhláška 201/2012 Sb. -Zákon o ochraně ovzduší. Česká republika: Sbírka zákonů ČR. 74p.

Naik SN, Goud VV, Rout PK, Dalai AK. 2010. Production of first and second generation biofuels: A comprehensive review. Renewable and Sustainable Energy Reviews 14 (2): 578-597.

NIIR Board. 2008. The Complete Book of Jatropha (Bio-diesel) with Ashwagandha, Stevia, Brahmi and Jatamansi Herbs (Cultivation, Processing and uses). Asia Pacific Business Press: 592p.

Nielsen F, Raghavan K, Jongh J, Huffman D. 2013. Jatropha for local development after the hype. The Hague: Hivos. 68p.

Nyer B. 2011. Jatropha fuel briquettes. University of Colorado- Engineering for developing communities Program. 18p.

Obernberger I, Brunner T, Bärnthaler G. 2006. Chemical properties of solid biofuels-significance and impact. Biomass and Bioenergy 30: 973–982.

Olsson M. 2006. Wheat straw and peat for fuel pellets—organic compounds from combustion. Biomass and Bioenergy 30 (6): 556-564.

Openshaw K. 2000. A review of Jatropha curcas: an oil plant of unfulfilled Promise. Biomass and Bioenergy 19: 1-15.

Pambudi NA, Torii S, Saptoadi H, Sumbodo W, Syamsiro M, Surono UB. 2010. Experimental study on combustion of bio briquettes Jatropha curcas solid waste. Environmental engineering management 20 (2): 133-136.

Pambudi NA, Torii S, Syamsiro M, Saptoadi H, Gandidi IM. 2012. Emission factor of single pellet cake seed Jatropha curcas in a fix bed reactor. Journal of the Brazilian Society of Mechanical Sciences and Engineering 34 (2).

Pandey VCh, Singh K, Singh JS, Kumar A, Singh B, Singh RP. 2012. Jatropha curcas: A potential biofuel plant for sustainable environmental development. Renewable and Sustainable Energy Reviews: 2870-2883.

Pastorek Z, Kára J, Jevič P. 2004. Biomasa obnovitelný zdrojenergie : obnovitelný zdroj energie. Praha: Fcc Publis. 288 p.

Perďochová M. 2010. Vliv samozahřívání pevného paliva z biomasy na kvalitu paliva a bezpečnost jeho skladování [Bc.]. Ostrava: Vysoká škola báňská - Technická univerzita Ostrava. 47p.

Petříková V. 2006. Energetické plodiny. Praha: Profi Press. 127p.

Picchi G, Silvestri S, Cristoforetti A. 2013. Vineyard residues as a fuel for domestic boilers in Trento Province: Comparison to wood chips and means of polluting emissions control. Fuel 113: 43-49.

Prade T. 2011. Industrial hemp (Cannabis Sativa L.): High Yielding energy crop [Doctoral Dissertation]. Alnarp: Swedish University of Agricultural Science, 93p.

Prakash S. 2012. Meta Evaluation of 6 Hivos Biofuel Projects: Meta Evaluation. The Hague: Hivos.

Prins MJ, Ptasinski KJ, Janssen FJJG. 2006. Torrefaction of wood: Part 2. Analysis of products. Journal of Analytical and Applied Pyrolysis 77 (1): 35-40.

Rabaçal M, Fernandes U, Costa M. 2013. Combustion and emission characteristics of a domestic boiler fired with pellets of pine, industrial wood wastes and peach stones. Renewable Energy 51: 220-226.

Rabier F, Temmerman M, Böhm T, Hartmann H, Jensen PD, Rathbauer J, Carrasco J, Fernández M. 2006. Particle density determination of pellets and briquettes. Biomass and Bioenergy 30: 954–963.

Remuzgo L, Trueba C, Sarabia JM. 2015. Evolution of the global inequality in greenhouse gases emissions using multidimensional generalized entropy measures. Physica A: Statistical Mechanics and its Applications 444: 146-157.

REN21. 2015. Renewables 2015 Global Status Report. Paris: REN21 Secretariat. 251p.

Sims REH, Hastings A, Schlamadinger B, Taylor G, Smith P. 2006. Energy crops: current status and future prospects. Global Change Biology 12: 2054–2076.

Shaw M. 2008. Feedstock and process variables influencing biomass densification [MSc]. Saskatoon: University of Saskatchewan, p. 159.

Sladký V, Dvořák J, Andert D. 2002. Obnovitelné zdroje energie – fytopaliva (Renewable energy sources – phytofuels). Prague: VÚZT. 64p.

Sricharoenchaikul V., Puavilai D, Thassanaprichayanont S, Atong D. 2011. Investigation on thermochemical conversion of pelletized Jatropha residue and glycerol waste using single particle reactivity technique. International Conference on Chemical Reactors. Chemical Engineering Journal 176: 217-224.

Stavjarská M. 2013. Využití odpadní biomasy z bavlníku pro energetické účely [Bc.]. Praha: Česká zemědělská univerzita v Praze. 54p.

Stupavský, V. 2010. Pelety z biomasy - dřevěné, rostlinné, kůrové pelety. Available at http://biom.cz/cz/odborne-clanky/pelety-z-biomasy-drevene-rostlinne-kurove-pelety: Accessed 2014-03-11.

Stupavský V, Holý T. 2010. Brikety z biomasy - dřevěné, rostlinné, směsné brikety. Available at http://biom.cz/cz/odborne-clanky/brikety-z-biomasydrevene-rostlinne-smesne-brikety: Accessed 2014-03-11.

Tewari DN. 2007. Jatropha and biodiesel. Ocean Books. India. 227p.

Trozzi, C. 2006. How Much Bioenergy can Europe Produce Without Harming the Environment. Brussels: EEA Report No 7.

Tumuluru JS, Wright CT, Kenny KL, Hess JR. 2010. A Review on Biomass Densification Technology for Energy Application. Idaho: Idaho National Laboratory. 96p.

Tumuluru JS, Sokhansanj S, Wright CT, Boardman RD, Yancey NA. 2011. A Review on Biomass Classification and Composition, Co-Firing Issues and Pretreatment Methods. ASABE International Meeting, Idaho: Idaho National Laboratory. 32p

Valíček P. 2002. Užitkové rostliny tropů a subtropů. Praha: Academia. 486p.

Van Look S, Koppejan J. 2002. Handbook of biomass combustion and co-firing. Iea bioenergy tasks, p171–213.

VEC. 2011. Výzkumné energetické centrum- Vysoká škola báňská, Technická univerzita Ostrava. Available at http://vec.vsb.cz/cz/ : Accessed 2013-11-25.

Werther J, Saenger M, Hartge EU, Ogada T, Siagi Z. 2000. Combustion of agricultural residues. Progress in Energy and combustion science 26 (1): 1-27.

Yong J, Ng Y, Tan S, Chew A. 2010. Effect of fertiliser application on photosynthesis and oil yield of Jatropha curcas. Photosynthetica 48(2): 208-218.

8 Annexes

Annex 1: Data values for determination of physical, chemical and mechanical properties of *Jatropha curcas* L. seed cakes and Jatropha pellets (Source: Author, 2016).

Ash content

Number of sample	The weight of the porcelain crucible [g]			Final ash content [%]
	empty	with wet sample	with ash	
1.	**24.8620**	**26.025**	**24.931**	**6.4394**
2.	24.1761	25.333	24.248	6.6987
3.	**25.7944**	**26.990**	**25.865**	**6.4206**

*** Arithmetic mean was calculated from the highlighted measurements, because stated repeatability limit is 0.2 %**

CHN content

Number of sample	C [%]	H [%]	N [%]
1.	48.628	6.400	4.204
2.	48.285	6.374	4.059
3.	48.680	6.402	9.988

Volatile matter content

Number of sample	The weight of empty vessel [g]	The weight of the vessel with sample [g]		Volatile matter [%]
		before heating	after heating	
1.	18.6445	19.6502	18.9206	72.5464
2.	18.6446	19.6538	18.9216	72.5525

Gross calorific value of wet and dried sample

Number of sample	Wet samples			Dried samples		
	weight [g]	GCV [$J.g^{-1}$]	NCV [$J.g^{-1}$]	weight [g]	GCV [$J.g^{-1}$]	NCV [$J.g^{-1}$]
1.	1.0469	19,131	17,544	0.9955	20,504	19,107
2.	1.0306	19,009	17,423	0.9177	20,503	19,106

Minor elements analysis, unit μg kg-^{1}in dry weight

Number of sample	Co	Ni	Cu	Zn	As	Cd	Hg	Pb
1.	135.354	316.16	7,618.117	17,496.7	29.748	3.833	10.013	142.573
2.	131.853	289.227	7,429.413	16,477.29	29.943	9.986	8.482	141.403
3.	137.11	314.12	7,756.39	17,475.45	31.659	3.275	10.237	157.708

Residual oil content

Number of sample	Mass of sample [g]	Mass of oil [g]	Content of oil [%]
1.	22.813	1.260	5.523
2.	22.214	1.225	5.515

Determination of length and diameter

Number of pellet sample	Length [mm]	Diameter [mm]	Number of pellet sample	Length [mm]	Diameter [mm]
1.	25.60	6.32	21.	23.57	6.23
2.	24.57	6.10	22.	27.92	6.35
3.	21.18	6.39	23.	18.01	6.36
4.	19.83	6.42	24.	20.32	6.35
5.	22.90	6.37	25.	19.84	6.30
6.	19.81	6.33	26.	18.74	6.22
7.	23.27	6.31	27.	18.53	6.26
8.	20.80	6.38	28.	14.16	6.34
9.	26.72	6.44	29.	19.58	6.41
10.	27.35	6.39	30.	23.57	6.38
11.	24.53	6.28	31.	24.66	6.35
12.	18.53	6.15	32.	22.38	6.31
13.	27.50	6.39	33.	28.63	6.43
14.	34.22	6.40	34.	25.87	6.20
15.	27.69	6.31	35.	22.97	6.39

16.	30.09	6.24	36.	19.91	6.22
17.	32.86	6.20	37.	22.63	6.38
18.	31.76	6.31	38.	18.90	6.25
19.	26.30	6.31	39.	18.91	6.32
20.	22.73	6.36	40.	17.82	6.14

Determination of bulk density

Number of sample	Mass of container [kg]		Bulk density as received [$kg.m^{-3}$]	Bulk density on dry basis [$kg.m^{-3}$]
	empty	with sample		
1.	2.19	5.30	622	558
2.	2.19	5.31	624	559

Determination of pellets moisture content

Number of sample	The mass of empty container [g]	The mass of the container [g]		The mass of sample [g]		Final moisture content [%]
		with wet sample	with dried sample	wet	dried	
1.	240.64	550.60	518.93	309.96	278.29	10.22
2.	146.23	456.55	424.63	310.32	278.40	10.29

Mechanical durability

Number of sample	Mass before test [kg]	Mass after test [kg]	Mechanical durability [%]
1.	0.5008	0.3501	69.90
2.	0.5014	0.3543	70.66

Annex 2*. Stoichiometric analysis for Jatropha pellets (Source: Author, 2016).

Jatropha pellets

Annex 3*. Stoichiometric analysis for Jatropha seed cakes (Source: Author, 2016).

Jatropha seed cakes

Annex 4*. Stoichiometric analysis for woody pellets (Source: Author, 2016).

Woody pellets

*Due to the huge number of measured data of stoichiometric analysis, it is presented in Microsoft Office Excel files (see details in electronic version).