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DOCTORAL THESIS

BRIQUETTING OF MATERIALS SUITABLE FOR THE ENERGY PRODUCTION

Department of Material Science and Manufacturing Technology

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Declaration

I declare that I have worked on my doctoral thesis titled “Briquetting of materials suitable for the energy production” by myself and I have used only the sources mentioned at the end of the thesis.

NAME AND SURNAME:

SIGNATURE:

DATE:

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Abstract

The present thesis provides an overall current insight into the briquetting technology issue; such technology is used for production of solid biofuel (bio-briquettes) and works with a densification process and biomass (renewable source of energy). Several factors which characterize and influence the technology of briquetting were investigated. Several questions were asked and answered within the performed research: **What (feedstock materials), how (briquetting technologies) and with what efficiency (chemical, mechanical and energy suitability) are we briquetting?** Primarily, experimental measurements were performed within a description of chemical parameters of waste biomass kinds (wood, herbaceous, fruit, aquatic, mixed) and their suitability for the briquetting and direct combustion processes. By using waste biomass, the generation of clean energy and principles of proper waste management were combined. Second, differences existed between pressing equipment; thus, pressure levels were compared, monitored and evaluated. In consequence, low- and high-pressure briquetting presses were used for bio-briquette sample production, and subsequently their mechanical quality indicators were tested and evaluated. Therefore, the entire process of manual low-pressure briquetting press development and verification was performed; namely, design creation, equipment manufacturing, its viability and practicability. The press' appropriateness for developing countries (target area) was proved due to its simplicity and intelligibility.

Key words: bio–briquettes; solid bio–fuels; renewable source of energy; waste biomass; proper waste management

Abstrakt

Tato práce poskytuje celkový současný vhled do problematiky technologie briketování; tato technologie se používá k výrobě pevných biopaliv (biobriket) a pracuje s procesem densifikace a biomasou (obnovitelným zdrojem energie). Několik faktorů, které charakterizují a ovlivňují technologii briketování, bylo předmětem výzkumu. V rámci provedeného výzkumu bylo kladeno a zodpovězeno několik otázek: **Co (vstupní suroviny), jak (briketovací technologie) a s jakou efektivitou (chemická, mechanická a energetická vhodnost) briketujeme?** Primárně byla provedena experimentální měření, která stanovila chemické parametry rozdílných druhů odpadní biomasy (dřevní, bylinná, ovocná, vodní, smíšená), a tím i jejich vhodnost pro briketovací proces a proces přímého spalování. Využitím odpadní biomasy byla spojena produkce čisté energie s principy zodpovědného nakládání s odpady. Sekundárně byly porovnávány, sledovány a vyhodnocovány rozdíly mezi lisovacími zařízeními a tedy i různými úrovněmi tlaku. V důsledku toho byly použity nízkotlaké a vysokotlaké briketovací lisy pro výrobu vzorků bio–briket, ty byly následně testovány a ukazatele jejich mechanické kvality byly zhodnoceny. V rámci čehož byl proveden kompletní proces vývoje a ověření manuálního nízkotlakého briketovacího lisu; jmenovitě, tvorba návrhů, výroba zařízení, ověření jeho životaschopnosti a proveditelnosti. Dále byla prokázána vhodnost lisu pro podmínky rozvojových zemí (cílová oblast) díky jeho jednoduchosti a srozumitelnosti.

Klíčová slova: bio–brikety; tuhá biopaliva; obnovitelný zdroj energie; odpadní biomasa; zodpovědné nakládání s odpady

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A_c Ash content, w.b. [%]

C_0 Force coefficient [N]

C_1 Deformation coefficient [m^{-1}]

C_2 Exponent of fitted function [–]

DU Mechanical durability [%]

E_d Deformation energy [J]

F Compressive force [N]

GCV Gross calorific value [$MJ \cdot kg^{-1}$]

M_c Moisture content (relative) [%]

NCV Net calorific value [$MJ \cdot kg^{-1}$]

P Operation pressure [MPa]

P_{max} Maximum compression loading [N]

RF Rupture force [$N \cdot mm^{-1}$]

s Piston trajectory, i.e. deformation of feedstock material [m]

v Adjustable speed [rpm]

VM_c Volatile matter content, w.b. [%]

v_p Pressing speed [$mm \cdot s^{-1}$]

ρ Density of bio–briquette samples [$kg \cdot m^{-3}$]

1. Introduction

A briquetting technology is not only the technology of clean renewable energy production, but it is also the technology of proper waste management.

Intensive forms of agriculture (also known as an intensive farming) are widely presented as an improvement of human living standards, but they cause serious environmental, ethical and social issues, due to a main focus on high product yields and financial earnings. Except other negative impacts of such form of agriculture, it is also uncontrolled <u>production of agriculture residues</u> and related <u>improper waste management,</u> which causes serious environmental issues. Intensive forms of agriculture result in production of enormous amounts of various biological residues; in other words, waste biomass. In consequence, processing or subsequent utilization of such waste biomass is highly recommended [1; 2]. Approximately five billion metric tons of waste biomass is produced every year in the agriculture sector worldwide; this amount represents an equivalent to 1.2 billion tons of oil (Btoe). Other sources report that waste biomass is the third most considerable energy source in the world, thus providing 14 % of annual energy supply [3]. In developing countries, utilization of waste biomass provides approximately 80 % of energy production [4].

In consequence, conversion of waste biomass into biofuel represents an adequate alternative to fossil fuels such as coal and oil, which cause irreversible damage to the environment and climate changes [5]. In comparison, utilization of waste biomass is an advantageous direct way to reduce greenhouse gases (GHGs), net carbon emissions and environmental pollution; use of waste biomass as an energy source is generally considered an option to mitigate greenhouse effects [6; 7].

Waste biomass is an alternative environmentally friendly renewable source of energy; for example, such waste materials could be used for biofuel production [8; 9; 10; 11], thus, its subsequent utilization should also be an important goal of the agriculture sector. However, within the increasing popularity of biofuels and clean energy, the need for more efficient reuse of waste biomass increases too [5; 12]. Unused waste biomass causes spontaneous production of air pollutants (leachate, methane, carbon dioxide, etc.), thus contributing to air, soil or water contamination [13]. Hence, necessary subsequent utilization of waste biomass also meets the principles of proper waste management. Moreover, the importance of waste biomass utilization for clean energy production will increase as national energy policies and strategies focus more heavily on renewable sources and environmental conservation [14].

The current form of waste biomass utilization differs from the traditional use of waste biomass by its conversion into highly efficient energy carriers, such as electricity [15]. Therefore, waste biomass is considered to be the renewable energy source with the highest potential to contribute to the energy needs of modern society for both industrialized and developing countries [14], while providing less harm to the environment [16]. The conversion of plant material into a suitable form of energy, usually electricity or a fuel for an internal combustion engine, can be achieved using a number of different routes, each with specific pros and cons [12, 14]. So far, much research has been focused on sustainable and environmentally friendly energy from waste biomass to replace conventional fossil fuels [17].

Waste biomass mostly originates from the agriculture production sector, and is therefore mostly represented by agricultural crop residues [7]. The amount of such residues is large and may have a significant energy potential [18]. The amount of agriculture crop residues left on site without any purpose usually ranges between 15–60% for most agricultural crops [19]. Thus, the next chapter is focused on agricultural production in different areas of the world.

1.1. Agriculture residue production

It is essential to realize that developing and emerging economies are facing a two-fold energy challenge in the 21st century because they need to meet the needs of billions of people who still lack access to basic, modern energy services while simultaneously needing to participate in a global transition to clean, low-carbon energy systems [20]. Of course, a much-debated question is how to achieve this challenge. However, with rising demands for clean energy and recurrent fuel scarcity, there is a need to diversify fuel supply and maximize use of natural resources and reuse of waste materials. Furthermore, progress toward increased efficiency, de-carbonization, greater fuel diversity and lower pollutant emissions needs to be accelerated [5; 12]. Regarding Asian countries, a cultivation of rice represents the major part of local agriculture production [21] together with maize, wheat, sugarcane and palm oil and others (Figures 1 and 2).

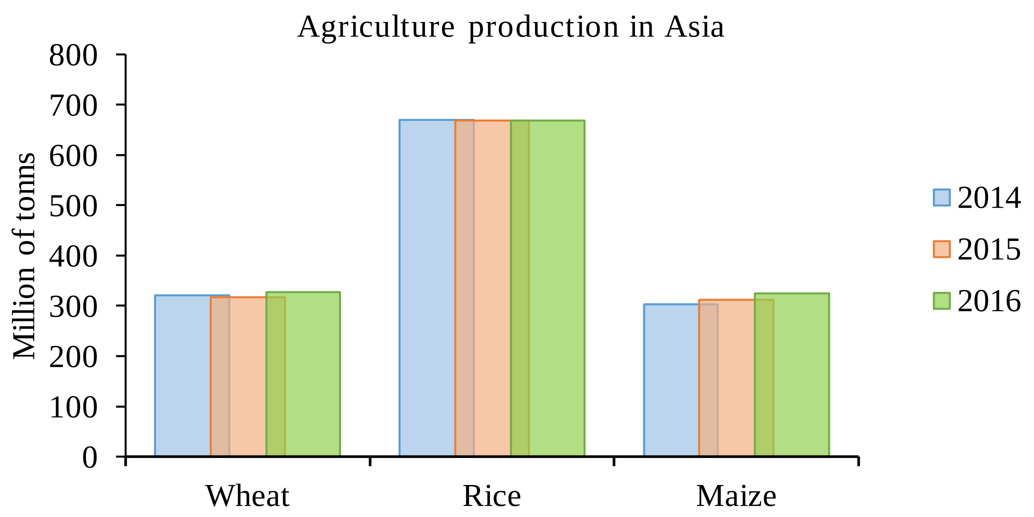


Figure 1: Amount of production of main agriculture crops in Asia (in millions of tonnes)

(Source: FAO, 2018) [22]

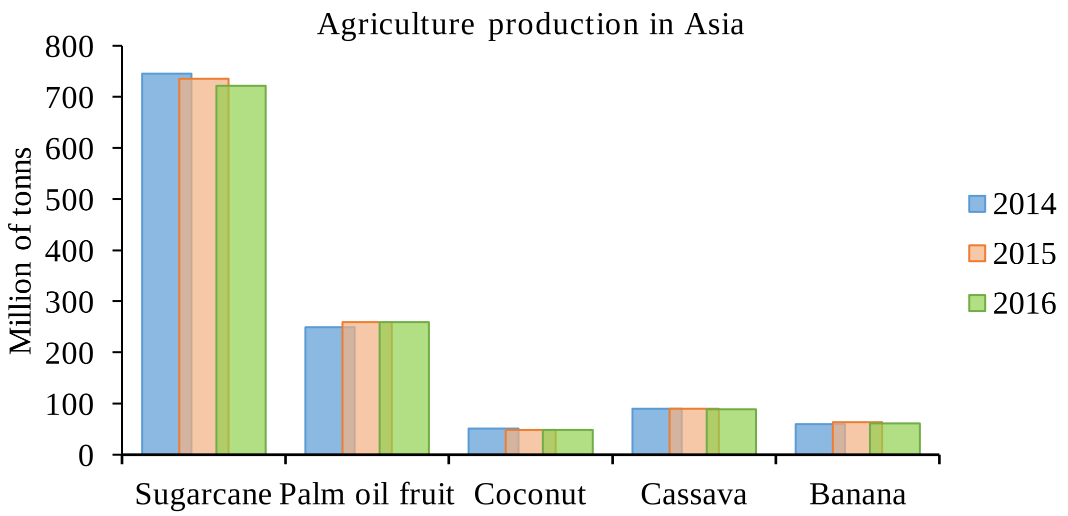


Figure 2: Amount of production of traditional agriculture crops in Asia (in millions of tonnes)

(Source: FAO, 2018) [22]

Focused on specific Asian countries, agricultural production in the Socialist Republic of Vietnam and the Republic of Indonesia are prevalently characterized by similar agriculture crops (Tables 1 and 2). Detailed information about agriculture sectors in such countries are mentioned due to the experimental focus of the present thesis, which will be further described in the following chapters.

Table 1: Production of main agriculture crops in Vietnam in 2014–2016 (in tonnes).

	Rice	**Sugarcane**	**Cassava**	**Maize**	**Bananas**	**Coconuts**
2014	44,974,206	19,822,851	10,209,882	5,202,511	1,857,641	1,374,404
2015	45,105,021	18,337,227	10,740,000	5,287,261	1,943,337	1,439,119
2016	43,437,229	16,313,145	11,045,184	5,244,140	1,941,935	1,469,960

(Source: FAO, 2018) [22]

Nevertheless, the biggest difference between such two production sectors is due to the cultivation of palm oil in Indonesia, which is the main agricultural crop in such countries. Moreover, the oil production sector in Asian countries also involves cultivation of other plants as a source of vegetable oil; for example *Jatropha Curcas* L. [23]. Oil-producing crops are cultivated on large plantations, which also results in a significant amount of different biological residues and thus various kinds of waste biomass [24]. Utilization of such waste biomass for production of solid biofuels has already been investigated, with positive results [25].

Table 2: Production of main agriculture crops in Indonesia in 2014–2016 (in tonnes)

	Palm oil	**Rice**	**Sugarcane**	**Cassava**	**Maize**	**Coconuts**
2014	139,952,542	70,846,465	25,753,920	23,436,384	19,008,426	18,300,000
2015	149,066,849	75,397,841	25,348,720	21,801,415	19,612,435	16,600,000
2016	160,135,795	77,297,509	27,158,830	20,744,674	20,369,551	17,722,429

(Source: FAO, 2018) [22]

Without a doubt, cultivation of palm oil represents the biggest source of waste biomass in Indonesia; approximately four kilograms of waste biomass, in the form of empty fruit bunches, are produced from the production of one kilogram of crude palm oil [26]. Nevertheless, production of palm oil products is considered controversial and faces worldwide criticism [27]. Overall, the area occupied by plantation of fruit trees in Indonesia was equal to 6,116,970 ha in 2014 including coconut, banana, cacao and coffee trees [28]. Unfortunately, subsequent utilization of fruit waste biomass, produced during the processing of the previously mentioned fruits, is not performed in the most effective way in many cases.

Meanwhile, unused waste biomass is a serious and growing problem not only in Asian countries, but also in developed countries such as the Czech Republic (Europe). However, if we compare the amount of mentioned agriculture production in Vietnam, Indonesia and the Czech Republic (see Table 3), it is clear that the amount of waste biomass originating from agricultural production in the Czech Republic occurs at a much lower level.

Table 3: Production of main agriculture crops in the Czech Republic in 2014–2016 (in tonnes).

	Wheat	**Maize**	**Oat**	**Poppy seed**
2014	5,442,349	832,235	152,232	24,665
2015	5,274,272	442,709	154,576	26,743
2016	5,454,663	845,765	132,220	28,574

(Source: FAO, 2018) [22]

Therefore, there are efforts to increase the subsequent use of waste biomass resources, particularly in the developing world [20]. If the waste biomass is reused in the developing world, produced energy is mainly used for cooking and heating [29]. Nevertheless, unfortunately it is still an extended practice that waste biomass is commonly burned by farmers in order to clear their fields without any energy purposes; nevertheless, utilization of waste biomass for heating purposes has been investigated by previous authors, with satisfactory results with respect to energy [30; 31]. The situation regarding the amount of burned waste biomass in monitored countries is expressed in Figure 3.

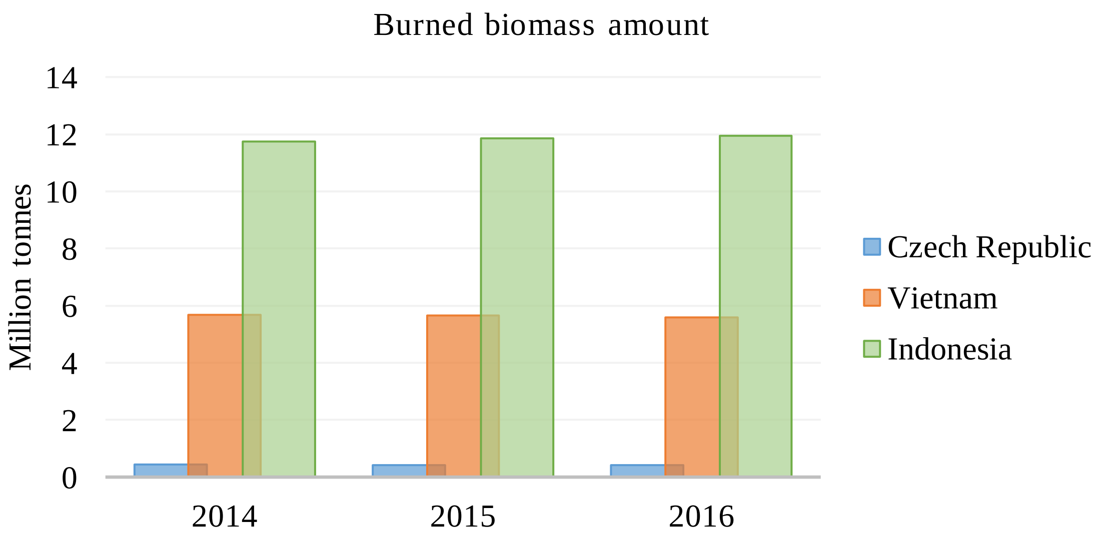


Figure 3: Amount of burned waste biomass in monitored countries (in mil. tonnes) (Source: FAO, 2018) [22]

The differences between specific monitored countries are undeniable. Thus, the potential of waste biomass production in countries such as Vietnam and Indonesia occurred at a higher level than in countries such as the Czech Republic. Such a statement also indicates the higher need of such waste biomass treatment and of proper waste management [32].

In case of completely unused and irresponsibly stored waste biomass, the spontaneous production of leachate and methane (CH_4) can occur, as well as production of carbon dioxide (CO_2) and other pollutants during the afore-mentioned waste biomass open burning. Such practice contribute to soil, air and water contamination [5; 33]. In view of these facts, the effort and obligation of subsequent utilization of waste biomass should represent a major goal of the agriculture sector. Moreover, several of the United Nations Sustainable Development Goals (SDGs) are related to environment conservation, and thus overall protection of planet Earth within a sustainable development agenda. Specifically, Goal 7: 'Ensure access to affordable, reliable, sustainable and modern energy for all' focused on global expansion of clean renewable energy (biomass) and its fossil fuels substitution [33].

1.2. Waste biomass bio-briquette fuel

As previously mentioned, there is an enormous potential for waste biomass as a renewable energy source. Despite untreated raw waste biomass having a low level of energy potential, this issue can be partly solved through conversion of raw waste biomass into solid biofuels, namely, bio-briquettes [34]. The present chapter thus focuses on a description of different waste biomass kinds and various kinds of bio-briquettes produced from them.

1.2.1. Waste biomass kinds

The official distribution of waste biomass is stated by mandatory technical standards, which include: wood, herbaceous, fruit, aquatic and mixed [17, 35]. In general, the most common waste biomass sources are represented by wood and wood waste, then by agricultural crops and their waste by-products, also by municipal solid waste, animal waste, fruit waste, residues from food processing, aquatic plants or algae [17; 36]. Considering that waste biomass kinds differ in accordance with their origin, several types of biomass have been officially defined: wood, herbaceous, fruit, aquatic and mixed [37;38]. Previous research indicates the following differences between various waste biomass kinds. Wood waste biomass is the most commonly used waste biomass kind for commercial purposes [39] and has satisfactory values with respect to calorific value; however, the values vary depending on the different parts of wood (bark, wood, etc.) [40; 41]. Herbaceous waste biomass exhibits lower calorific values and higher (undesirable) levels of ash content [42]. The exception represents energy crops, which are characterized by high levels of calorific value; such biomass is not of waste origin, but is purposely cultivated (for biofuel production) and is considered as controversial. Fruit waste biomass exhibits comparatively high levels of calorific value ($MJ \cdot kg^{-1}$) due to the presence of residual oils, but such biomass is limited by its high moisture content [43]. Satisfactory levels of calorific value but extremely high levels of ash content were found for aquatic waste biomass [44; 55], while evaluation of mixed-waste biomass energy potential is very complex and cannot be easily summarized because the mixed biomass contains from two or more different waste biomass kinds in different combinations and ratios. Nevertheless, despite some specific limitations of each waste biomass kind, the fact is that all of them represent waste materials, and thus their subsequent utilization should always be supported.

1.2.2. Bio-briquette fuel kinds

Untreated raw waste biomass has a low level of energy potential. However, this issue can be partly solved through conversion of raw waste biomass into solid biofuels, namely, bio-briquettes [34]. Bio-briquette fuel is produced by using the densification process, which works with the application of high pressure to increase raw waste biomass (feedstock material) density. Compaction of raw waste biomass eliminates bio-briquettes' undesirable mechanical properties (low density, irregular shape, high moisture content) and improves their chemical properties (higher calorific value, less smoke, more produced heat) [39], as well as providing easier handling and transportation of fuel than in the case of raw waste biomass [14].

Bio-briquette fuel can be produced from various waste biomass kinds. In consequence, such fuel exhibits different mechanical and chemical parameters related to the origin of waste biomass used as a feedstock material. Wood biomass is the most commonly used kind of biomass for the production of bio-briquette fuel for commercial purposes (high content of natural binder lignin) [39]. Such a fact can be primarily caused by the advantageous properties of wood bio-briquette fuel, but also by a lack of awareness in the wider public about the possibilities of utilization of other waste biomass kinds for such purposes. Nevertheless, other waste biomass kinds can also be suitable for bio-briquette production. As previousl studies indicate, not only do solid biofuels from wood waste biomass provide satisfactory energy potential, but also different waste biomass types (herbaceous, fruit, mixed) can represent a suitable source of renewable energy that can compete with fossil fuels [46-49]. Waste biomass originating from various agricultural crops, such as palm oil, coconut, corn, bean, cassava and sugar cane have already been used in some developing countries as a fuel alternative [5; 50]. As mentioned previously, production of bio-briquette fuel represents not only the technology of production of clean renewable energy, but also the procedure of proper waste management; that is the right view which the wider public need to have about bio-briquette fuel production. Such a statement indicates the importance of subsequent utilization of all waste biomass kinds (herbaceous, fruit, aquatic, mixed), not only the wood one. The mentioned waste biomass kinds have their specific properties which need to be determined with respect to wood bio-briquettes. But in many cases, such waste biomass kinds exhibit even better levels of specific mechanical or chemical parameters. In consequence, using the mentioned waste biomass kinds requires more experimental measurements and determination of their advantages and disadvantages. Nevertheless, by defining and subsequent using properly selected pressing technology, external binding agents or proper ratio of mixing with other waste biomass kinds, all of the undesirable limits can be improved and such waste biomass kinds represent significant potential for clean energy generation. Moreover, principles of proper waste management urge the utilization of all kinds of biomass; thus, the current investigations are focused on bio-briquette production from various waste biomass kinds. The following sub-chapters describe the production of bio-briquette fuel from specific waste biomass kinds.

1.2.2.1. Wood waste biomass bio-briquettes

As mentioned, wood waste biomass is widely used for commercial production of bio-briquette fuel due to its suitable chemical and mechanical parameters, such as high lignin content (natural binder). Technology for high-pressure briquetting operates without using of any external binders; thus, such parameter ensure a high level of bio-briquette final quality [39]. Differences within energy potentials and level of suitability of specific wood types can be found between deciduous and coniferous trees, between trees from tropical or temperate zones or between different parts of the trees (trunk, branch, bark).

One previous study found differences between the profitability of bio-briquettes produced from sawdust of six different tropical hardwoods, namely *Triplochiton scleroxylon*, *Ceiba pentandra*, *Aningeria robusta*, *Terminalia superba*, *Celtis mildbreadii* and *Piptadenia Africana*, while investigated samples represented both deciduous and coniferous trees [51]. Other authors analyzed bio-briquette fuel from mixed sawdust of another tropical hardwood species, specifically *Afzelia africana*, *Terminalia superba* and *Melicia elcelsa*. The authors investigated a combination of selected sawdust with different binding agents and its impact on the final mechanical quality of produced bio-briquette samples [39]. The authors focused on production of bio-briquettes from temperate zone trees suggesting the suitability of the following feedstock materials (wood waste biomass): sawdust of pine (*Pinus* spp.), fir (*Abies* spp.), beech (*Fagus* spp.), poplar (*Populus* spp.) and oak (*Quercus* spp.) trees [29; 52]. Comparison between different parts of the tree (i.e. wood vs. bark), was investigated within different kinds of tree barks with good results in comparison with wood bio-briquettes [52; 53]. The suitability of solid biofuel production from wood waste biomass from fruit orchards was also found [54; 55]. Further, the potential of fruit orchard pruning was also investigated in relation to its energy potential, again with satisfactory results [56].

1.2.2.2. Herbaceous waste biomass bio-briquettes

Herbaceous waste biomass is characterized by great diversity and variability; many different plants and their parts are included in this waste biomass kind. Thus, the result of chemical analysis or final mechanical quality of such bio-briquettes differs in accordance with the investigated plants' taxonomy.

In general, the agricultural sector produces a significant amount of herbaceous waste biomass suitable for bio-briquette production. Thus, many studies have dealt with the issue of utilization of herbaceous biomass originating from technological processing of agriculture crops for production of bio-briquettes. For example, bio-briquettes produced from straw and husk of wheat (*Triticum* spp.), oat (*Avena sativa*), canola (*Brassica napus*), rye (*Secale cereale*) and barley (*Hordeum vulgare*) were investigated [37; 57–61]. Other studies investigated the suitability of bio-briquettes produced from waste corn stovers (*Zea mays*), with satisfactory results [62]. The suitability of bio-briquette fuel from maize husk (*Zea mays*) was also found [63], as well as bio-briquette fuel from husk of sunflower (*Helianthus annuus*), buckwheat (*Fagopyrum esculentum*) and flax (*Linum usitatissimum*) [64] or from cotton stalks (*Gossypium* spp.) [31].

Research on the potential of herbaceous waste biomass bio-briquettes in developing countries is mostly focused on utilization of residue originating from cultivation of rice (*Oryza sativa*). Both rice straw and husk represent suitable feedstock material for such purposes according to previous research [16; 21; 30; 31; 47; 65].

Nevertheless, herbaceous waste biomass can occur in different forms; an example is the production of bio-briquette fuel from banana leaves (*Musa* spp.) [66], mango leaves (*Mangifera indica*), eucalyptus leaves (*Eucalyptus globulus*) [67] or subabul leaves (*Leucaena leucocephala*) [68]. The variability of herbaceous waste biomass is significantly wide.

1.2.2.3. Fruit waste biomass bio-briquettes

Specific forms of fruit waste biomass can also differ with respect to fruit peelings, skins, fibres, pits, seeds, kernels et cetera. A possibility of reusing of such residues for direct combustion purposes has been noted in specific case of olive pits (*Olea europapea*), cherry seeds (*Prunus avium*), apricot kernels (*Prunus armeniaca*), peach kernels (*Prunus persica*), watermelon seeds (*Citrullus lanatus*) or grape seeds (*Vitis vinifera*) [69]. Other research has determined the advantage of production of bio-briquette fuel from olive cake (*Olea europaea*) (residue after compressing of olive oil) [70]. Subsequent utilization of Jatropha (*Jatropha curcas*) press-cake and pomace for solid biofuel energy generation purposes was investigated previously [71], with positive results. Briquetting of fruit waste biomass originating from palm oils (*Elaeis guineensis*) has become very popular in recent years. Empty fruit bunches, fibres, palm kernels, shells or nuts are used as a feedstock material for bio-briquette production [43; 50].

The available literature also describes the production of bio-briquette fuel from durian fruit (*Durio zibethinus*) waste biomass in the form of peelings [71; 72]. Due to the significant extension of coconut palm (*Cocos nucifera*) cultivation in developing countries, the production of bio-briquette fuel from coconut fruit waste biomass was also monitored [28; 73]. Residues originating from processing of cacao fruits (*Theobroma cacao*) were also considered as a suitable feedstock material [28], while other research notes the suitability of coffee fruit (*Coffea arabica*) waste biomass [73]. Also, the production of banana fruit (*Musa acuminata*) waste biomass bio-briquettes was investigated, with satisfactory results [74]. In general, the production of such bio-briquette fuel is not common practice; thus, the mentioned investigations were mostly focused on the feasibility and practicality of creating such bio-briquettes.

1.2.2.4. Aquatic waste biomass bio-briquettes

The present waste biomass kind includes biological wastes originating from aquatic plants. Such plants provide positive impacts for local water environments, but some of them cause serious problems due to their invasive behaviour and profuse vegetation [75; 76]. Several aquatic plant species are considered undesirable in local ecosystems in developing countries (and beyond); thus, they comprise aquatic pollution. Namely, the following species of water hyacinth *Eichhornia crassipes* and aquatic weeds *Hydrilla verticillata* and *Myriophyllum spicatum* [77–79].

Such plants contribute to aquatic pollution due to their extremely high biomass yield; desirably thick impenetrable mats are created at the bottom and surface of polluted water areas [80; 81]. Such negative impacts include inhibition of growth of other vegetation and complicate utilization of water areas by local people for fishing or recreation, but also for activities such as irrigation or energy generation [82]. Within the prevention of the mentioned negative impacts and prevention of further plant reproduction, existing plant populations are commonly harvested from water areas by manual or mechanical harvesting performed by heavy machinery [79; 83]. After such activities, a large amount of aquatic plants are harvested; thus, waste biomass is produced but its subsequent efficient utilization is not ensured in most cases; occasionally, it is used as a cheap fertilizer or as a livestock feed by small farmers [84–86].

In general, with respect to the energy generation issue, such aquatic waste biomass provides a point of interest mostly in terms of liquid (bioethanol) and gaseous (biogas) biofuel production [87; 88]. Nevertheless, aquatic pollution caused by such aquatic waste biomass is still a current issue, and utilization for production of bio-briquette fuel (solid biofuel) is thus the goal of much current research. Such research originates mostly from countries which are dealing with this kind of aquatic pollution; viability and sustainability of such bio-briquette fuel production has been found in countries including Zimbabwe, Nigeria and Kenya [89–91].

1.2.2.5. Mixed waste biomass bio-briquettes

Mixed waste biomass is also characterized by a great deal of variability, originality and individuality. Specifications of such waste biomass kinds define it as a mixture of two or more waste biomass kinds. Other specifications, such as the ratio of chosen waste biomass kinds or specific kinds of waste biomass which can be mixed, are not specified by any mandatory technical standards. Such a fact offers a great opportunity for new investigations or improvement of possible negative properties of specific types of bio-briquette fuel. Thus, there have been countless different types of bio-briquette fuel investigated, namely, bio-briquettes produced from solid municipal waste [92] or from municipal sewage sludge [93]. Further, a mixture of wood and herbaceous waste biomass kinds was found in the case of production of bio-briquettes from mango leaves (*Mangifera indica*), subabul leaves (*Leucaena leucocephala*), sawdust and dry cow dung [68]. Mixed biomass also comprises specific waste biomass kinds mixed with waste paper or waste cardboard. Waste paper in combination with coconut husk (*Cocos nucifera*) represented a suitable feedstock material [94], as well as waste cardboard mixed with sawdust [95] for bio-briquette production.

Moreover, second used waste biomass kind could be replaced by a high ratio of specific external binder. Such combinations were monitored and evaluated in cases of bio-briquette fuel produced from sawdust mixed with lignite [96], rice husk (*Oryza sativa*) blend mixed with palm oil (*Elaeis guineensis*) mill sludge [47] or from sawdust mixed with raw glycerol (waste of bio-diesel production) [97]. Other research dealing with such issues noted the suitability of bio-briquette fuel produced from fruit and herbaceous waste biomass kinds, namely using carbonized cashew shells (*Anacardium occidentale*) and rice husk (*Oryza sativa*) [98].

1.3. Bio-briquette fuel quality

Bio-briquette fuel is intended for direct combustion [37]. Thus, it must be subjected to a detailed analysis of its chemical and mechanical parameters to ensure environmental safety and fuel efficiency. Consequently, utilization of untested (potentially unsuitable) bio-briquette fuel from untested waste biomass could primarily result in fuels of a low level of energy potential and calorific value or high levels of undesirable moisture and ash. It also may have a negative impact on combustion equipment or on the environment in general [37; 99; 100]. Thus, primarily the feedstock materials (waste biomass) must be subjected to a statement of their suitability for direct combustion processes and for bio-briquette fuel production. Further, the suitability and efficiency of the produced bio-briquette fuel itself must be determined.

All potential feedstock materials (waste biomass) have their own specific chemical and mechanical properties which directly affect the final quality of a bio-briquette fuel. Such properties include moisture content M_c (%), ash content A_c (%), volatile matter content (%), gross calorific value GCV ($MJ \cdot kg^{-1}$), net calorific value NCV ($MJ \cdot kg^{-1}$), as well as the elemental composition *C, H, N, S, O* (all in %) and many others; hence, all kinds of feedstock materials must be subjected to a determination of their chemical quality [62]. Subsequently, bio-briquette fuels must be subjected to a determination of their mechanical quality. The main bio-briquette fuel mechanical quality indicators are **mechanical durability *DU*** (%) and **density *ρ*** ($kg \cdot m^{-3}$) [58; 62; 65]. Several other tests suitable for bio-briquette fuel mechanical quality are commonly used in practice; for example, **rupture force *RF*** ($N \cdot mm^{-1}$) [101-105].

Mechanical durability *DU* (%) (also termed abrasion resistance), is considered the main indicator of bio-briquette fuel quality [58; 62; 65]. Previous studies have shown that *DU* is the prevalent form of expression of mechanical quality of bio-briquette fuel, and thus its determination helps to produce high-quality bio-briquette fuel [62; 106]. *DU* also describes the success of the densification process and measures the resistance and abrasion of the products during storage, transportation and handling [107]. Procedures for assessment of *DU* use a simulation of the bio-briquette fuel damage in practice; a detailed description of such experimental tests is given in the 'Methodology' chapter.

'*High durability means high quality briquettes*.' [62]

Bio-briquette fuel density ρ ($kg \cdot m^{-3}$) is defined as the ratio of mass to volume or ratio of energy content to volume [108]. In general, density ρ itself is defined as the degree of compactness of a substance [109]. The level of the bio-briquette fuel density ρ shows the effectiveness of the densification process and mechanical quality of the final products [50]. A previous study shows that high bio-briquette fuel density ρ leads to a high *DU* [110]. The process of densification can reduce the density ρ of raw feedstock materials which ranges from 40 to 200 $kg \cdot m^{-3}$ to the density ρ of produced bio-briquette fuel which ranges from 800 to 1,000 $kg \cdot m^{-3}$ [111; 112].

In the case of commercial bio-briquette fuel production, there are standardized criteria related to the accepted levels for their mechanical and chemical quality indicators. Table 4 illustrates the mandatory requirements for quality indicators of bio-briquette fuel from wood and non-wood feedstock materials (from wood, herbaceous, fruit, aquatic or mixed-waste biomass).

Table 4: Specification of wood and non-wood bio-briquette fuel.

Category	Non-wood A	Non-wood B	Wood	Standard
Biomass origin	Herbaceous Fruit Aquatic Mixed	Herbaceous Fruit Aquatic Mixed	Wood	[113-115]
Moisture content M_c (%), w.b.	$M_c \leq 12.0$	$M_c \leq 15.0$	$M_c \leq 15.0$	[116-117]
Ash content A_c (%), d.b.	$A_c \leq 6$	$A_c \leq 10$	$A_c \leq 10$	[118]
Density ρ (kg·m^3)	$\rho \geq 900$	$\rho \geq 600$	$\rho \geq 900$	[119]
Net calorific value NCV (MJ·kg^{-1}), w.b.	NCV ≥ 14.5	NCV ≥ 14.5	NCV ≥ 14.9	[120]
Nitrogen N (%), d.b.	N ≤ 1.5	N ≤ 2.0	N ≤ 1.0	[121]
Sulphur S (%), d.b.	S ≤ 0.20	S ≤ 0.30	S ≤ 0.04	[122]

1.4. Briquetting technologies

Another factor which influences the success of the densification process and final bio-briquette fuel quality are the properties of the used briquetting technology. In general, briquetting commonly involves use of heavy machinery with high-pressure briquetting presses which are associated with high initial financial costs (purchase of the machine, after-sales service, change of the components or oil), high electrical energy consumption (operation of the press) and the need for properly trained operators (human resources investments) [123–127]. Production of bio-briquette fuel has significant potential in developing countries, but the mentioned financial, energy and human requirements indicate limitations for implementation of briquetting technology in such countries. In response, a low-pressure briquetting technology has started to form a key focus. Several studies have been performed involving the design and use of manual low-pressure briquetting presses powered by manual power [128–130].

1.4.1. Low-pressure briquetting technology

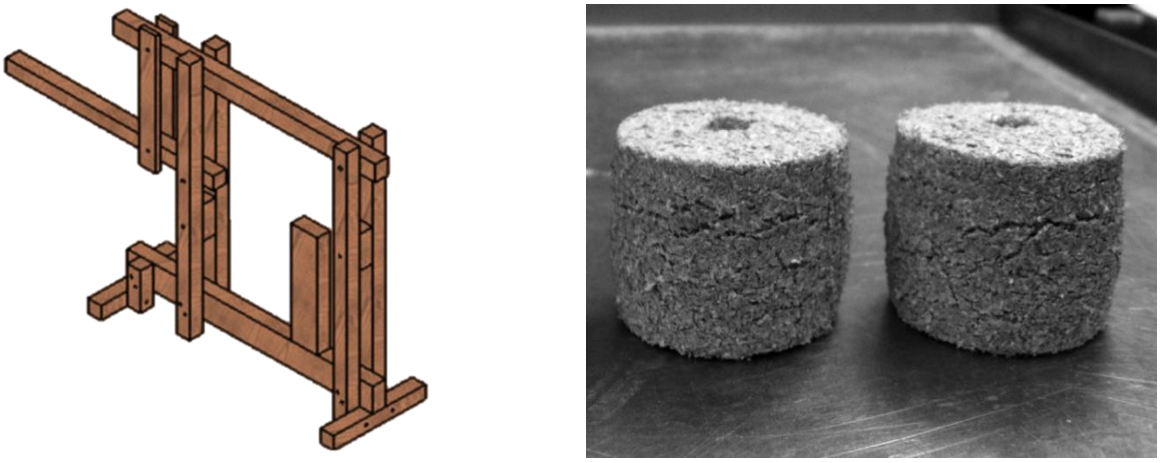
As mentioned, the implementation of briquetting technology into the developing countries, moreover, to rural areas of developing countries, is not suitable. Thus, such efforts represent a challenge in energy production. To achieve the requirements and possibilities of such areas, briquetting technology was subjected to a detailed analysis and evaluation of its needs and possibilities in an attempt to decrease the financial costs, remove the necessity of electrical energy, simplify the operation of the briquetting press and the entire process of bio-briquette fuel production. Such efforts try to cover the widest field of the briquetting technology application, which is now limited [123–127].

Therefore, manual low-pressure briquetting technology could represent a relevant solution for adequate waste biomass utilization in developing countries. Currently, there are several designs of manual low-pressure briquetting presses implemented in Asia and Africa using different pressing mechanisms [127-131]. Previously published research indicates that such alternative technology offers a variety of press design options which differ in press size, construction materials (wood, metal), number of produced briquettes at a time, pressing mechanisms (piston, screw) or shape of pressing chamber, and thus shape of briquettes (square, cylindrical, molds), as shown in Figure 4 [130; 132].

Figure 4: Examples of various bio-briquette samples produced by low-pressure briquetting presses (Source: Engineeringforchange.org; Legacyfound.org).

Such diversity offers a significant opportunity to combine technical specifications and manufacturing of the most efficient manual low-pressure briquetting press in respect to the local requirements and chosen feedstock materials. Within use of such technology, it is also necessary to use external binding agents for agglomeration of feedstock materials; the ratio of feedstock material and binding agent differs in accordance with their variety. Such a ratio represents an important factor influencing final quality in the produced briquette sample. Focused on biological waste production in developing countries, the biggest part of biological waste is formed by herbaceous waste biomass; waste from production and processing of rice, corn, cassava, coffee, tobacco, sugar cane and spice or simply sawdust [133]. Manual low-pressure briquetting presses commonly work with an operation pressure of P < 5 MPa and operate with single- or double-lever technologies, using a piston as a pressing body [128; 130; 134], which is sufficient for the densification process of such herbaceous waste biomass [129-131].

Such technology is not commonly well-known and used in the energy production sector today. Thus, the development and verification of such equipment is still in process globally. Moreover, research activities focused on low-pressure briquetting presses are mostly represented by the efforts and initiative of different non-profit organisations or individuals. Thus, literature regarding such technology is quite limited because the greatest amount of information on this topic is published only on organisations' websites or as a content of specific handbooks intended for use in the field. Nevertheless, several studies have published satisfactory results (see Figures 5, 6 and 7). Such a limitation represents the complications during appropriate literature review compilation. On the other hand, it also indicates that the topic is yet to be thoroughly investigated, and that the possibility to perform original research and contribute to development of the topic with completely new knowledge exists.

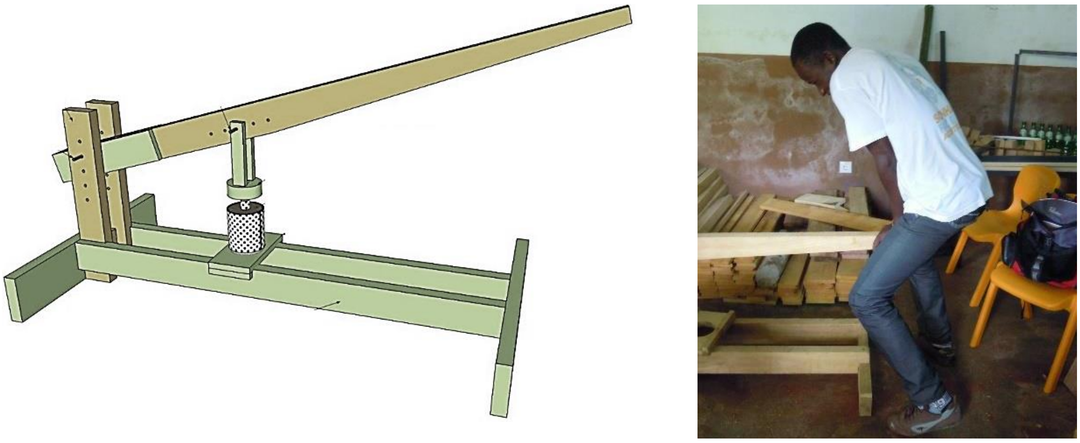


a) b)

Figure 5: Manual low-pressure double-lever press: a) scheme, b) produced bio-briquette samples [130]

a) b)

Figure 6: a) Low-pressure moulding machine, b) produced bio-briquette samples [128]



a) b)

Figure 7: Manual single lever low-pressure manual press: a) scheme, b) in use [129]

2. Objectives

This chapter defines the stated objectives of the present dissertation thesis. Thus, it contains the main objective and several specific objectives, which were stated to achieve the main one.

2.1. Main objective

The main objective of this dissertation thesis is to evaluate the quality of production of specific briquette biofuel produced under different conditions from various biological waste feedstock materials (waste biomass). In order to achieve the main objective, the interconnected specific objectives of the work have been established, which are described below.

2.2. Specific objectives

The specific objectives are divided into two interrelated groups; the results of qualitative tests of individual feedstock materials (waste biomass) and briquette samples produced from these feedstocks will be monitored and evaluated first. Qualitative testing will focus on indicators of feedstock materials and briquettes' chemical and mechanical quality. Second, the use of various briquetting technologies and briquetting presses (low and high pressure) will be monitored and evaluated for production of the briquette samples. After achieving the above-mentioned specific objectives, the obtained primary data will produce an assessment of the efficiency of the production of specific briquettes and will identify input materials showing the most suitable parameters for briquettes under the given conditions.

Theoretical part

- Study and review of previously published research to complement the theoretical background regarding waste biomass production and briquetting biofuel quality.
- Determination of the limit values for evaluation of the results of qualitative tests of selected types of waste biomass and subsequently produced briquettes samples based on valid technical standards of the Czech Republic and already published secondary data from previous research activities in this field.

- Studying and summarizing the current state of low-pressure briquetting technology, its development and use in practice. Subsequent design of manual low-pressure briquetting press design and briquette production method using this technology.

Practical part

- Pre-production preparation of raw feedstock materials and experimental testing of their chemical quality indicators according to valid technical standards of the Czech Republic (see Chapter Methodology / Experimental Measurement).
- Production of own samples of briquettes from different input materials according to valid technical standards of the Czech Republic (see Chapter Methodology / Experimental Measurement).
- Qualitative testing of briquette samples focused on indicators of their mechanical quality according to valid technical standards of the Czech Republic (see Chapter Methodology / Experimental Measurement).
- Development and verification of a low-pressure briquetting press from wood and its use for the production of briquettes and measurement of their mechanical properties.

Evaluation part

- Evaluation of the final values of qualitative tests of selected feedstock materials and briquettes produced from them according to the above standards and results of previous published research activities.
- Determination of chemical parameters of specific types of waste biomass in order to evaluate their suitability for production of briquette fuel.
- Identification of feedstock materials with optimal properties for briquette production and determination of qualitative characteristics of produced briquette biofuels.
- Final evaluation of efficiency of briquette fuel production using different briquetting technologies (low- and high-pressure).

3. Methodology

Present chapter was divided to several parts according to the points of interest of present research. Firstly, the description of investigated waste materials samples, their origin and processing was performed. Furthermore, two different types of briquetting technologies used for bio–briquette samples production and characteristics of such biofuel samples were described. Finally, all processes of experimental measurements used for determination of chemical and mechanical properties of investigated feedstock materials and subsequently produced bio–briquette fuel samples were described.

3.1. Materials and samples

Investigated waste materials samples, which represented various waste biomass kinds, originated from different countries and were collected in different period. It needs to be considered that all investigated samples were produced as agriculture residues, thus, the level of their processing during and after the collection differed. Detail information about specific countries of samples origin, collection target areas and time periods are noted in subchapters below.

3.1.1. Waste materials origin and collection

All waste biomass kinds (wood, herbaceous, fruit, aquatic, mixed), thus, different types of feedstock materials which were investigated within present research, originated from local mostly rural conditions of Czech Republic and also from rural conditions of foreign countries like Republic of Indonesia, Socialist Republic of Vietnam, People's Republic of China and Federative Republic of Brazil. The distribution of target areas of data collecting within the whole world is expressed in Figure 8. Samples collection was performed during years 2015 – 2018; detail time periods of collection are noted in specific countries description.

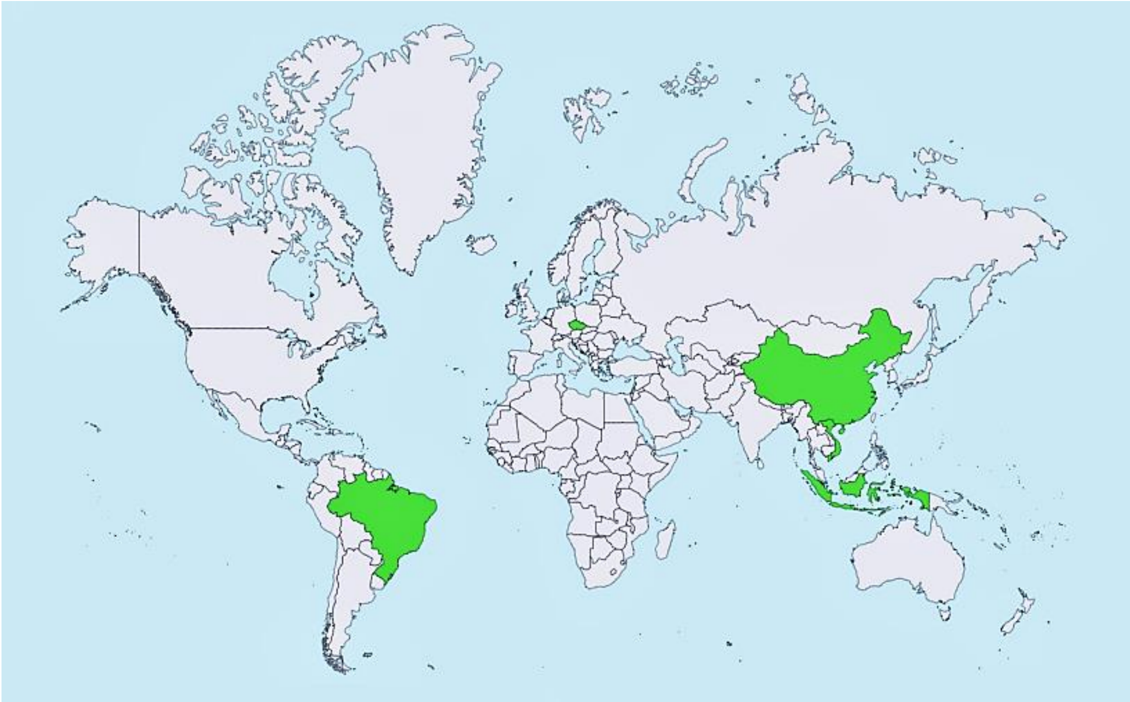


Figure 8: Investigated waste feedstock materials countries of origin

Waste feedstock materials collected from Czech Republic were produced in following regions: The Capital City of Prague, Central Bohemia Region and South Moravian Region (as shown in Figure 9). The time period of samples collection was during different seasons in years 2015 – 2017.

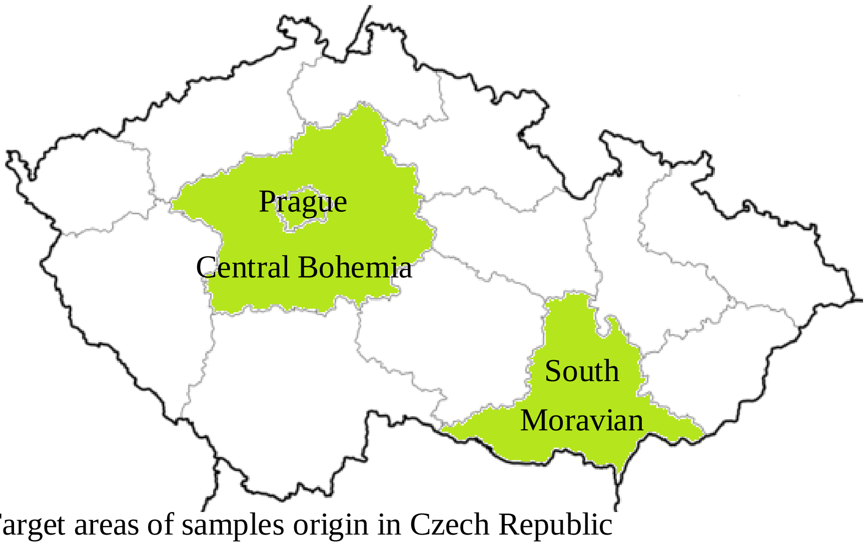


Figure 9: Target areas of samples origin in Czech Republic

Waste biomass samples collected in Republic of Indonesia originated from Toba Samosir district, Sumatera Utara province and samples collected in Socialist Republic of Vietnam originated from Huế disctrict, Thừa Thiên - Huế province, Central Vietnam (expressed in Figure 10). A research activities related to the samples collection held in Republic of Indonesia were performed in the year 2016 from July to September and during November in the year 2017. While, collection of investigated waste biomass samples in

Socialist Republic of Vietnam were held in January and May of year 2017 and from March to April of year 2018.

Figure 10: The areas of samples collection in Republic of Indonesia and Socialist Republic of Vietnam

The list of all investigated waste materials samples with countries of their origin in expressed in Table 5.

Table 5: List of specific investigated waste biomass feedstock materials

Biomass kind	Samples name	Latin name	Country of origin
Wood	Pine bark	*Pinus* spp.	CZ
	Spruce bark	*Picea* spp.	CZ
	Fruit tree branches	*Prunus* spp.	CZ
	Larch sawdust	*Larix* spp.	CZ
	Spruce chips	*Picea* spp.	CZ
	Jatoba sawdust	*Hymenaea courbaril*	BR
	Garapa sawdust	*Apuleia leiocarpa*	BR
	Ash tree chips	*Fraxinus* spp.	CZ
Herbaceous	Tropical greenhouse plants*	See description above	CZ
	Rice husk	*Oryza sativa*	IDN, VN
	Cacao leaves	*Theobroma cacao*	IDN

	Banana leaves	*Musa acuminata*	IDN
	Aloe Vera leaves	*Aloe barbadensis*	IDN
	Coffee leaves	*Coffea arabica*	IDN
	Bamboo leaves	*Bambusoideae* spp.	IDN
	Bamboo fibres	*Bambusoideae* spp.	VN
	Japanese knotweed stems	*Fallopia japonica*	CZ
	Oat husk	*Avena sativa*	CZ
	Poppy residue	*Papaver somniferum*	CZ
	Wheat husk	*Triticum* ssp.	CZ
	Cassava stover	*Manihot esculenta*	IDN, VN
	Sugar cane skin	*Saccharum officinarum*	VN
	Sugar cane bagasse	*Saccharum officinarum*	VN
Fruit	Vine residue	*Vitis vinifera*	CZ
	Date skin	*Phoenix dactylifera*	PRC
	Date pits	*Phoenix dactylifera*	PRC
	Jatropha shells	*Jatropha curcas*	IDN
	Jatropha press–cake	*Jatropha curcas*	IDN
	Durian skin	*Durio zibethinus*	IDN, VN
	Coconut skin	*Cocos nucifera*	IDN
	Coffee skin	*Coffea arabica*	IDN
	Cacao skin	*Theobroma cacao*	IDN
	Banana skin	*Musa acuminata*	IDN, VN
	Rambutan skin	*Nephelium lappaceum*	IDN, VN
	Oil palm kernel	*Elaeis guineensis*	IDN
	Oil palm fibre	*Elaeis guineensis*	IDN
	Tapioca skin	*Manihot esculenta*	IDN
	Coffee ground	*Coffea arabica*	CZ
Aquatic	Water hyacinth plant body	*Eichhornia crassipes*	IDN, VN
	Water–thyme plant body	*Hydrilla verticillata*	IDN
	Eurasian water milfoil plant body	*Myriophyllum spicatum*	IDN, VN
Mixed	Coffee ground + larch sawdust		CZ

Coffee ground + spruce shavings	CZ
Oat + poppy + wheat husks	CZ
Waste cardboad	CZ
Waste paper	CZ

CZ – Czech Republic, IDN – Republic of Indonesia, VN – Socialist Republic of Vietnam, PRC – People's Republic of China, BR – Federative Republic of Brazil

* Material called "Tropical plants" contained from mixture of herbaceous waste biomass originating from tropical greenhouse (Tropical greenhouse Fata Morgana, Prague), namely, whole plant body of species *Ficus, Parmentiera, Malpighia, Malvaviscus, Araceae (Monstery), Trevesia, Nepenthes* and leaves of *Begonia, Afrocarpus, Hibiscus, Thunbergia, Pandanus.*

Waste materials samples investigated within present research prevalently originated from the processing of agriculture crops. Such agriculture crops were selected and chosen according to their importance for agriculture sector of specific countries. Therefore, investigated waste materials originated from the agriculture crops, which plays important roles in local agriculture sectors, thus, such crops represented:

- Major agriculture crops (highest yield)
- Agriculture crops with largest cultivation areas
- Agriculture crops with highest potential for waste biomass production

Selected waste materials were collected during the different processing and production levels in agriculture sector, thus, the places of their collection differed. Prevalently, the waste biomass samples were collected at:

- Place of the agriculture crops growth (fields, plantations)
- Place of agriculture crops processing (processing plants, processing manufactures, processing by the individuals)
- Place of the agriculture crops sale (markets, shops)

Places of samples origin and collection are shown at Figure 11.

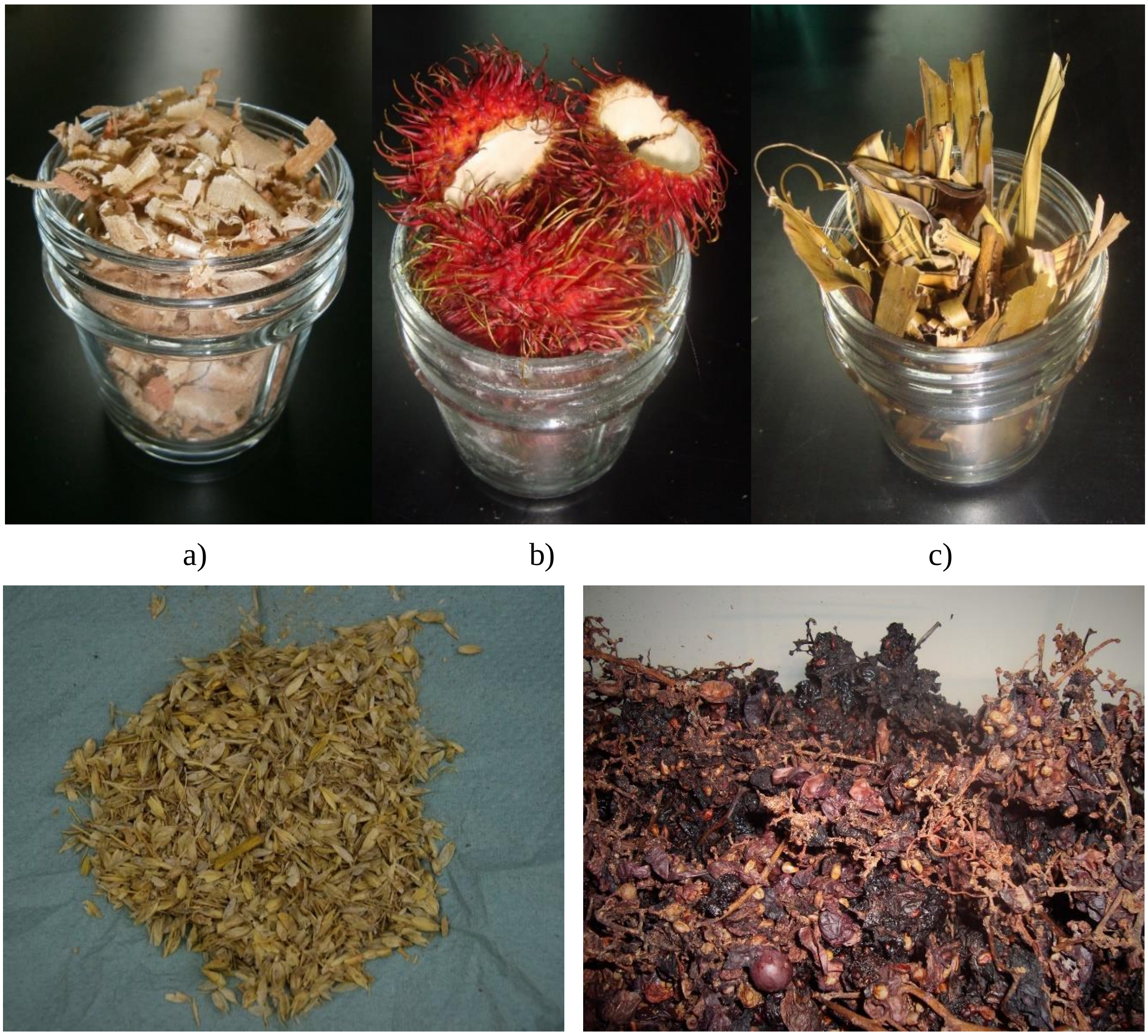
a)

b)

c)

Figure 11: Investigated waste materials in the place of originating agriculture crops: a) growth, b) processing, c) sale

Therefore, all collected waste biomass samples originated from the different levels of the agriculture crops treatment process. It indicates that the waste biomass samples occurred at the different level of their own processing, thus, occurred in the different forms (particle size, particle shape, moisture content, contamination) as is visible at Figure 12.



a) b) c)

d) e)

Figure 12: Collected samples of waste biomass before initial proper processing: a) wood chips, b) rambutan skins, c), banana leaves, d) wheat husk, e) grapevine residues

In response to the variability of collected waste materials, all potential feedstock materials had to be subjected to the identical process of treatment, thus, to proper preparation in accordance to the requirements of briquetting technology. The aim of such treatment was to unify all investigated feedstock materials to the identical form with the same properties. Process of such performance is described below in following chapter in detail.

3.1.2. Waste materials samples processing

All chosen waste biomass samples were collected in rural areas of mentioned districts (with the exception of the capital city of Prague) and properly processed directly after their collection; such processing consist of ensuring of suitable moisture content and particle size. Waste materials samples collected in foreign countries were partly processed right after the collection and preserved within their transportation to target area of their experimental testing (Prague, Czech Republic); see chapter “Chemical analysis”. Such waste biomass samples were initially cut and crushed by using of machete and kitchen blender (as shown at Figure 13), in respect to the local conditions, and subsequently dried in laboratory drier (at 105° C for 24 hour) or by using of sun energy in attempt to stabilize their properties. Immediately after such processes were stored in hermetically sealed laboratory vessels and bags.

a) b)

Figure 13: Processing of collected waste materials: a) equipment for cutting, b) sun drying

Processing of waste materials was held in laboratories at CULS Prague were performed by using equipment with different working units (see in Figure 14) due to the different feedstock materials properties and needs. Namely, by shredder AL–KO, type New Tec 2400 R (Kötz, Germany), grinder Bosch, type AXT 25 TC (Stuttgart, Germany), grinder Hecht, type 6224 (Praha, Czech Republic) or by the Hammer mill, type 9FQ – 40C (Henan, China).

Figure 14: Used equipment for grinding and milling of raw waste materials

Further, process of subsequent feedstock preparation differs in respect to the requirements of specific used briquetting technologies (high-pressure or low-pressure); processes of feedstock preparation differ in both cases. Therefore, both briquetting technologies are described in separate chapters below.

3.2. Briquetting technologies

In respect to the diametrical differences between two briquetting technologies used within present research, each of the technology is described in separate chapters below. High–pressure briquetting technology is commonly known and used for commercial bio–briquette fuel production and sale, while low–pressure briquetting technology is the alternative (sustainable) technology used mostly in developing countries and developed by non–profit organisations or individuals. Such technology is still under development.

3.2.1. High-pressure briquetting technology

Feedstock materials used for high–pressure briquetting technology were subsequently dried until the proper level of moister content (< 10 %) were achieved according to standard EN ISO 18134-2 (2015) [116] in laboratory dryer LAC, type S100/03 (Rajhrad, Czech Republic).

3.2.1.1. High-pressure briquetting press

Within the high-pressure briquetting technology, a hydraulic piston briquetting press were used, namely, Briklis, type BrikStar 30-12 (shown in Figures 15 and 16) (Malšice city, Czech Republic). Mentioned press operates with automatically settings, which ensures specific chosen density ρ of produced bio-briquette fuel. Produced briquette samples were cylindrically shaped with diameters of 50 mm (BrikStar 30-12).

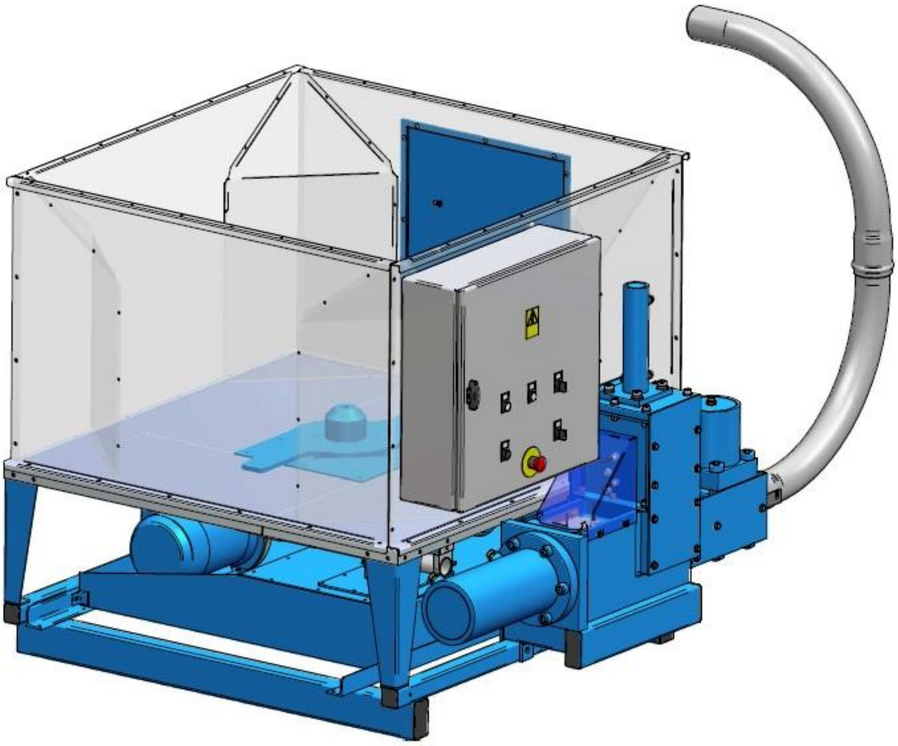


Figure 15: Used high-pressure briquetting press Briklis, type BrikStar 30-12

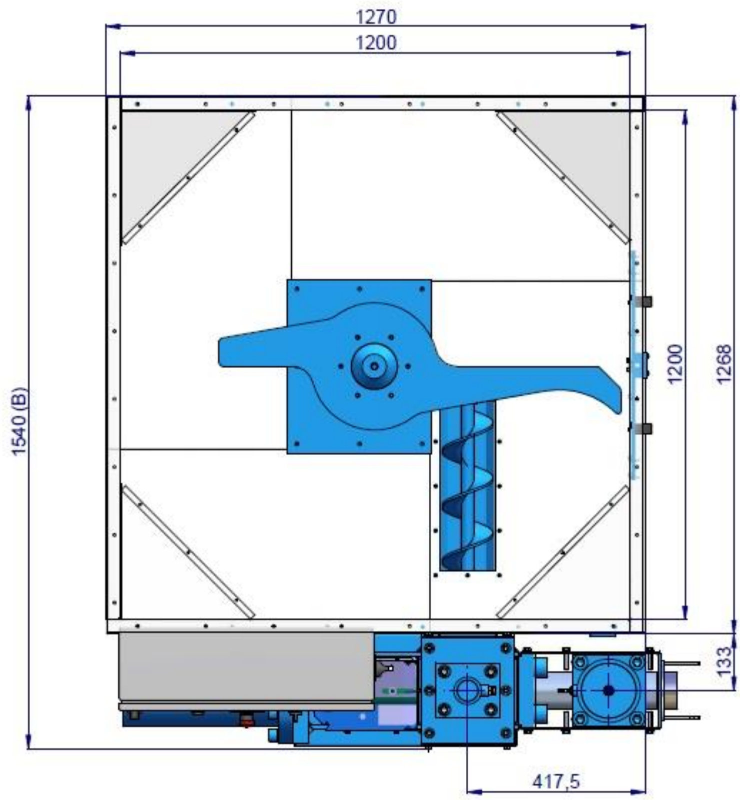


Figure 16: Scheme of used high-pressure briquetting press with dimensions (in mm)

3.2.1.2. Bio-briquette samples

All waste materials mentioned in present chapter were used for production of bio-briquette samples by using of high-pressure briquetting presses (samples identified as a diameter 50 mm) or of special designed laboratory hand crafted briquetting press (samples identified as a diameter 40 mm). Bio-briquette samples produced by high-pressure briquetting presses with matrix of diameter 50 mm occurred at identical shape with similar dimensions; specific values of such samples dimensions are noted in Table 6 and examples of produced bio–briquette samples are expressed in Figure 17.

Table 6: Dimensions of produced bio–briquette samples in average

Length (mm)	**Diameter** (mm)	**Weight** (g)
56.67±9.69	51.53±0.75	116.64±22.16

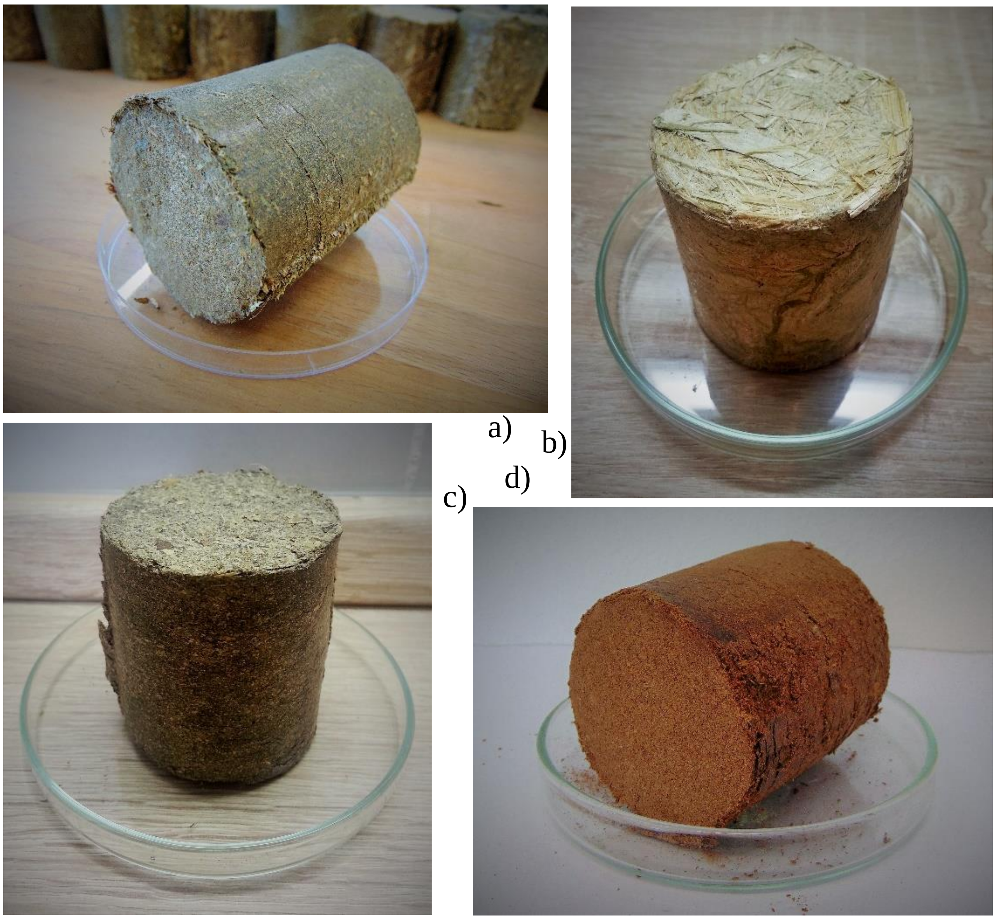


Figure 17: Bio-briquette samples produced by high-pressure briquetting press from: a) tropical greenhouse residues, b) Bamboo fibre, c) Sugarcane skin, d) Jatoba sawdust.

Due to the fact, that produced bio-briquette samples were produced from different feedstock materials with different properties, their dimensions ranged extensively. In response, the following chart with the range expression were made, as shown in Figures 18 and 19.

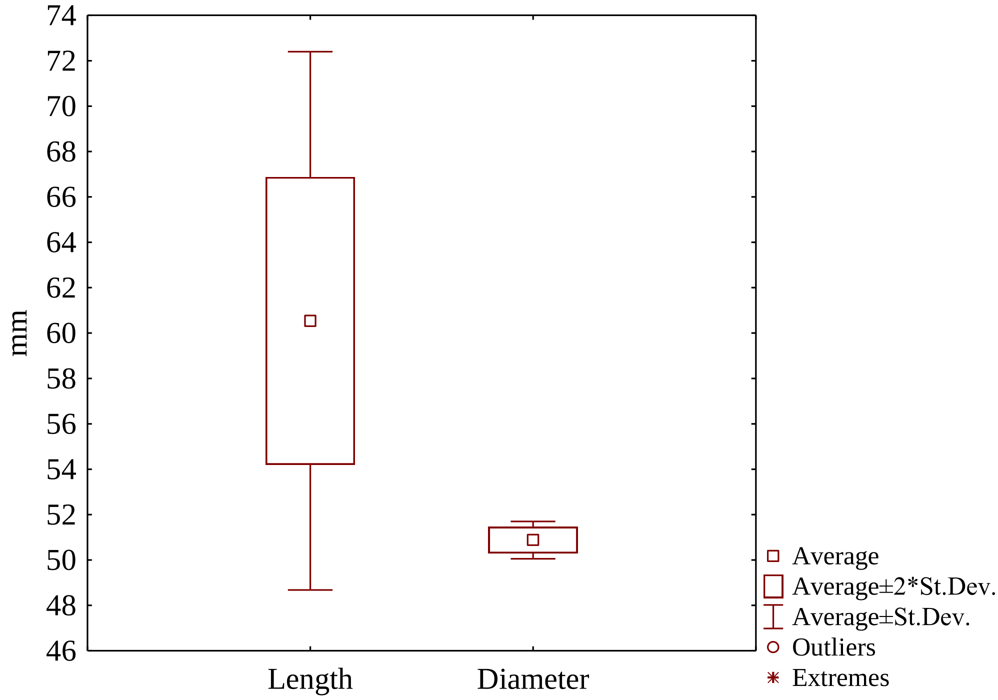


Figure 18: Range of produced bio-briquette samples dimensions

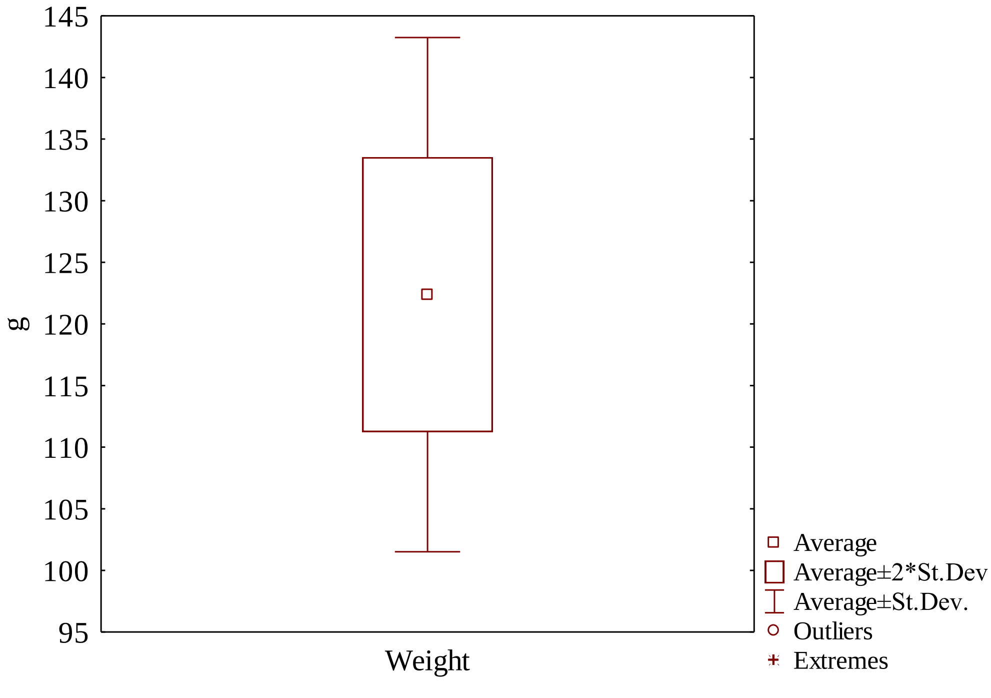


Figure 19: Range of produced bio-briquette samples weight

3.2.2. Low-pressure briquetting technology

The result of this section is represented by construction of manual low–pressure briquetting press constructed from wood components producing bio–briquettes of square shape. Methodology of manual low–pressure briquetting presses consist of several parts;

starting with the designing of components and creation of manual of such components, then, creation of user manual with process of press construction and use. Follows manufacturing of designed components and construction of manual briquetting presses and finally, the production of bio–briquette samples by constructed manual presses. In consequence, present chapter is divided according to mentioned issues.

3.2.2.1. Design of manual briquetting presses

Design of low–pressure briquetting press was based on models firstly done by Leland Hite and Dr. Zan Smith in 2011 presented on their non–profit organization Hands–on Engineering website managed by Leland Hite (http://leehite.org/). Their photo documentation served as an initial exemplar for creation of components design and construction and use manual.

Initial documents were created by using of Microsoft office software; the design of manual briquetting presses was updated and modified according to the needs during construction and utilization due to achievement of highest practicability and efficiency of such equipment. In addition, several necessary changes were done in the manual briquetting presses design, as there were several irregularities observed when putting press into the practice. Subsequently, complete professional technical documentation, including interactive 3D models of designed press was created using of SolidWorks software. Mentioned model is further expressed in chapter “Results and discussion” and in Annexes of present thesis.

3.2.2.2. Manual briquetting presses construction

Primarily, the manual low–pressure briquetting press was manufactured mainly from wood components; movable parts are screwed by metal components. Construction of press allows easy dismantling within exchangeability of components or press transportation. Square-shaped pressing chamber indicates production of bio-briquette fuel in the form of square-shaped blocks and operates with lever-powered piston using of man power. The pressing chamber is also equipped with water drainage mechanism (feedstock material occurs in wet base). Wood version of manual press was successfully manufactured and currently is used for the production of bio–briquette fuel by low-pressure technology.

Furthermore, investigated version of the manual low–pressure briquetting press should be able to operate with higher operating pressure $P < 5$ MPa.

3.2.2.3. Bio–briquette samples production

Currently, wood version of low–pressure briquetting press is completely manufactured, thus, the production of bio–briquette samples (intended for subsequent testing) was performed only by using of such equipment.

The process of proper feedstock preparation for low–pressure briquetting technology is completely opposite than in case of high–pressure briquetting technology. Although, the feedstock materials must be crushed to smaller particle size (in both cases) in case of low–pressure briquetting technology are feedstock materials subsequently mixed with water and external binding agents. Such procedure is related to the lower level of used pressure during densification process. During the feedstock preparation, water was used as a surrounding medium of feedstock materials in which were waste biomass and external binders mixed; waste paper and waste cardboard were used as external binging agents. To achieve the high quality level of produced bio-briquette fuel, following ratios of waste biomass and binding agents were investigated: (biomass:binder) – 1:1, 2:1. The selection of suitable feedstock materials was related to the conditions of target area (rural areas in developing countries) of manufactured manual low–pressure briquetting press utilization. Thus, coconut fibre was used as an investigated feedstock material. To cover also the local conditions of countries as a Czech Republic, also the wood sawdust was used as a feedstock material. Mixed feedstock materials prepared for compression were kept in the mixing vessels because of the mechanical properties of waste paper and waste cardboard; both binding agents must stayed in the water before compression to be softened and dissolved. The examples of prepared feedstock materials before pressing are shown in Figure 20.

a) b) c)

Figure 20: Feedstock materials prepared for compression: a) waste paper, b) waste paper + sawdust (1:1), c) waste paper + rice husk (1:1)

3.3. Experimental measurements

Present chapter represent all used experimental processes used within the determination of final quality of investigated waste biomass, as well as all investigated bio–briquette samples. Specifically, following mandatory technical standards were used: EN ISO 17831–2 (2015) [134], ISO 1928 (2010) [136], EN ISO 18134–2 (2015) [117], EN ISO 18123 (2016) [137], EN 643 (2014) [138], EN 14918 (2010) [139], EN ISO 16559 (2014) [140], EN ISO 16948 (2016) [121], EN ISO 18122 (2015) [118], EN 15234–1 (2011) [141] and EN ISO 17225–1 (2015) [35]. Whole names of mentioned standards are noted in the References section of present dissertation; specific processes of all practiced procedures are described in separate chapters below.

3.3.1. Chemical analysis

Following experimental testing were performed within the determination of suitability of investigated waste biomass types for direct combustion, thus, for as a feedstock materials for bio–briquette production. The safety and efficiency of such materials must be proved before their utilization.

3.3.1.1. Chemical parameters

Moisture content M_c (%), ash content A_c (%) of all tested waste biomass were the object of investigations within present measurements. Preparation of samples consisted of grinding the samples into powder with particle size < 0.1 mm, subsequently, the analysis were performed. A thermogravimetric analyser LECO TGA 701 (Saint Joseph, United States) was used for such purpose; the temperatures achieved 107 °C due to the moisture content determination, 900 °C due to the volatile matter content and 550 °C due to the ash content. Used procedures are described in detail in following technical mandatory standards: EN 18134–2 (2015) for determination of moisture content, EN ISO 18122 (2015) for determination of ash content.

3.3.1.2. Calorific values

Main indicator of waste biomass energy potential, the calorific value, was the main point of interest within the chemical analysis. Both, gross calorific value *GCV* (MJ·kg^{-1}) and net calorific value *NCV* (MJ·kg^{-1}), were stated by using of isoperibol calorimeter LECO, type AC 600 (Saint Joseph, United States). As indicated related mandatory technical standard EN 14918 (2010), tested samples were pressed into pellets and then burned in mentioned measuring equipment. Result values of gross calorific value were expressed by supplied software; three or more measurements were performed within each sample. Net calorific value was stated by considering the relationship between gross calorific value and net calorific value and its statement was performed according to mandatory technical standard ISO 1928 (2010). For accurate determination of net calorific value, following formula (Equation 1) was used:

$$NCV = GCV - 24.42 \cdot (M_c + 8.94 \cdot H) \qquad \text{(Eq. 1)}$$

(*NCV* – net calorific value (MJ·kg^{-1}), *GCV* – gross calorific value (MJ·kg^{-1}), 24.42 – coefficient of 1% of water in the sample at 25 °C (MJ·kg^{-1}), M_c – moisture content in analytical sample (%), 8.94 – coefficient of hydrogen to water conversion, H – hydrogen content in analytical sample (%))

3.3.1.3. Elementary composition

Analysis of elemental composition of investigated waste biomass kinds determined the content of carbon C (%), hydrogen H (%), nitrogen N (%), sulphur S (%) and oxygen O (%). To achieve such values the laboratory instrument LECO CHN628+S (Saint Joseph, United States) was used for the experimental procedures; a helium was used as a carrier gas. Primarily, prepared samples were burned in oxygen and secondary, the resulting flue gases were analysed. For statement of C, H and S content, the infrared absorption cells were used, while, N content was stated by using of thermal conductivity cell. Detail procedures of mentioned measurements were conducted to technical mandatory standard EN ISO 16948 (2016).

Theoretical amount of oxygen O_{min} ($m^3 \cdot kg^{-1}$) was determined according to following formulas (Equation 2, 3, 4 and 5):

$$O_{min} = \frac{22.39}{12.01} \cdot C + \frac{22.39}{4.032} \cdot H + \frac{22.39}{32.06} \cdot S - \frac{22.39}{31.99} \cdot O \qquad \text{(Eq. 2)}$$

(C – carbon content (%), H – hydrogen content (%), S – sulphur content (%), O – oxygen content (%))

Theoretical amount of dry air L ($m^3 \cdot kg^{-1}$) was determined according to following formula:

$$L = O_{min} \cdot \frac{100}{21} \qquad \text{(Eq. 3)}$$

(O_{min} – theoretical amount of oxygen ($m^3 \cdot kg^{-1}$))

The theoretical amount of dry flue gases $v_{sp_{min}}^{s}$ ($m^3 \cdot kg^{-1}$) was determined according to following formula:

$$v_{sp_{min}}^{s} = \frac{22.27}{12.01} \cdot C + \frac{21.89}{32.06} \cdot S + \frac{22.40}{28.013} \cdot N + 0.7805 \cdot L \qquad \text{(Eq. 4)}$$

(C – carbon content (%); S – sulphur content (%); N – nitrogen content (%); L – theoretical amount of dry air ($m^3 \cdot kg^{-1}$))

The theoretical amount of emission concentrations of CO_2 ($m^3 \cdot kg^{-1}$) was determined according to following formula:

$$CO_2 = \frac{\frac{22.27}{12.01} \cdot C}{v^s_{sp_{min}}} \cdot 100 \quad \text{(Eq. 5)}$$

($v^s_{sp_{min}}$ – theoretical amount of dry flue gases; C – carbon content (%))

3.3.2. Mechanical analysis

Several experimental measurements were chosen for testing, determination and evaluation of final mechanical quality of investigated bio–briquette samples; following mechanical quality indicators were performed within the present issue:

3.3.2.1. Density (*ρ*)

Basic determined parameter of investigated bio–briquette samples related to their dimensions and mechanical quality was a density ρ (kg·m^{-3}). Dimensions of all investigated bio–briquette samples were measured and subsequent calculations were performed by using of following formula (Equation 6):

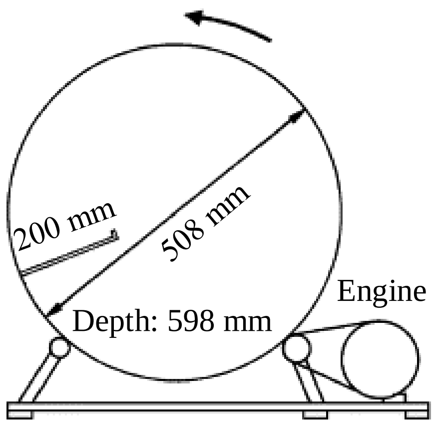
$$\rho = \frac{m}{V} \quad \text{(Eq. 6)}$$

(ρ – density (kg·m^{-3}); V – bio–briquette samples volume (m^3); m – bio–briquette samples mass (kg))

3.3.2.2. Mechanical durability (*DU*)

Mechanical durability was most important indicator of bio–briquette fuel final mechanical quality. Process of measurement were performed in accordance to technical mandatory standard ISO 17831–2 (2015) which consist of requirements and conditions related to such test. Experimental testing was performed in special rotating dust–proof drum powered by electricity with rectangular steel partition (see Figure 21).

a)



b)

Figure 21: Special rotating drum: a) author´s photo, b) scheme

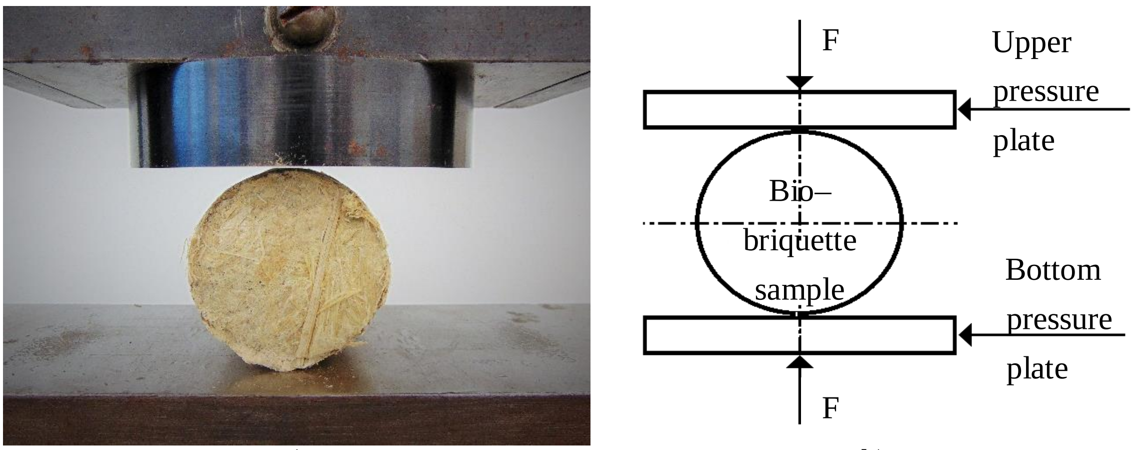
Due to the measurement process, all investigated bio–briquette samples were weighed before and after measurement. Result values of mechanical durability of such bio–briquette samples were determined by following formula (Eq. 7):

$$DU = \frac{m_a}{m_e} \cdot 100 \quad \text{(Eq. 7)}$$

(DU – mechanical durability (%); m_e – samples weight before testing (g); m_a – samples weight after testing (g))

3.3.2.3. Rupture force (*RF*)

Last investigated indicator of bio–briquette mechanical quality was rupture force RF ($N \cdot mm^{-1}$), thus the applied force (N) on the bio-briquette sample length (mm) were the measured indicators. Principle of such indicator is not defined by any mandatory technical standard, but originates from previous researches [101-105]. Principle of such measurement described tests the maximal stress force applied to a specific sample which is able to hold before it disintegrates. I case of bio–briquette fuel, rupture force simulates the influence of transportation, handling and storage of bio–briquettes in reality and the potential damages. All investigated bio–briquette samples were subjected to experimental measurements sting performed by plate-loading test (principle is shown in Figure 22, b)). A universal hydraulic tensile machine, type ZDM 5 (VEB, Dresden, Germany), operating with loading speed equal to 20 $mm \cdot min^{-1}$ and maximal force equal to 5 tons, was used as a source of power; scheme of machine is expressed in Figure 22, a). The maximal loading force before the briquette sample was irreversibly deformed was measured.

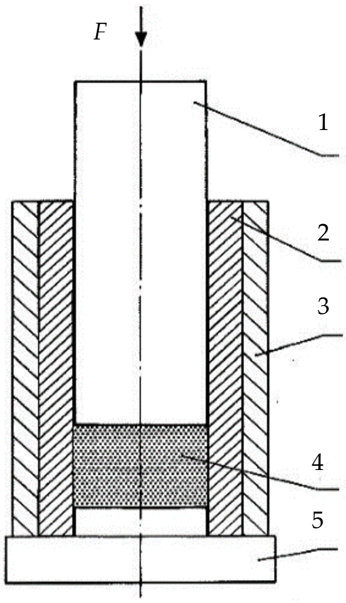


a) b)

Figure 22: Principle of rupture force test: a) in practice, b) scheme of plate–loading test

3.3.3. Energy demand of bio–briquette production

Last of the investigated aspects of waste biomass bio–briquette production was the energy demands of such production. Within such observation, the energy inputs of feedstock compression process and final mechanical quality of produced bio–briquette samples were monitored. Selected feedstock materials were compressed by using of specially designed laboratory hand–crafted briquetting press [142]. As shown at Figure 23, a pressing chamber of used laboratory press had two different diameters: namely, 40 mm and 65 mm. Therefore, produced bio–briquette samples had such diameters. The pressing chamber was 120 mm height, while, the underlay high placed in the chamber was 9 mm. The pressing chamber could not be filled to the edge, thus, the initial height of investigated feedstock materials before pressing was equal to 108 mm.



a) b)

Figure 23: Used laboratory hand crafted briquetting press: a) in practice, b) scheme

(*F* – compressive force, 1 – piston, 2 – pressing chamber, 3 – metal casing, 4 – feedstock material, 5 – bottom pressure plate) [142]

As a source of loading force served the universal hydraulic tensile compression machine type ZDM 50 (VEB, Dresden, Germany) with maximal compression loading P_{max} equal to 500 kN and pressing speed v_p equal to 1 mm·s^{-1}.

Primarily, a displacement of the piston *s* (mm) and a compression force *F* (N) were monitored, while, movement of the piston caused deformation of inserted feedstock materials, thus, increasing of bio–briquette samples density ρ (kg·m^{-3}). Result values were measured directly during the compression of feedstock materials. Observed values served as an initial data for subsequent determination of required deformation energy E_d (J) consumed during the densification process, which was the main aim of present experimental measurements. In general, result values of bio–briquette samples density ρ (kg·m^{-3}) and required deformation energy E_d (J) were assigned to each other at specific levels. Thus, bio–

briquette samples density ρ were monitored at levels from 800 until 1,300 $kg \cdot m^{-3}$ (interval 50 $kg \cdot m^{-3}$) and corresponding levels of required deformation energy E_d for such density ρ levels were assigned. In such context, required deformation energy E_d represented financial demands of densification process and density ρ represented bio–briquette mechanical quality.

For expression of deformation energy E_d was chosen specific tangent function (shown in Equation 8); in respect to published studies [143; 144].

$$F(x) = C_0 . \tan(C_1 . x)^{C_2} \qquad \text{(Eq. 8)}$$

(C_0 – force coefficient (N), C_1 – deformation coefficient (m^{-1}), C_2 – exponent of fitted function (–))

Determination of tangent curve model coefficients were performed for each investigated wastes biomass samples; observed data (compressing force F (N), feedstock deformation s (m)) were processed by using of MathCAD 14 software (PTC, Needham, USA) through the "genefit" function.

Result values of required deformation energy E_d were expressed by statement of integral of chosen tangent curve function (as shown in Equation 9).While, such result values were expressed as an area located under the tangent curve.

$$E_d(s) = \int_0^s F(x)dx \qquad \text{(Eq. 9)}$$

4. Results and discussion

The present chapter is divided into three parts: 1) related to the chemical properties of the investigated waste biomass kinds in an attempt to define its suitability for combustion purposes regarding their low impact on the environment and efficiency during burning (from the perspective of using such materials as a feedstock for bio-briquette fuel production), 2) focused on the mechanical quality of subsequently produced bio-briquette samples within the statement of their strength and resistance during their use, transportation and handling; it also describes the efficiency of tested waste biomass kinds within its utilization for clean renewable energy generation, and 3) monitoring and evaluating developed and verified technology of low-pressure briquetting; thus, the practicability and viability of such equipment is determined.

A list of all investigated waste materials with information of experimental measurements undertaken is given in Table 7. Selected waste materials were subjected to analysis of their chemical parameters or were used for bio-briquette production with subsequent determination of final mechanical quality of such products, or both procedures were performed within one specific investigated waste material. Not all materials were used for bio-briquette sample production due to the limitation of their amount (exotic samples).

Table 7: Description of performed experimental analyses of specific waste materials.

Biomass kind	Samples name	Chemical analysis of waste biomass	Mechanical analysis of bio–briquette samples
Wood	Pine bark	Yes	Yes
	Spruce bark	Yes	Yes
	Fruit tree branches	No	Yes
	Larch sawdust	Yes	Yes
	Spruce chips	Yes	Yes
	Jatoba sawdust	Yes	Yes
	Garapa sawdust	Yes	No
	Ash tree chips	No	Yes
Herbaceous	Tropical plants	No	Yes
	Rice husk	Yes	No
	Cacao leaves	Yes	No
	Banana leaves	Yes	No
	Aloe Vera leaves	Yes	No

	Coffee leaves	Yes	No
	Bamboo leaves	Yes	No
	Bamboo fibres	Yes	Yes
	Japanese knotweed stems	Yes	Yes
	Oat husk	Yes	Yes
	Poppy residue	Yes	Yes
	Wheat husk	Yes	Yes
	Cassava stover	Yes	No
	Sugar cane skin	Yes	Yes
	Sugar cane bagasse	Yes	No
Fruit	Vine residue	Yes	Yes
	Date skin	Yes	No
	Date pits	Yes	No
	Jatropha shells	Yes	No
	Jatropha press–cake	Yes	No
	Durian skin	Yes	Yes
	Coconut skin	Yes	Yes
	Coffee skin	Yes	Yes
	Cacao skin	Yes	Yes
	Banana skin	Yes	Yes
	Rambutan skin	Yes	Yes
	Oil palm kernel	Yes	No
	Oil palm fibre	Yes	No
	Tapioca skin	Yes	No
	Coffee ground	Yes	Yes
Aquatic	Water hyacinth plant	Yes	No
	Water–thyme plant	Yes	No
	Eurasian water milfoil plant	Yes	No
Mixed	Coffee ground + larch sawdust	No	Yes
	Coffee ground + spruce shavings	No	Yes
	Oat + poppy + wheat husks	Yes	Yes
	Waste cardboad	No	Yes
	Waste paper	Yes	Yes

4.1. Waste biomass chemical parameters

Within the chemical analysis, the samples of selected materials were conducted to the set of experimental measurements which together described their suitability for the purpose of energy generation by combustion methods. Obtained results were primarily expressed for each specific investigated waste material; subsequently, such values were used for calculation of chemical parameters of specific biomass kinds.

4.1.1. Basic chemical parameters (M_c, A_c, *GCV*, *NCV*)

Chosen parameters (ash content, moisture content, volatile matter content, gross calorific value and net calorific value) were considered adequate quality indicators of bio-briquette fuel chemical quality. A complete chemical analysis was not available for all investigated samples due to limitations in samples amounts or to its inappropriateness for specific experimental measurements (homogeneity, contamination). Result values of specific investigated **waste materials** obtained during determination of the basic chemical parameters are noted in Table 8, while results of chemical parameters of whole specific **biomass kinds** are noted in Table 9.

Values considered as extremely good results are highlighted by **bold letters** and extremely bad results are <u>underlined</u> in Tables 8 and 9**,** as well as in all following Tables 10, 11, 12 and 13 in the following chapters. All values presented in the following Tables were obtained during experimental measurements in an accredited laboratory.

Thus, the overall evaluation of the present investigated parameters and their results provide findings and knowledge resulting in problematics understanding, optimal setting and proper performance of combustion devices. Moreover, the technologies for waste biomass processing (to solid biofuels) could also be positively influenced and improved [145].

Table 8: Results of basic chemical parameters (in w.b.) of representative samples of investigated waste biomass kinds (averages).

Biomass kind	Samples name	Country of origin	M_c (%)	A_c (%)	*GCV* ($MJ \cdot kg^{-1}$)	*NCV* ($MJ \cdot kg^{-1}$)
Wood	Pine bark	Czech rep.	<u>14.02</u>	1.87	18.60	17.62
	Spruce bark	Czech rep.	11.91	5.15	**19.30**	18.01
	Larch sawdust	Czech rep.	<u>14.36</u>	**0.43**	17.42	14.92
	Spruce chips	Czech rep.	8.25	**0.31**	18.68	17.27
	Jatoba sawdust	Brazil	7.46	**0.31**	**20.16**	**18.92**
	Garapa sawdust	Brazil	7.77	3.02	**19.61**	**18.39**
Herbaceous	Rice husk	Indonesia	6.79	<u>22.10</u>	14.93	13.91
	Rice husk	Vietnam	6.06	<u>19.48</u>	14.43	13.32
	Cacao leaves	Indonesia	8.73	13.50	17.90	16.34
	Banana leaves	Indonesia	4.56	9.16	18.00	17.18
	Aloe Vera leaves	Indonesia	4.01	<u>13.53</u>	17.61	16.90
	Coffee leaves	Indonesia	9.33	9.42	**19.65**	17.82
	Bamboo leaves	Indonesia	7.38	12.50	18.05	16.71
	Bamboo fibres	Vietnam	7.62	**1.16**	**19.76**	**18.51**
	Japanese knotweed stems	Czech Rep.	11.5	**1.14**	19.43	17.71
	Oat husk	Czech Rep.	9.95	2.65	19.31	17.39
	Poppy residue	Czech Rep.	<u>13.70</u>	10.13	16.78	14.48
	Wheat husk	Czech Rep.	6.95	5.01	18.31	17.04

	Cassava stover	Indonesia	6.31	3.14	**19.80**	**18.55**
	Cassava stover	Vietnam	5.93	2.75	**20.60**	**18.81**
	Sugar cane skin	Vietnam	8.05	8.62	**20.23**	**18.95**
	Sugar cane bagasse	Vietnam	7.00	**0.84**	19.18	17.84
Fruit	Vine residue	Czech Rep.	6.43	6.60	19.17	17.94
	Date skin	China	6.88	2.65	16.52	15.10
	Date pits	China	5.90	**1.18**	18.13	16.65
	Jatropha shell	Indonesia	7.39	1.45	**19.59**	**18.29**
	Jatropha press–cake	Indonesia	4.94	4.36	**24.83**	**23.12**
	Durian skin	Indonesia	5.81	5.05	18.78	17.61
	Durian skin	Vietnam	8.53	5.13	18.16	16.61
	Coconut skin	Indonesia	5.80	4.52	**19.33**	**18.22**
	Coffee skin	Indonesia	4.85	8.84	18.55	17.37
	Cacao skin	Indonesia	4.43	9.50	17.84	16.73
	Banana skin	Indonesia	3.91	9.87	19.02	17.79
	Banana skin	Vietnam	8.27	12.02	**20.24**	**18.56**
	Rambutan skin	Indonesia	5.82	3.67	18.32	17.24
	Rambutan skin	Vietnam	7.55	3.21	18.42	17.03
	Tapioca skin	Indonesia	1.52	<u>32.15</u>	<u>12.68</u>	<u>11.55</u>
	Oil palm kernel	Indonesia	4.24	**1.07**	**21.30**	**20.40**
	Oil palm fibre	Indonesia	4.80	1.89	**20.85**	**19.85**

	Coffee ground	Czech rep.	9.56	**1.49**	**21.58**	**19.96**
Aquatic	*Eichhornia crassipes*	Indonesia	7.50	11.60	16.31	15.09
	Eichhornia crassipes	Vietnam	7.48	14.16	15.10	<u>13.97</u>
	Myriophyllum spicatum	Indonesia	6.11	**36.99**	<u>11.27</u>	<u>10.58</u>
	Myriophyllum spicatum	Vietnam	5.18	**53.31**	<u>9.10</u>	<u>8.63</u>
	Hydrilla verticillata	Indonesia	8.63	**15.53**	15.24	<u>13.93</u>
Mixed	Coffee ground + larch sawdust (1:1)	Czech Rep.	11.50	1.49	**19.72**	**18.19**
	Coffee ground + larch sawdust (1:3)	Czech Rep.	**13.52**	1.49	18.77	17.31
	Coffee ground + spruce shavings (1:1)	Czech Rep.	9.90	**0.91**	**20.13**	**18.62**
	Coffee ground + spruce shavings (1:3)	Czech Rep.	10.31	**0.61**	19.41	17.94
	Oat husk + poppy residue + wheat husk (1:1:1)	Czech Rep.	7.26	3.21	18.83	17.46
	Waste paper	Czech Rep.	4.99	**37.85**	15.55	<u>12.15</u>

M_c – moisture content A_c – ash content, VM_c – volatile matter content, *GCV* – gross calorific value, *NCV* – net calorific value

Table 9: Chemical analysis of specific waste biomass kinds in w.b. (averages).

Biomass kind	$\boldsymbol{M_c}$ **(%)**	$\boldsymbol{A_c}$ **(%)**	***GCV*** **(MJ·kg^{-1})**	***NCV*** **(MJ·kg^{-1})**
Wood	10.63 ± 3.19	**1.02 ± 1.34**	18.97 ± 1.20	17.38 ± 1.78
Herbaceous	7.74 ± 2.48	8.98 ± 6.73	18.18 ± 1.82	16.76 ± 1.72
Fruit	5.92 ± 1.93	6.21 ± 6.98	**19.09 ± 2.29**	**18.22 ± 1.84**
Aquatic	6.98 ± 1.35	18.19 ± 26.32	13.40 ± 3.07	12.44 ± 2.72
Mixed	9.58 ± 3.04	7.59 ± 14.85	**19.37 ± 0.58**	**17.51 ± 1.07**

M_c – moisture content, A_c – ash content, *GCV* – gross calorific value, *NCV* – net calorific value, ± – standard deviation

Result values noted in Table 9 were calculated by using of values noted in Table 8 and by using of the statistical method of sum of quantile deviance, thus it ensure the occurrence of the values in positive numbers.

Primarily, it must be considered that investigated waste materials differed within their biological classification, the taxonomic rank, and thus the evaluation of obtained results is represented by significant differences in several cases. Such knowledge must also be considered during the evaluation of mechanical quality of bio-briquettes produced from such waste biomass kinds.

The level of moisture content noted in Table 8 represents the moisture content M_c of investigated samples during the experimental testing. Such levels can be easily changed by the drying process; thus, such data were informative only. Considering the fact that all materials were agriculture wastes, some of them had already been dried prior to the previous technological processes. Nevertheless, initial moisture contents in M_c of several investigated materials, which described the level of moisture content right after waste material separation and collection, are noted in Table 10.

Initial moisture content M_c (%)

The initial moisture content M_c (%) of several selected waste biomass kinds was determined immediately after their collection. Such materials were selected due to their assumptions for extremely high moisture content. This parameter played an important role in subsequent treatment; inappropriate moisture content (> 10 %) could complicate subsequent bio-briquette production [116; 117]. All investigated samples originated from the Republic of Indonesia.

Results noted in Table 8 indicate an exceptionally high level of moisture content; such observations did not represent a suitable state for the purposes of bio-briquette production (requirements of densification process). Thus, investigated waste biomass kinds must be dried at first (before its subsequent utilization), and specific energy input is required. Such an issue could be partly solved by using a sun-drying technique, which is possible in target developing countries and in similar geographic areas.

Table 10: Initial moisture content of selected waste materials.

Biomass kind	Sample name	Initial M_c (%)
Fruit	Durian skin	83.50
	Coconut skin	83.46
	Cacao skin	84.49
	Coffee skin	80.06
	Banana skin	63.35
	Rambutan skin	74.47
Aquatic	*Eichhornia crassipes* body	85.30
	Hydrilla verticillata body	88.50
	Myriophyllum spicatum body	89.60

Initial M_c – water content of waste biomass kinds in initial form of residue.

Comparable values were reported in a paper related to aquatic biomass potential for energy generation in countries such as Indonesia and Malaysia. That study dealt with moisture content of different parts of the water hyacinth (*Eichhornia crassipes*) and determined the moisture content as ranging from 77.5 % to 95.2 % [49].

Determination of ash content A_c levels reflected the differences between specific waste biomass kinds very visibly. Best results were achieved using wood waste biomass (A_c = 1.02 % in average) and the worst by aquatic biomass (A_c up to 53.31 %). Focusing on specific waste biomass kinds, the biggest differences were observed for the herbaceous biomass (A_c ranged from 1.14 % to 22.10 %), while the A_c of fruit waste biomass occurred at a similar level in the case of all investigated waste materials, except one – Tapioca skin (A_c = 32.15 %). Such results could have been influenced by contamination of the samples by external agents (earth) due to the samples' origin. Nevertheless, Tapioca skin samples were tested in their initial form (contaminated) to express their suitability in real situations. In general, as stated before, non-woody waste biomass kinds exhibit a higher level of ash content compared with wood waste biomass. Nevertheless, undesirably high levels of ash content represent a problem during biofuel combustion and negatively influences the level of calorific values [99; 100]. Such phenomena can be clearly visible in the lower levels of investigated waste materials calorific values [99; 100]. By comparison, the lowest level of net calorific values *NCV* was achieved by aquatic waste biomass (12.44 $MJ \cdot kg^{-1}$ in average), which is an extremely unsatisfactory result. In contrast, fruit waste biomass exhibited a high level of *NCV* (18.22 in average $MJ \cdot kg^{-1}$), particularly waste materials originating from Jatropha (23.12 $MJ \cdot kg^{-1}$) and palm oil (21.30 $MJ \cdot kg^{-1}$), which was caused by the presence of residual oil. Similar results were observed in the case of sunflower –

21.23 MJ·kg^{-1} and rapeseed – 21.57 MJ·kg^{-1} residues [69]. Mixed and wood waste biomass exhibited satisfactory levels of such energy potential indicators, as well as herbaceous waste biomass. The only exception was within represented rice husk (both samples), which exhibited unsatisfactory levels of *NCV*.

The energy potential of other agriculture residues used for bio-briquette fuel production have already been investigated; Table 11 provides observed data for comparison with results from the present research thesis.

Table 11. Energy potential of fruit waste biomass kinds found by other authors.

Biomass kind	Feedstock material	NCV (MJ·kg^{-1})	Author of Research
Wood	Tasmanian bluegum wood	14.41	[146; 147]
	Wild cherry wood	15.55	
	Willow wood	15.37	
	Sycamore wood	15.62	
	Vine prunnings	19.19	[148]
	Pine sawdust	18.14	[29]
Herbaceous	Rape straw	16.13	[29]
	Wheat straw	17.30	[149]
	Barley straw	16.10	
	Rice straw	15.07	[150]
	Banana leaf	17.76	
	Sugarcane bagasse	18.20	
	Corncob	18.76	
Fruit	Durian peel	15.92	[71]
	Coconut fibre	19.40	[26]
	Cacao peel	17.00	[151]
	Coffee peel	16.93	[152]
	Banana peel	18.89	[153]
	Grape seeds	20.39	[69]
Aquatic	Water hyacinth	16.65	[150]
Mixed	Rice husk + Oil palm sludge	21.68	[47]
	Sawdust + palm kernel	19.53	[154]
	Tropical hardwood species	18.94	
	Rice straw + Sugarcane	17.83	[155]

NCV – net calorifc value

4.1.2. Elementary composition (*C*, *H*, *N*, *S*, *O*)

Elementary composition of waste biomass influences its calorific value and behaviour of subsequently produced biofuel during combustion. In particular, high levels of oxygen influence air consumption during combustion and amounts of produced flue gas. Thus, it is important to determine such parameters to ensure an adequate combustion process. Results of specific parameters of elementary composition of investigated waste materials are given in Table 12.

Table 12: Values of elementary composition analysis of selected waste materials.

Biomass kind	Sample name	Country of origin	*C* (%)	*H* (%)	*N* (%)	*S* (%)	*O* (%)
Wood	Jatoba	Brazil	52.62	5.71	0.23	0.03	41.10
	Garapa	Brazil	51.16	5.60	0.23	0.02	39.97
	Larch sawdust	Czech rep.	45.00	6.61	0.09	–	43.09
	Spruce chips	Czech rep.	46.87	6.48	0.04	–	42.62
Herbaceous	Rice husk	Vietnam	37.28	4.43	0.38	0.06	**32.32**
	Bamboo fibre	Indonesia	50.42	5.75	0.48	0.04	42.15
	Sugar cane skin	Indonesia	50.21	5.90	1.05	0.19	34.02
Fruit	Durian	Indonesia	48.95	5.38	1.25	0.13	38.75
	Coconut	Indonesia	51.19	5.11	0.48	0.09	38.06
	Cacao	Indonesia	47.78	5.11	1.38	0.11	36.18
	Coffee	Indonesia	47.63	5.42	1.60	0.34	**35.42**
	Banana	Indonesia	47.68	5.68	1.45	0.09	33.86
	Rambutan	Indonesia	50.41	4.94	1.17	0.09	39.42
	Date skin	China	42.20	5.72	0.52	0.08	41.97
	Date pits	China	44.24	6.13	1.04	0.10	41.42
	Jatropha shell	Indonesia	49.77	5.15	0.49	0.04	**35.71**
	Jatropha press–cake	Indonesia	**54.83**	7.32	**3.05**	0.21	**25.30**
	Coffee ground	Czech rep.	50.19	7.46	2.16	–	**33.97**

C – carbon, *H* – hydrogen, *N* – nitrogen, *S* – sulphur, *O* – oxygen.

In general, a low content of oxygen is required; such results were primarily observed; in the case of Jatropha press-cake, observed values were distinctly better than for other investigated waste materials. A satisfactory level of oxygen should occur at 40 % of the maximum; higher values are undesirable.

Table 13: Elementary composition of specific waste biomass kinds.

Biomass kind	***C*** (%)	***H*** (%)	***N*** (%)	***S*** (%)	***O*** (%)
Wood	48.91 ± 3.57	6.10 ± 0.52	0.15 ± 0.10	0.03 ± 0.01	41.70 ± 1.43
Herbaceous	43.85 ± 9.29	5.09 ± 0.93	0.43 ± 0.07	0.05 ± 0.01	37.24 ± 6.95
Fruit	48.76 ± 3.27	5.78 ± 0.83	1.30 ± 0.74	0.13 ± 0.08	**36.17 ± 4.43**

C – carbon, *H* – hydrogen, *N* – nitrogen, *S* – sulphur, *O* – oxygen, ± – standard deviation

Overall evaluation of elementary composition of specific waste biomass kinds is expressed in Table 13, which represents the average values of specific material results.

4.2. Bio–briquette fuel mechanical parameters

The present chapter describes the results of bio-briquette fuel production. Thus, experimental measurements of their quality indicators are related to their strength and durability. Nevertheless, not all previously tested waste materials were used for bio-briquette sample production and their subsequent quality testing. According to the previously performed experimental measurements, the waste materials which exhibited unsatisfactory results with respect to their chemical analysis (material suitability for the process of direct burning) were identified, and further excluded from all other subsequent analysis due to their undesirable parameters. Within such an evaluation, the waste materials of aquatic biomass were identified as an unsuitable feedstock for solid biofuel; thus, such waste materials were not used for bio-briquette sample production and were no longer used in other experimental measurements.

Analysis of mechanical quality indicators follow up on the ‘Methodology’ section of the present thesis. Thus, three specific indicators are here described and evaluated. Namely, density ρ (kg·m^{-3}), rupture force *RF* (N·mm^{-1}) and mechanical durability *DU* (%). Results for the mentioned indicators are noted in Table 14 (specific waste materials) and Table 15 (specific waste biomass) below; while a clear comparison between specific waste biomass kinds, as well as between specific waste materials can be easily performed. With respect to the quantity limitation of specific investigated feedstock materials of aquatic biomass kinds, such samples were not used for bio-briquette production; thus, analysis of such bio-briquette fuel mechanical quality was not stated.

Table 14: Values of produced bio-briquette samples' mechanical quality parameters (averages).

Biomass kind	Sample name	Sample diameter (mm)	*ρ* (kg·m^{-3})	*RF* (N·mm^{-1})	*DU* (%)
Wood	Pine bark	50	976.87 ± 37.91	56.02 ± 16.47	92.77 ± 0.45
	Spruce bark	50	913.23 ± 48.23	45.33 ± 3.67	91.37 ± 0.61
	Fruit tree branches	50	951.40 ± 34.70	**94.30 ± 23.58**	94.87 ± 0.82
	Larch sawdust	50	1026.39 ± 27.08	**102.78 ± 29.78**	**98.44** ± 0.08
	Spruce shavings	50	1036.53 ± 24.44	**179.48 ± 24.43**	**96.70 ± 1.00**
	Jatoba sawdust	50	871.69 ± 35.93	49.70 ± 18.78	<u>77.60</u> ± 0.57
Herbaceous	Tropical plants	50	1,029.76 ± 32.50	112.92 ± 22.90	**97.40 ± 0.10**
	Bamboo fibres	50	986.37 ± 11.18	**143.31** ± 1.70	**97.80 ± 0.04**
	Japanese knotweed stems	50	989.11 ± 15.70	112.11 ± 15.90	95.10 ± 0.20
	Poppy residue	50	**1,141.43** ± 44.05	58.73 ± 11.02	94.70 ± 0.90
	Wheat husk	50	**1,023.19 ± 32.42**	44.18 ± 5.40	89.11 ± 2.00
	Sugar cane skin	50	1,067.08 ± 39.08	46.51 ± 0.80	**97.70 ± 0.08**
Fruit	Vine residue	50	**1,183.21 ± 44.05**	<u>19.11 ± 6.28</u>	<u>28.32 ± 3.50</u>
	Durian skin*	40	**1,264.00**	–	–
	Coconut skin*	40	1,186.00	–	–
	Coffee skin*	40	1,221.00	–	–
	Cacao skin*	40	1,089.00	–	–
	Banana skin*	40	**1,280.00**	–	–

	Rambutan skin*	40	**1,339.00**	–	–
Mixed	Coffee ground + larch (1:1)	50	1,112.58 ± 34.83	46.07 ± 8.98	90.05 ± 1.04
	Coffee ground + larch (1:3)	50	1042.39 ± 57.86	50.85 ± 11.64	90.12 ± 0.03
	Coffee ground + spruce (1:1)	50	956.45 ± 68.40	37.09 ± 11.25	<u>49.00</u> ± 0.38
	Coffee ground + spruce (1:3)	50	842.42 ± 69.99	31.06 ± 8.87	<u>44.00</u> ± 0.11
	Oat + poppy + wheat husks	50	972.49 ± 34.99	24.79 ± 15.85	<u>62.71</u> ± 3.50
	Waste paper	50	1,126.03 ± 87.04	**95.77** ± 15.61	**98.97** ± 0.56

*samples produced in laboratory condition; *ρ* – density, *RF* – rupture force, *DU* – mechanical durability

Bio–briquette samples of fruit waste biomass highlighted by * in Table 14 were not subjected to the deformation experimental measurement due to the limitation of their amount. Such bio–briquette samples were produced in laboratory conditions by special laboratory press in limited numbers, thus, it was not possible to keep the requirements of experimental testing of their mechanical quality, also it was not suitable to performed the simple statistical evaluation of observed result values.

Result values noted in Table 14 represent the average values of experimental tests performed within the one specific feedstock material. Thus, during the overall evaluation of the specific waste biomass kinds characterization was performed by using of mentioned data from Table 14 and the statistical method of sum of quantile deviance, which ensures that all values occur in positive numbers. The results of such calculations are noted in Table 15.

Table 15: Mechanical parameters of bio-briquette fuel from specific kinds of waste biomass.

Biomass kind	ρ (kg·m^{-3})	*RF* (N·mm^{-1})	*DU* (%)
Wood	962.69 ± 87.11	87.94 ± 51.74	91.96 ± 1.61
Herbaceous	1039.49 ± 77.11	94.25 ± 30.52	**95.30 ± 2.21**
Fruit	**1203.87 ± 6.64**	19.11 ± 6.28	28.32 ± 3.50
Mixed*	–	–	–

ρ – density, *RF* – rupture force, *DU* – mechanical durability, ± – standard deviation

*present set of data of result values of specific bio–briquette samples of different mixed feedstock materials could not be summarized and characterized by the statistical method of sum of quantile deviance, due to the excessive diversity of used feedstock materials; also the standard deviation of such result values could not be stated.

Bio-briquette fuel density ρ

Primarily, the density ρ of all bio-briquette samples was evaluated, while satisfactory results were observed in cases of all investigated samples. Bio-briquette fuel density ρ expresses the efficiency of densification process, as well as the suitability of specific feedstock materials for briquette production and briquette burning ability. Previous research indicated that briquette physical-mechanical quality increases with increasing bio-briquette sample density ρ [58; 146; 156]. Higher density ρ provides longer time of bio-briquette fuel burning and greater amount of produced heat, which is highly required [157]. Other studies suggest that density ρ of high quality bio-briquette fuel should be higher than 1,000 kg·m⁻

^{3} [47; 62; 158]. Hence, it can result in a satisfactory level of density ρ being achieved; only the bio-briquette sample produced from Jatoba sawdust exhibited a lower level (871.69 $kg \cdot m^{-3}$).

Density ρ of high-quality bio-briquette fuel ranges between 1,000 – 1,200 $kg \cdot m^{-3}$ and its level depends on used feedstock material [47; 62; 158]. If considerning commonly used technical mandatory standards, according to ÖNORM M7135 (2000) [159] the bio-briquette density ρ must be > 1,000 $kg \cdot m^{-3}$, German standard DIN 51731 (1996) [160] states a bio-briquette density ρ > 1,120 $kg \cdot m^{-3}$ [29]. European standard ISO 13061–2 (2014) [161] requires density ρ of wood bio-briquettes > 1,000 $kg \cdot m^{-3}$, while American mandatory technical standards ASAE 269.4 (1996) [162]. Previous studies indicated that bio-briquette physical-mechanical quality increases with increasing bio-briquette density ρ. Therefore, bio-briquettes which exhibit a density ρ equal to 1,000 $kg \cdot m^{-3}$ can be considered high–quality fuel [58; 146; 156].

Another two experimental measurements represented destructive methods. Thus, bio-briquette samples were damaged during test performance. Investigated bio-briquette samples before and after *RF* ($N \cdot mm^{-1}$) and *DU* (%) testing are shown in Figures 24 and 25.

Bio-briquette rupture force RF

Experimental measurement of rupture force *RF* was performed mostly in the case of wood and herbaceous waste biomass kinds; thus, comparison between those two groups is possible. On average, wood waste biomass represented *RF* equal to 87.51 $N \cdot mm^{-1}$, while herbaceous waste biomass exhibited an *RF* equal to 94.97 $N \cdot mm^{-1}$. Nevertheless, in the case of wood waste biomass, large differences between specific samples related to different tree parts (wood vs. bark) were observed.

a) b)

Figure 24: Investigated bio–briquette samples: a) before *RF* test, b) after *RF* test

Bio-briquette mechanical durability *DU*

Mechanical durability *DU* is the prevalent form of expression of physical quality of bio-briquette fuel. It helps for selection of optimal parameters for bio-briquette production and for production of high-quality briquettes [62; 106]. Mechanical durability (also termed abrasion resistance), is considered the main indicator of bio-briquette fuel quality which describes the ability of bio-briquette samples to remain intact during their handling, transportation and storage [58; 62; 65]. *DU* is influenced by several factors, such as characteristics of used feedstock material, technical specification of pressing machine and storage conditions [58; 62; 110].

a) b)

Figure 25: Investigated bio–briquette samples: a) before *DU* test, b) after *DU* test

Evaluation of observed values of *DU* is performed by mandatory technical standards; bio-briquette samples intended for commercial production must achieve a level of mechanical durability ≥ 90 % [135].

As seen in Table 16, most of the investigated waste biomass kinds exhibited a satisfactory level of this indicator. However, several bio-briquette samples did not achieve the stated limitation, for example those produced from Jatoba sawdust or wheat husk. But the worst results were achieved by residues from wine production, with an extremely low level of mechanical durability (28.32 %). Also, a mixture of coffee ground with spruce shavings resulted in production of bio-briquette samples with poor mechanical durability (46.5 % on average). Thus, such a mixture does not represent a suitable feedstock material for briquette biofuel production; nevertheless, it may be a suitable feedstock for combustion purposes due to the high energy potential and chemical composition.

Table 16: Comparison of mechanical durability of different bio-briquette fuel kinds.

Mechanical durability (%)	Feedstock material	Research author
< 90	Wheat straw Canola straw	[58]
	Big bluestem sawdust	[163]
	Corn stover	[164]
≥ 90	Corn cob Rice husk	[65]
	canary grass	[106]
	Pine sawdust Oak sawdust	[165]
≥ 95	Cotton	[31]
	Soybean stalk	[166]

Results from previous studies related to compacting pressure suggest that *DU* increases with increasing compacting pressure *P* (MPa) [70; 110]. Such a statement was the impulse for the subsequent experimental testing, which is described below.

4.3. Energy demands of bio-briquette fuel production

The present chapter evaluated the suitability of the investigated waste biomass kinds for bio-briquette fuel production with respect to the energy demands for such production. Within the present investigations, the required deformation energy E_d (J) used for the production of the bio-briquette samples was monitored and compared with related bio-briquette density ρ ($kg \cdot m^{-3}$). By considering these two indicators, it was possible to state the ideal production of bio-briquettes from investigated feedstock materials at specific levels of densities ρ. Moreover, the densification process has a specific moment where the increase of the required deformation energy E_d (J) is disproportionately faster than increasing bio-briquette density ρ ($kg \cdot m^{-3}$). In that case, such bio-briquette production represented energy loss, and thus its disadvantage could be indicated.

It is also important to highlight that deformation energy E_d, which was monitored by the present experimental measurements, involved energy consumed exclusively for specific bio-briquette sample production (densification process) and not energy consumed by the work of the pressing machine or other consumed energies associated with the briquetting process. Table 17 illustrates coefficient values of the tangent curve model, which were used within the initial mathematical calculations.

Table 17: Coefficients of tangent curve model stated for investigated bio-briquette samples.

Biomas kind	Samples name	Diameter	C_0	C_1	C_2
		(mm)	(N)	(m^{-1})	(–)
Wood	Ash tree	40	6,915	18.421	1.639
		65	14,130	13.968	2.492
Herbaceous	Bamboo	40	768.0	16.884	2.291
	Energy crop	40	2,306	18.359	2.272
Fruit	Durian	40	12,240.20	18.54	1.58
	Coconut	40	7,195.80	16.38	1.71
	Cacao	40	286,729.50	13.12	3.62
	Coffee	40	7,493.80	20.57	2.44
	Banana	40	13,676.40	23.68	1.91
	Rambutan	40	28,462.50	21.39	2.12
	Sugarcane	40	1012.5	18.481	1.977
Mixed	Cardboard	40	2,796	18.446	2.492
		65	1,921	11.686	4.004

*diameter of pressing chamber

Next, the observed results were used for the statement of maximal achieved density ρ of specific bio-briquette samples, thereby stating the level of such bio-briquette mechanical quality. The maximal density ρ achieved by specific waste biomass kinds are noted in detail in Table 18. Specific amounts of required deformation energy E_d were assigned to all monitored bio-briquette densities ρ; ranged from 800 to 1,300 $kg \cdot m^{-3}$ (with step 50 $kg \cdot m^{-3}$) for fruit waste biomass kind and ranged from 800 to 1,200 $kg \cdot m^{-3}$ (with step 100 $kg \cdot m^{-3}$) for wood and mixed waste biomass kinds. These relations evaluate the efficiency of the densification process, as well as the comparison between all investigated waste biomass kinds.

Table 18: Required deformation energy E_d (J) consumed for production of samples with specific density ρ (kg·m^{-3})

	Wood	Herbaceous			Fruit					Mix
	Ash tree	**Miscanthus**	**Sugarcane**	**Bamboo**	**Durian**	**Coconut**	**Coffee**	**Banana**	**Rambutan**	**Cardboard**
ρ (kg·m^{-3})	**E_d (J)**									
800	709.7	449.2	375.1	325.7	702.5	970.3	202.6	106.9	117.8	204.9
850	866.1	621.7	501.5	400.4	843.2	1,127.9	290.3	172.2	202.7	261.4
900	1,022.4	794.2	694.2	489.8	1,002.4	1,297.7	401.5	255.4	317.2	317.8
950	1,252.4	1,125.5	1,009.3	602.2	1,177.7	1,496.4	544.2	364.3	462.4	400.7
1,000	1,482.3	1,456.7	–	744.4	1,379.3	1,718.7	725.6	502.6	646.5	483.5
1,050	1,839.8	–	–	927.4	1,603.9	1,960.7	964.6	677.5	871.6	598.7
1,100	2,197.3	–	–	1,164.2	1,868.9	2,257.5	1,270.	907.4	1,148.7	713.9
1,150	–	–	–	–	2,185.0	2,596.8	1,685.	1,210.8	1,490.5	885.7
1,200	–	–	–	–	2,550.2	–	2,243.	1,624.2	1,912.3	1,057.4
1,250	–	–	–	–	3,013.0	–	–	2,206.0	2,435.6	–
1,300	–	–	–	–	–	–	–	–	3,103.3	–

Boxes unfilled in Table 18 by specific values of deformation energy E_d expressed the inability of investigated feedstock material to be densified into the briquette samples with specific density ρ. The level of maximal achieved density ρ, as well as the amount of required deformation energy E_d, varied in relation to the materials' diversity (waste biomass kinds).

In the case of fruit waste biomass, the highest level of density ρ was achieved by the rambutan fruit waste biomass samples. The measurements also suggest that the rambutan fruit waste is the only sample which achieved all monitored density ρ levels (800 – 1,300 $kg \cdot m^{-3}$). The second highest level of bio-briquette density ρ was achieved by durian fruit and banana fruit waste biomass samples. Bio-briquette samples produced from coffee fruit waste biomass also achieved a very high level of density ρ (1,200 $kg \cdot m^{-3}$). However, when compared with other results, it is obvious that production of such bio-briquette samples (coffee fruit waste biomass) consumed more deformation energy E_d than the banana or rambutan fruit waste biomass samples. The fastest growth (negative effect) of required deformation energy E_d was observed in the case of cacao fruit waste biomass. If comparing required deformation energy E_d of banana fruit waste biomass (lowest amount of consumed energy – positive impact) with cacao fruit waste biomass (highest amount of consumed energy), the resulting values were more than ten times higher. The second worst results were achieved with coconut fruit waste biomass bio-briquette samples, while the lowest efficiency level was obtained for bio-briquette samples from cacao fruit waste biomass.

Nevertheless, it is important to consider that the bio-briquette densities ρ achieved by investigated fruit waste biomass bio-briquettes occurred at a satisfactory level in general, therefore fulfilling mandatory requirements for commercial production.

Due to the differences between tested waste materials and their energy requirements and increasing of the density ρ levels, Figure 26 was created for better expression of results. The process of increasing deformation energy E_d, which plays a role in the energy demands of the briquetting process, is expressed in Figure 26.

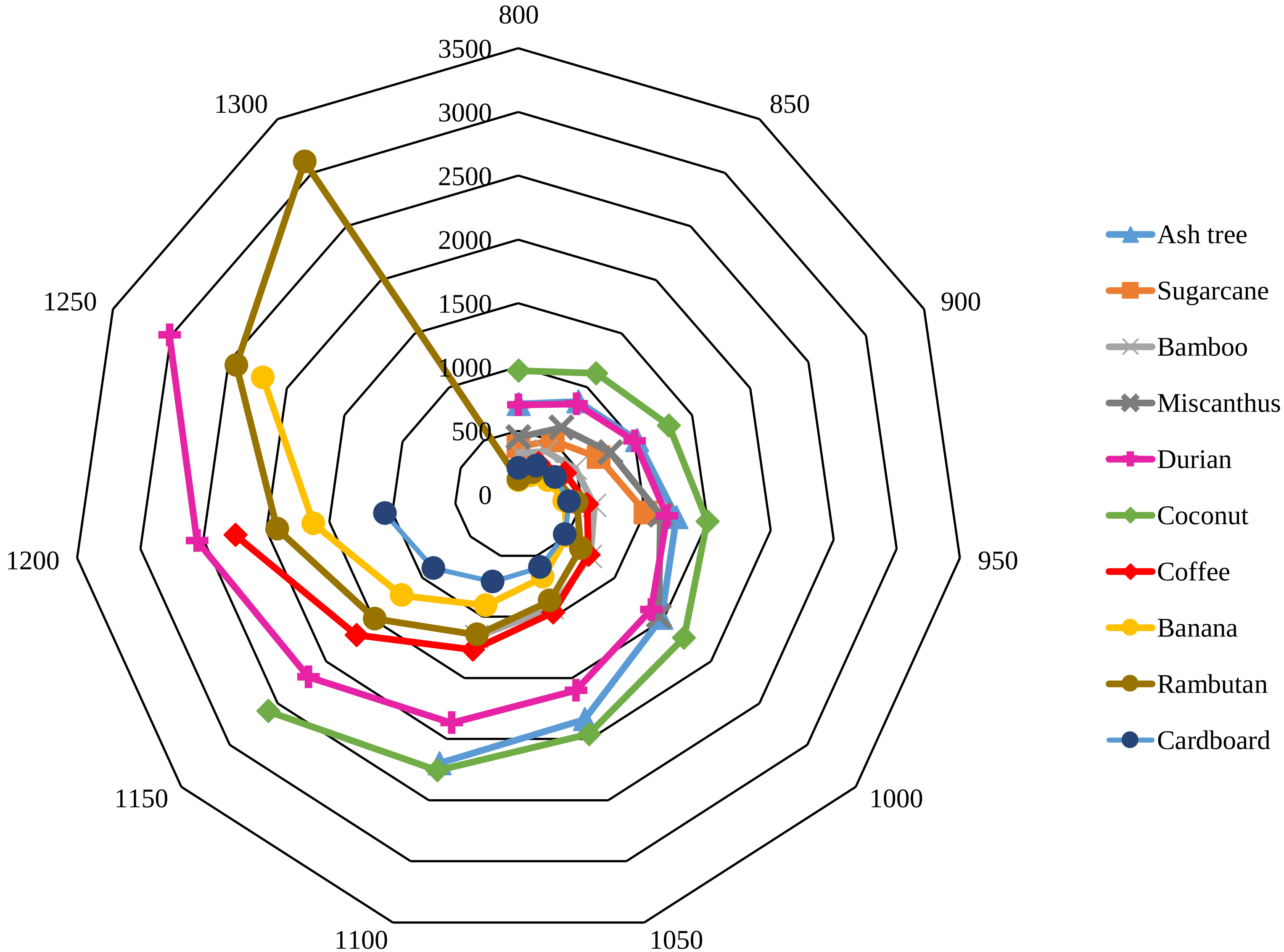


Figure 26: Progress of relation between deformation energy E_d (J) and bio-briquette density ρ (kg·m^{-3}) investigated in waste biomass kinds.

Within evaluation of wood and mixed waste biomass kinds, the analysis indicated better results (lowest energy consumption, highest maximal achieved density ρ) achieved by bio-briquette samples produced from cardboard material, followed by wood briquette samples. Comparison between each investigated materials at specific monitored density levels is clearly expressed in Figure 27.

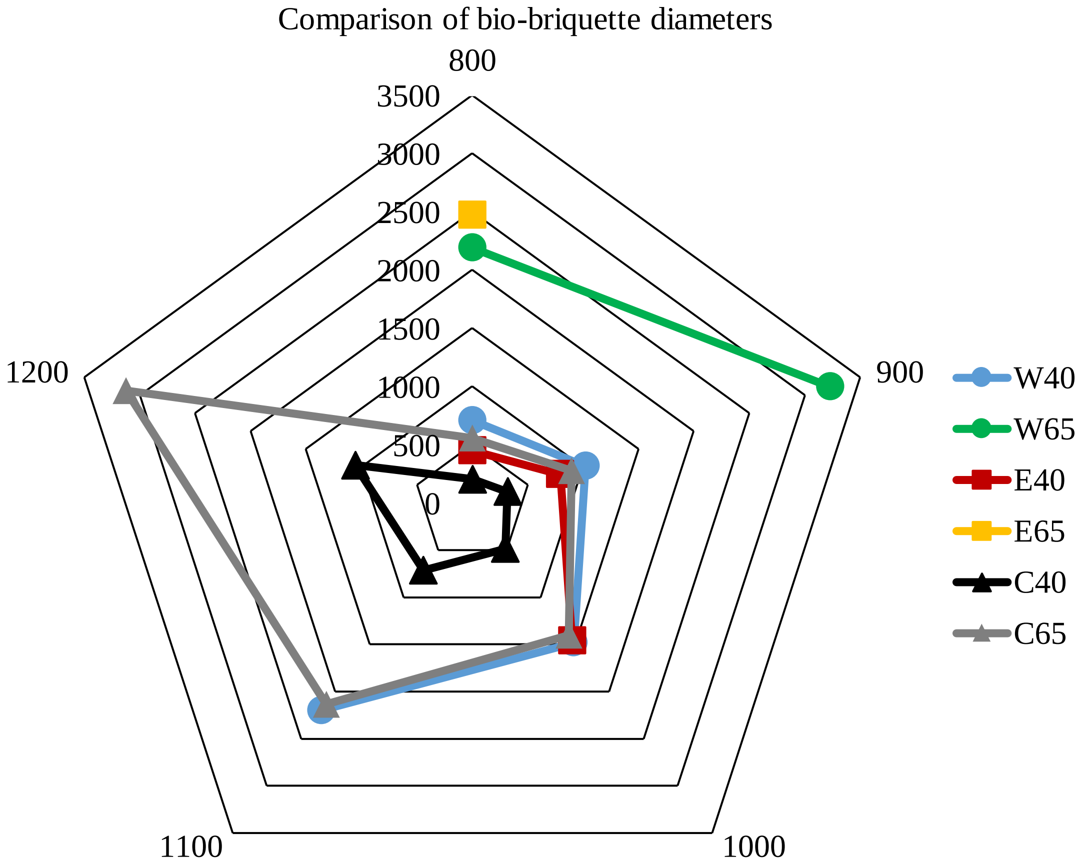


Figure 27: Progress of relation between deformation energy E_d (J) and bio-briquette density ρ (kg·m^{-3}) of bio-briquette samples of different diameters.

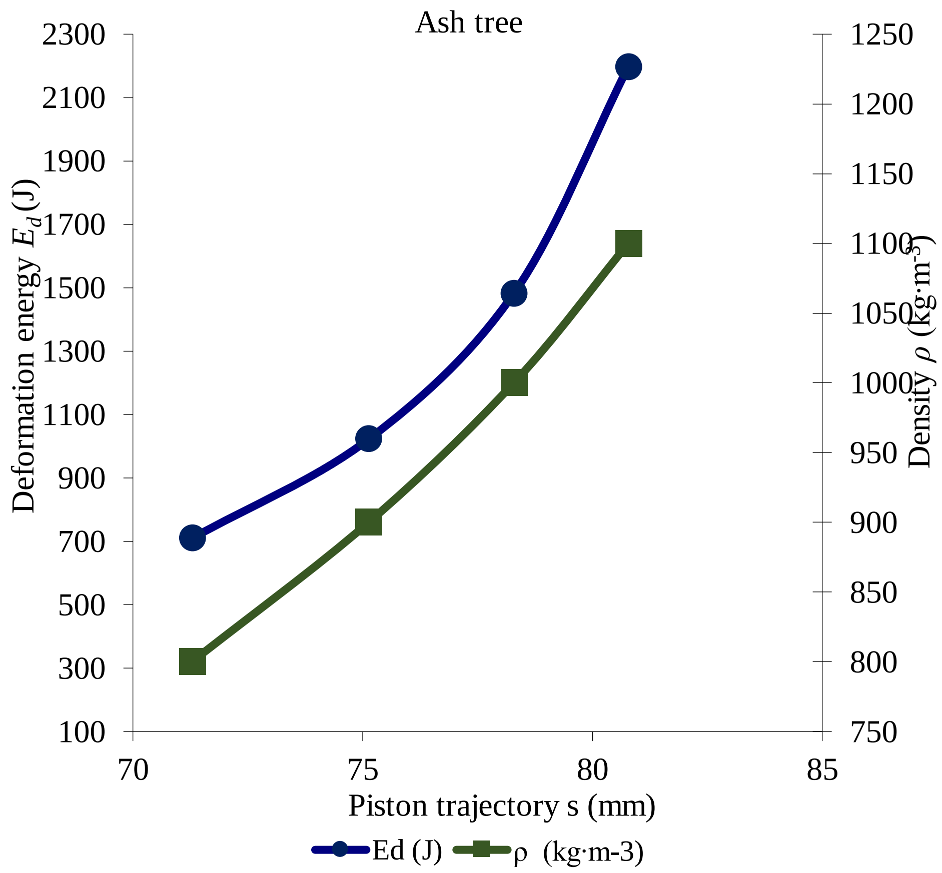
Furthermore, it was found that bio-briquette samples produced with minor diameter (40 mm) indicated better result values; i.e. a lower level of deformation energy E_d was consumed for achieving of the identical levels of density ρ as in the case of bio-briquette samples of larger diameter (65 mm).

As seen in Figure 27, cardboard bio-briquette samples achieved all investigated levels of density ρ (800 – 1200 kg·m^{-3}), in contrast with wood waste biomass bio-briquette samples. Moreover, wood bio-briquette samples of 65 mm diameter did not achieve the required density ρ level ($\rho \geq 1000$ kg·m^{-3}). In accordance with mandatory technical standards and previously published observations, the density ρ equal to 1,000 $kg \cdot m^{-3}$ was stated as a sufficient level for high quality briquette production [62; 47; 158].

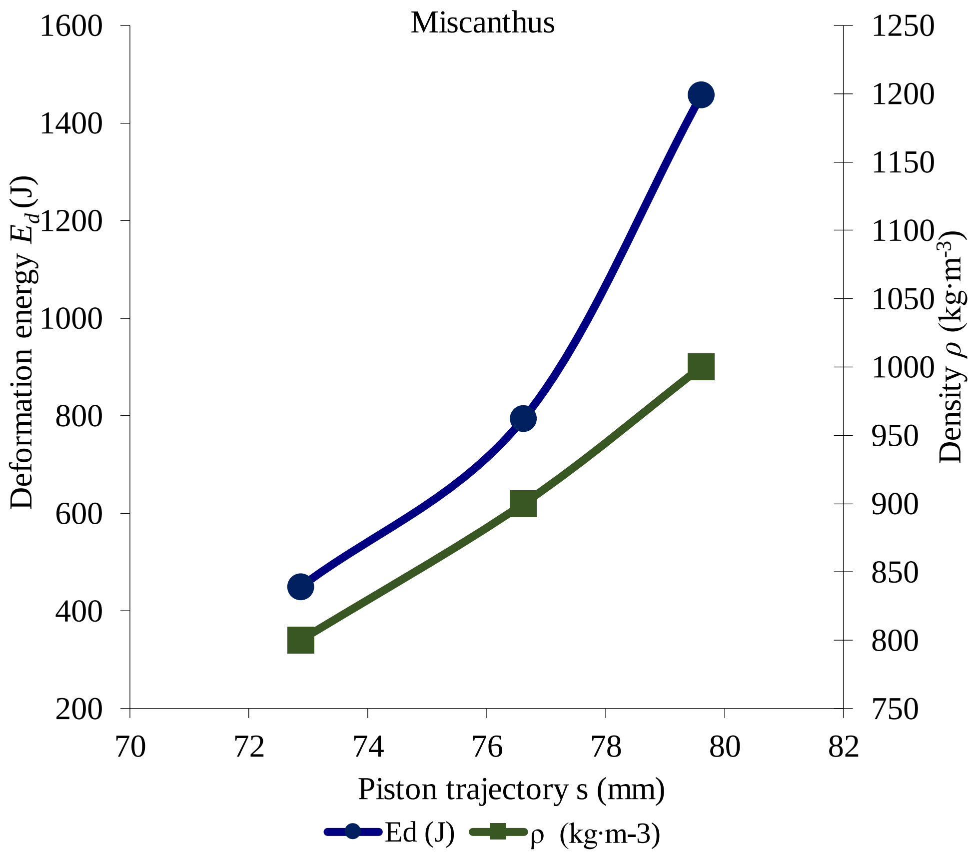
Energy consumption of bio-briquette fuel production has also been investigated by previous authors. However, published studies were mainly focused on energy demands of overall operation of briquetting press or of the entire manufacturing process of briquette production. In contrast, the aim of the present experimental measurements was to determine the energy consumed purely during the production of one of each specific briquette sample, and no other consumed energies were considered.

Nevertheless, such investigations indicate energy consumption (electric, human, chemical and thermic energy) of bio-briquette plant operation was investigated, with results indicating that production of 1 tonne of sawdust bio-briquettes consumed 101.66 $kWh \cdot t^{-1}$ in total. Electrical energy for all production processes (briquetting, drying, sieving, etc.) represented 65.12 $kWh \cdot t^{-1}$ of total result value (101.66 $kWh \cdot t^{-1}$); nevertheless, the pure briquetting process (operation of bio-briquetting press) consumed 49.73 $kWh \cdot t^{-1}$ of total values. The study did not describe the number of produced bio-briquettes per one tonne, and thus it was not possible to state the consumed energy for production of one bio-briquette sample to compare with results observed within the research of the present paper [167]. Moreover, other published research indicated that overall energy used for specific bio-briquette sample production contains 40 % of energy consumed for compressing of feedstock material and the remaining 60 % represented energy consumed for overcoming friction [168]. The mentioned observations suggest that production of bio-briquette biofuel from herbaceous biomass consumes a larger amount of energy than production of bio-briquette biofuel from wood biomass; such results were also observed in the present research.

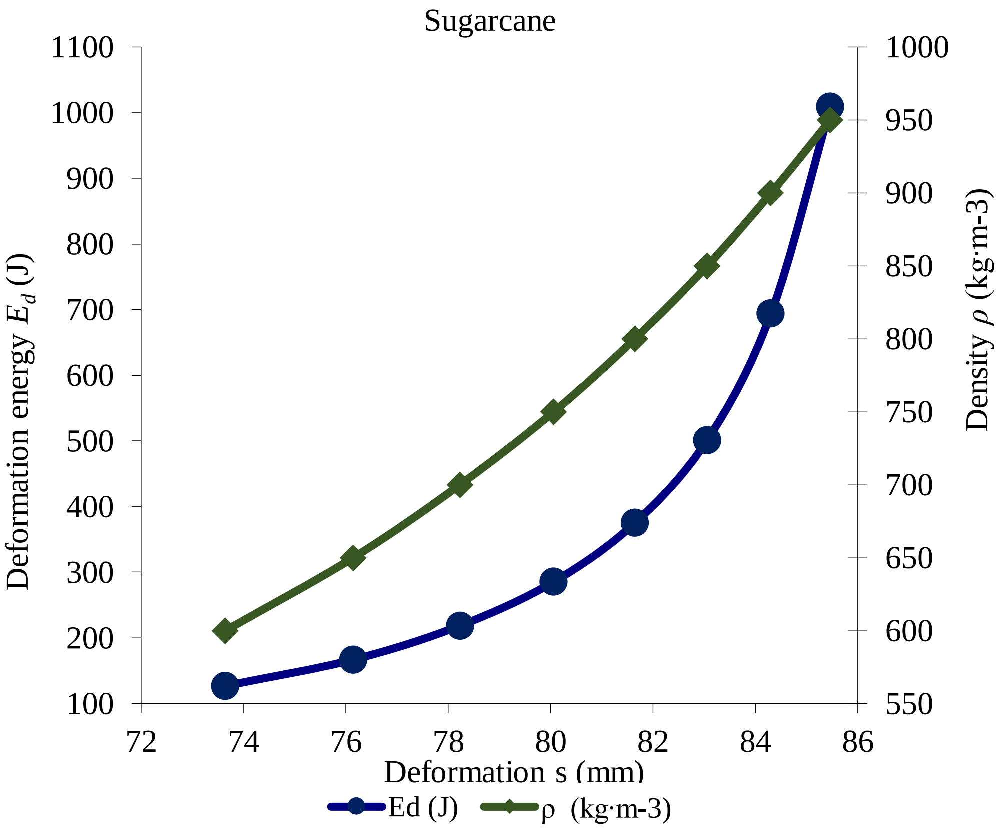
Within the current research, another interesting issue was also monitored, measured and evaluated – the process of increasing of required deformation energy E_d (J) and bio-briquette density ρ ($kg \cdot m^{-3}$) and their relation during such process. The visualization of the curves of deformation energy E_d (J) and bio-briquette density ρ ($kg \cdot m^{-3}$) were used for determination of efficiency of bio-briquette production produced from different waste biomass kinds. Monitoring of both mentioned growth curves and subsequent intersection was used for statement of one specific moment during the bio-briquette sample production, which indicates that the production is not efficient anymore. Such moments were monitored in the following Figure 28.


Ash tree
Deformation energy E_d (J)
Density ρ (kg·m^{-3})
Piston trajectory s (mm)
Ed (J)
ρ (kg·m-3)

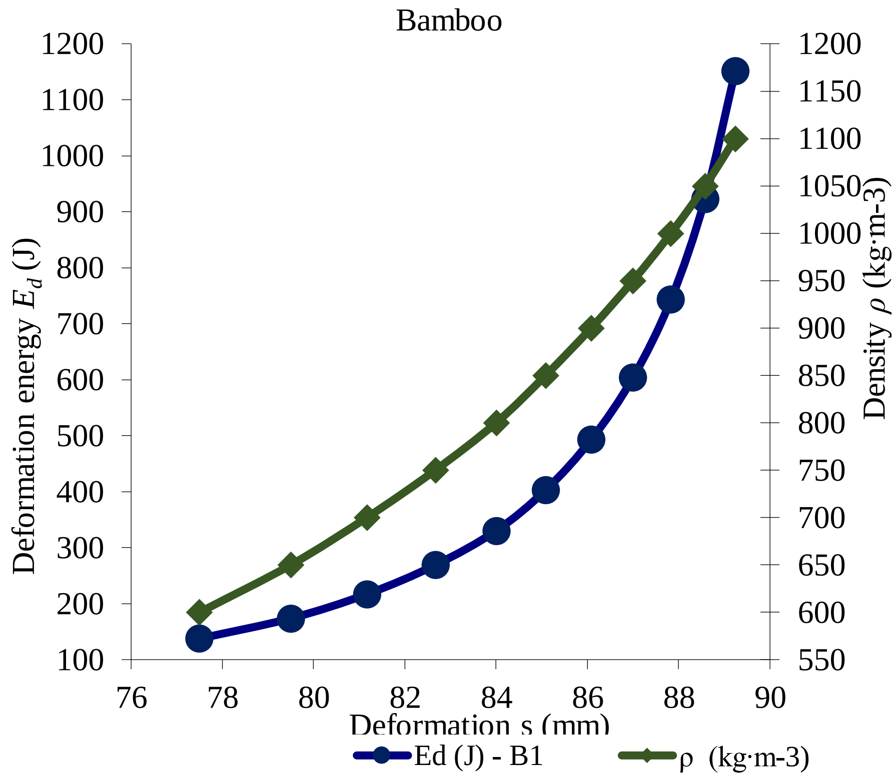
a)


Miscanthus
Deformation energy E_d (J)
Density ρ (kg·m^{-3})
Piston trajectory s (mm)
Ed (J)
ρ (kg·m-3)

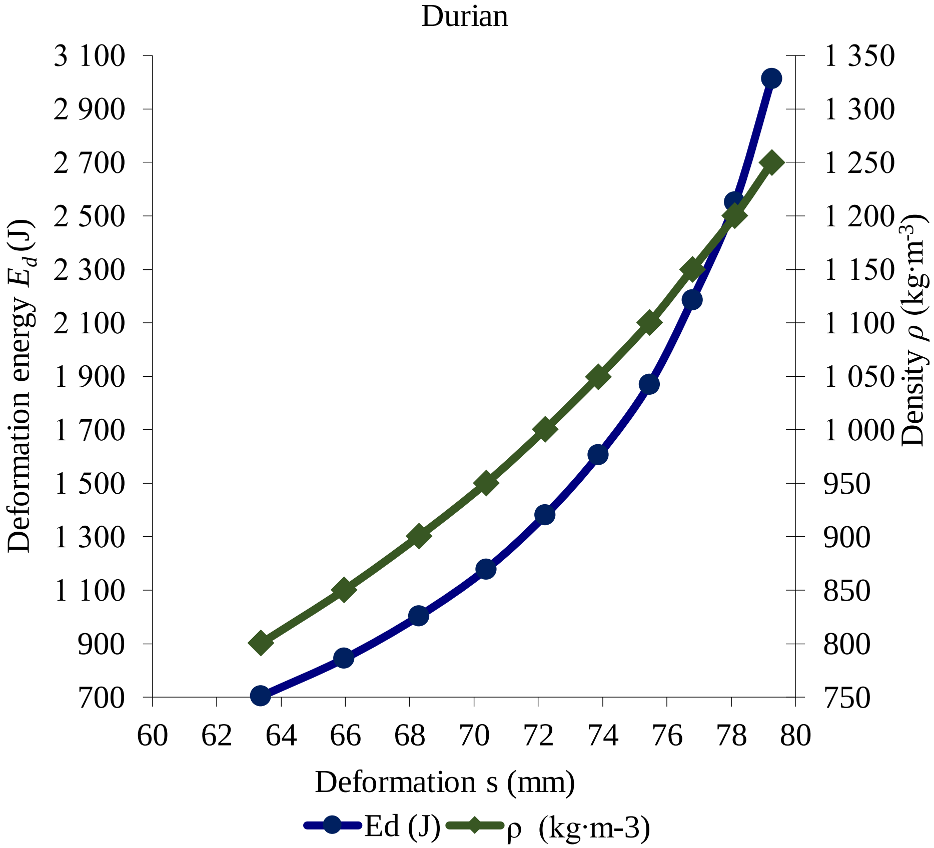
b)


Sugarcane
Deformation energy E_d (J)
Density ρ (kg·m-3)
Deformation s (mm)
Ed (J)
ρ (kg·m-3)

c)

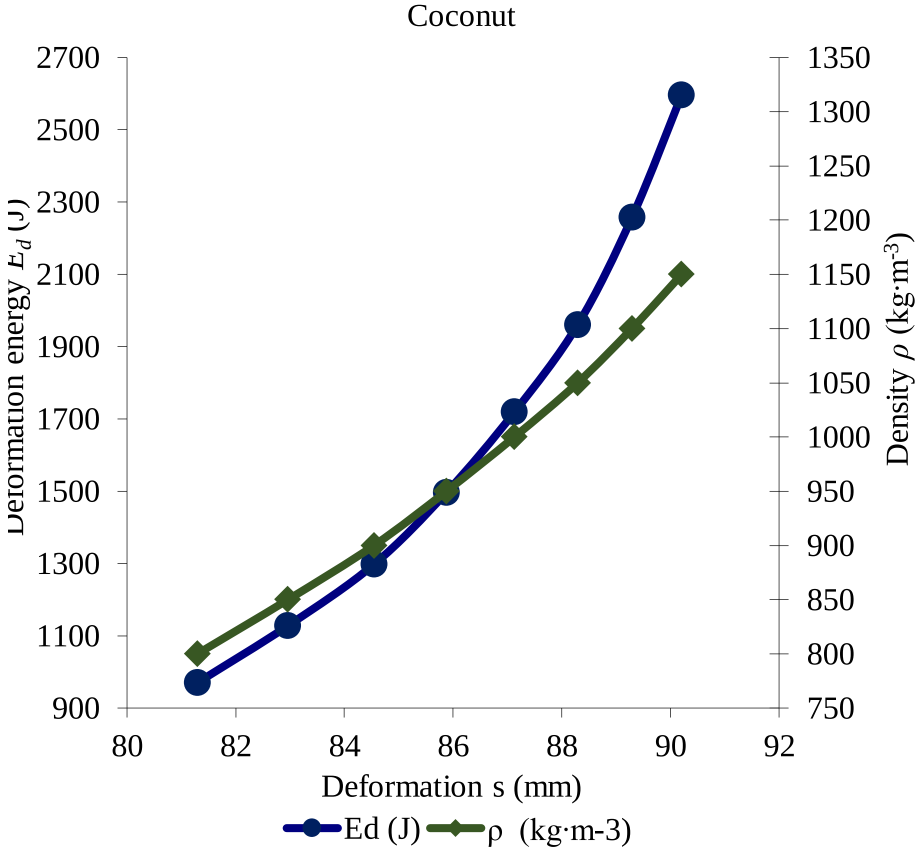

Bamboo
Deformation energy E_d (J)
Density ρ (kg·m-3)
Deformation s (mm)
Ed (J) - B1
ρ (kg·m-3)

d)



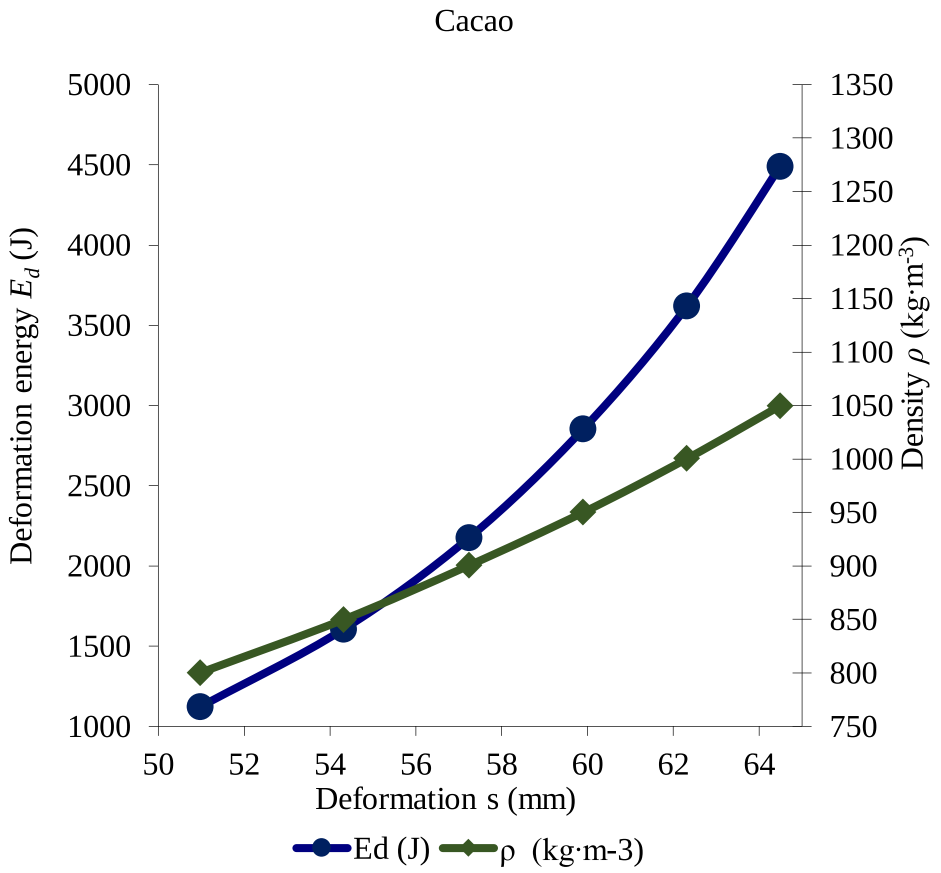
Durian
Deformation energy E_d (J)
Density ρ (kg·m^{-3})
Deformation s (mm)
Ed (J)
ρ (kg·m-3)

e)

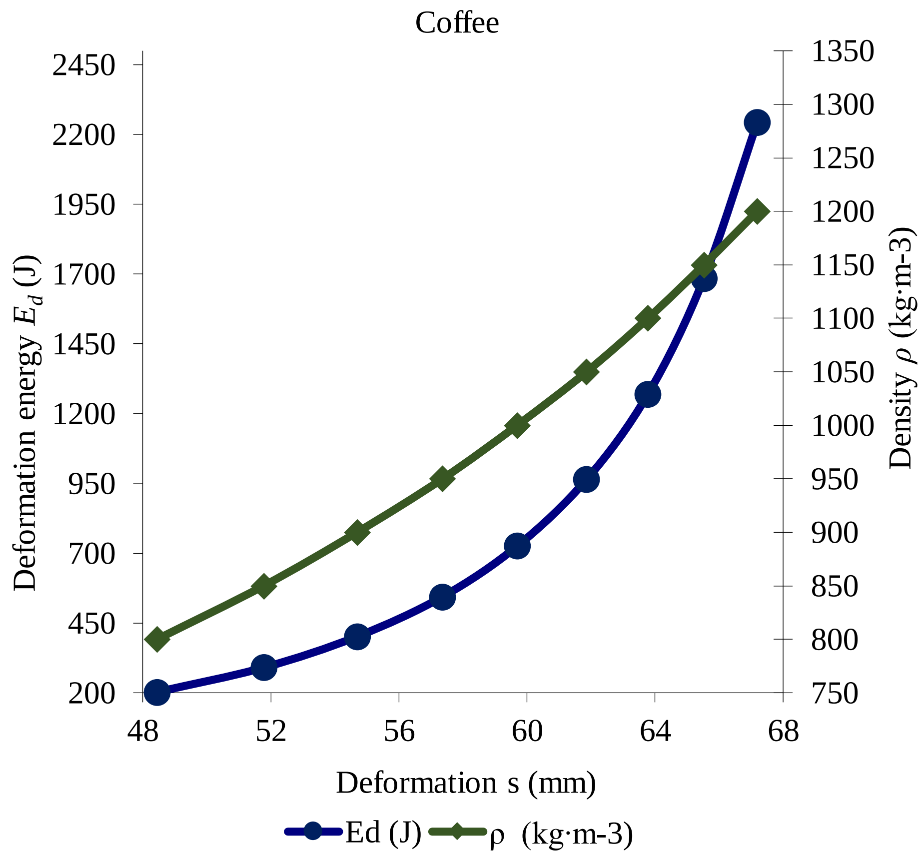


Coconut
Deformation energy E_d (J)
Density ρ (kg·m^{-3})
Deformation s (mm)
Ed (J)
ρ (kg·m-3)

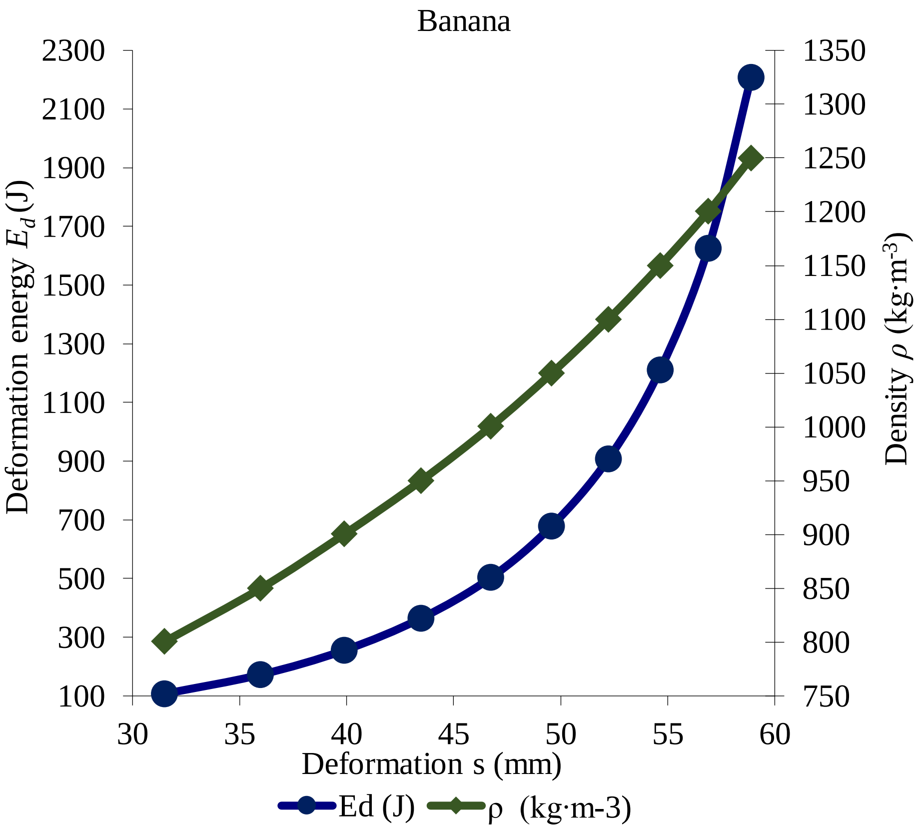
f)


Cacao
Deformation energy E_d (J)
Density ρ (kg·m^{-3})
Deformation s (mm)
Ed (J)
ρ (kg·m-3)
5000
4500
4000
3500
3000
2500
2000
1500
1000
1350
1300
1250
1200
1150
1100
1050
1000
950
900
850
800
750
50
52
54
56
58
60
62
64

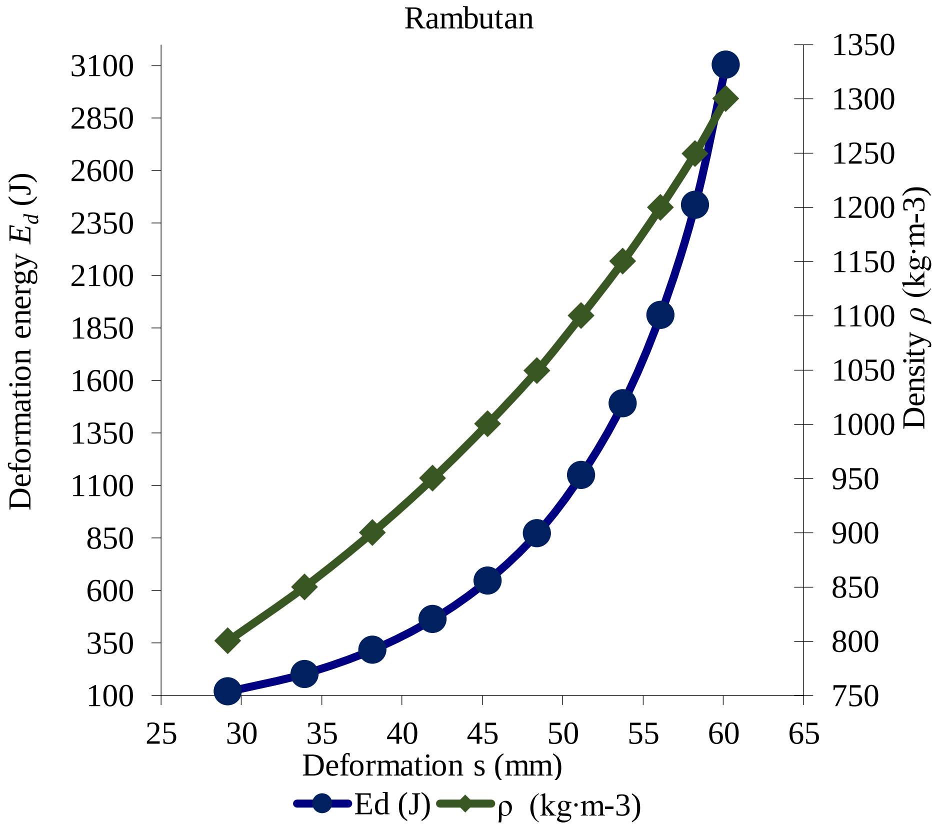
i)


Coffee
Deformation energy E_d (J)
Density ρ (kg·m-3)
Deformation s (mm)
Ed (J)
ρ (kg·m-3)
2450
2200
1950
1700
1450
1200
950
700
450
200
1350
1300
1250
1200
1150
1100
1050
1000
950
900
850
800
750
48
52
56
60
64
68

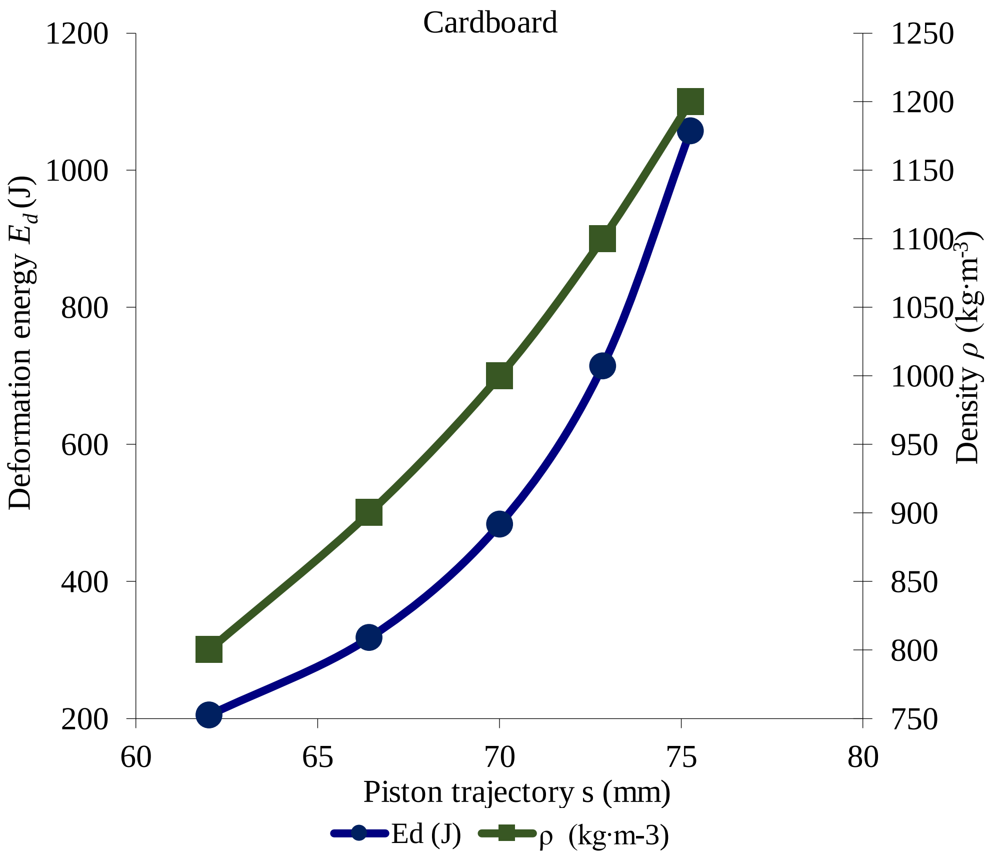
j)


Banana
Deformation energy E_d (J)
Density ρ (kg·m^{-3})
Deformation s (mm)
Ed (J)
ρ (kg·m-3)

k)


Rambutan
Deformation energy E_d (J)
Density ρ (kg·m-3)
Deformation s (mm)
Ed (J)
ρ (kg·m-3)

l)



m)

Figure 28: Intersection of required deformation energy E_d (J) and bio-briquette density ρ (kg·m^{-3}) curves determining efficiency of bio-briquette production.

It must also be considered that according to standards and previous investigations, the bio-briquettes density ρ in the range 800 – 1,000 kg·m^{-3} is sufficient for high-quality bio-briquettes [62; 47; 158]. Thus, production of bio-briquettes with higher density ρ is not necessary and is indeed questionable when considering the high energy demands of such production.

The process of increasing both of the mentioned parameters (*Ed*, ρ) was different for each waste biomass samples, but the maximal achieved densities ρ, which were still advantageous, were as follows (expressed in Table 19):

Table 19. Maximal advantageous density ρ of bio-briquette samples.

Biomass kind	**Feedstock material**	**Density ρ (kg·m^{-3})**
Wood	Ash tree	1,000
Herbaceous	Miscanthus	900
	Sugarcane	950
	Bamboo	1,050
Fruit	Durian	1,200
	Coconut	950
	Coffee	1,150
	Banana	1,200
	Rambutan	1,250
Mix	Cardboard	1,200

The relation between bio-briquette density ρ and deformation energy E_d (J) (used for compressing of feedstock materials) was already investigated in previous research. In general, increasing bio-briquette density ρ causes increasing of required deformation energy E_d (J) increases, and thus increasing financial costs too. Consequently, it is important to monitor the relation between those two factors during the densification process and state its highest profitability and efficiency. The amount of required deformation energy E_d (J) also expresses energy demands of specific investigated bio-briquette kind production; such energy demands differ in relation to the variability of used feedstock materials (biomass kind) and their chemical and mechanical properties [57].

Other study dealt with the energy demands of bio-briquette production from olive oil milling solid residues with different diameters. The highest level of mechanical quality was demonstrated for briquette samples with density ρ equal to 747.5 $kg \cdot m^{-3}$ (on average), which was not the highest observed level of density ρ. Other investigated bio-briquette samples exhibited a higher level of density ρ; thus, it was found that the highest level of bio-briquette density ρ did not always correspond to the highest bio-briquette mechanical quality – the effort to produce bio-briquette fuel with the highest possible density ρ may not always be a guarantee of best bio-briquette quality [158]. Such a statement was also supported by previous research, which indicated that bio-briquette samples with density ρ higher than 1,000 $kg \cdot m^{-3}$ do not exhibited a distinctly higher level of quality than bio-briquette samples with lower density ρ. However, as the results of the present research suggest, production of bio-briquette samples with higher density ρ always indicated higher energy consumption, and thus higher financial costs [169].

4.4. Low-pressure briquetting technology

Research activities performed within the low-pressure briquetting technology contained several parts. Because such technology is not publicly well known, it is not frequently used in the bio-briquette production sector. In general, such technology represents an alternative to high-pressure briquetting technology, but its development is still in the process. Therefore, the first aim of the present research was the design of such equipment – a manual low-pressure briquetting press from mainly wood components. Further, designed equipment were manufactured, while a handbook with the equipment construction was created. Subsequently, verification of their viability and feasibility was developed. The final parts of the results contained an evaluation of bio-briquette samples produced by such manual low-pressure briquetting presses.

4.4.1. Desing of low-pressure briquetting presses

In the first step, the form and shape of such equipment was designed, and the developed form of a low-pressure briquetting press is given in Figure 29.

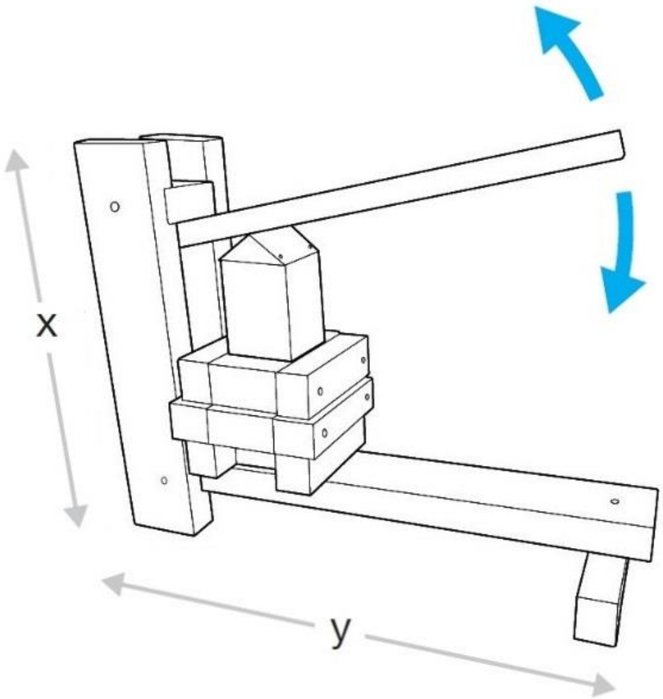


Figure 29: The design of a low-pressure briquetting press.

Subsequently, the supporting documents as a handbook of press components and construction used were created; their previews are expressed in Figures 30 and 31. The full versions are attached in the annexes of the present thesis, namely Annex A and B.

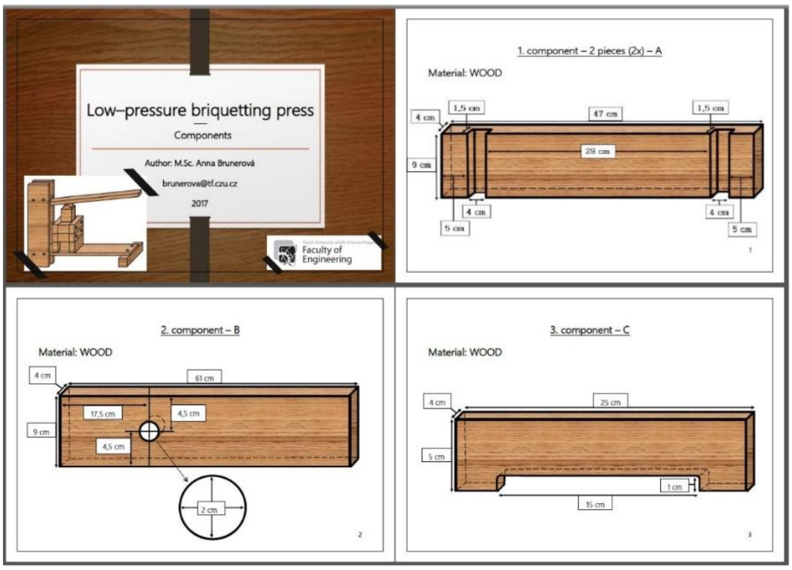


Figure 30: Preview of created handbook of press components.

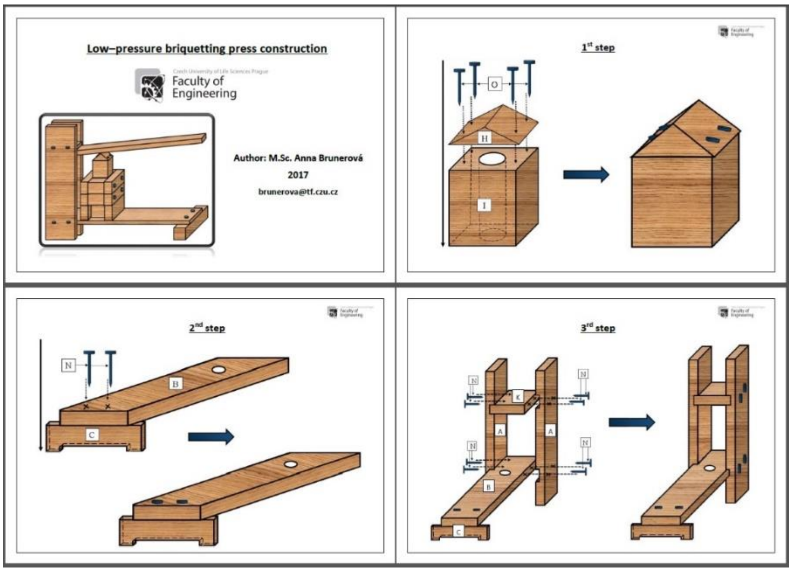


Figure 31: Preview of created handbook of press construction and use.

Intelligibility and functionalities of such handbooks were demonstrated during field surveys held in rural areas of Toba Samosir regency, North Sumatra, Republic of Indonesia and in Hue province, Central Vietnam, where the pilot studies were performed in 2016 and 2018. Based on the mentioned handbook, the local carpenters were able to manufacture the components, and subsequently to produce the wood version of the press. The mentioned documents were also used in Thua Thien Hue province, central Vietnam, where the wooden versions of designed low-pressure briquetting presses were also manufactured to demonstrate that it is in an understandable form for local communities. Related to such purposes, both of the handbooks were created in a very simple manner by using an easy description and illustration.

The feasibility of such equipment was also demonstrated in the local conditions of the Czech Republic, specifically Prague, where the press was not only manufactured but also used for bio-briquette sample production, and which were subjected to the determination of their mechanical quality indicators.

4.4.2. Construction and use of low-pressure briquetting press

After achieving the manufactured components, the manual low -pressure briquetting press was constructed. Firstly, due to the pilot study in rural areas of a developing country (target area of such research) and secondly in local conditions of the Czech Republic for the purpose of laboratory use and subsequent testing. Photographs of the developed press in laboratory conditions are illustrated in Figure 32.

Figure 32: Developed manual low-pressure briquetting press from wood components.

Developed equipment was used for practical testing (shown in Figure 33) and ability of equipment for production of bio-briquette fuel was demonstrated.

Figure 33: Developed manual low-pressure briquetting press in use.

Manufactured equipment was also completed with technical documentation and an interactive 3D model (expressed in Figure 34**).** The interactive 3D model was created for better expression and understanding of press functions and construction for the users and manufacturers. Such software offers a 360°-degree view of the 3D model of the press and contains a set of views, stack disasters, visualizations, animation of clusters or movements of the press assembly. By using the present software, each part of the 3D model can be converted to an invisible form; thus, the internal construction of the press is visible. The file with the Interactive 3D model in the content is given in Annex C.

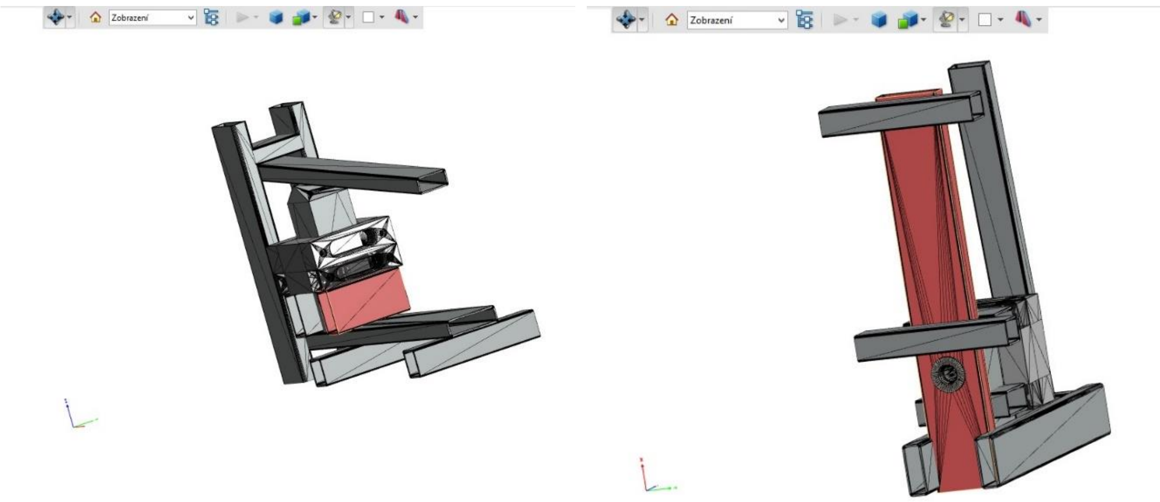


Figure 34: Interactive 3D model of developed manual low-pressure briquetting press.

4.4.3. Basic operation calculations

Within the determination of basic operation parameters of the manufactured low-pressure briquetting press, the quantities described below were investigated and the following calculations were performed:

Magnitude of torque *M*

The magnitude of the torque *M* depends on the force, the direction of the force, and where the force is applied. Thus, for its determination, the following Equation 8 was used:

$$M = F \cdot h \qquad \text{Eq. 8}$$

where: *F* – force (N), *h* – moment arm of force (m)

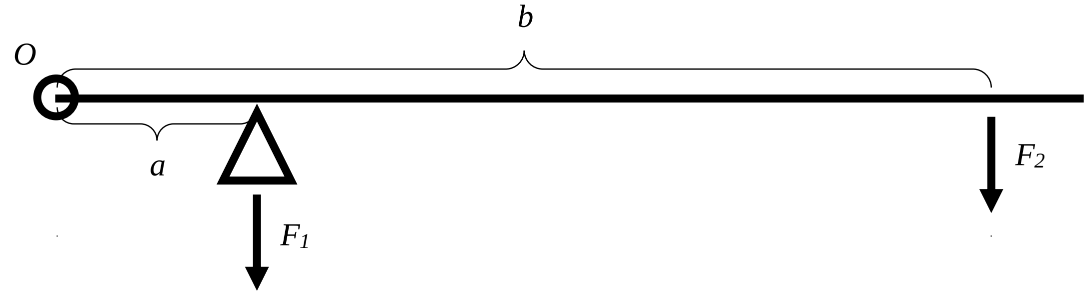
The SI unit for torque [M] = [F] · [h] = N·m (Newton·metre)

Moment arm of force *h*

Such a quantity describes the perpendicular distance between the axis of rotation *O* and the line running through the vector of force *F*.

Distribution of forces

The dimensions and placement of the lever during bio-briquette sample production:



where: a = 8.5 cm = 0.085 m, b = 50 cm = 0.5 m

By use of such a statement, the following relations were used (Eq. 9, 10 and 11):

$$M_1 = M_2 \qquad \text{Eq. 9}$$

where: M_1 – distance between the axis of rotation O and the line running through the vector of force F_1, M_2 – distance between the axis of rotation O and the line running through the vector of force F_2.

$$F_1 \cdot a = F_2 \cdot b \qquad \text{Eq. 10}$$

where: F_1 – force applied to the piston, a – the distance between the axis of rotation O and the piston, F_2 – force applied by the source of energy, b – the distance between the axis of rotation O and the source of energy.

$$F_1 = \frac{F_2 \cdot b}{a} \qquad \text{Eq. 11}$$

where: F_1 – force applied to the piston, a – the distance between the axis of rotation O and the piston, F_2 – force applied by the source of energy, b – the distance between the axis of rotation O and the energy source.

The force F_2 applied by the manual work was equal to approximately 500 N. Thus, subsequent calculations of used pressure were performed to state the force F_1, which was applied to the piston, and further, to the feedstock material:

$$F_1 = \frac{500\ \mathrm{N} \cdot 0.5\ \mathrm{m}}{0.085\ \mathrm{m}} = \frac{250\ \mathrm{N} \cdot \mathrm{m}}{0.085\ \mathrm{m}} = 2{,}941.18\ \mathrm{N}\ (\cong 2.94\ \mathrm{kN})$$

Within the determination of the press operation pressure P (MPa), the area of the bottom part of the piston S (m^2), which compresses the feedstock material, had to be calculated (expressed in Figure 35).

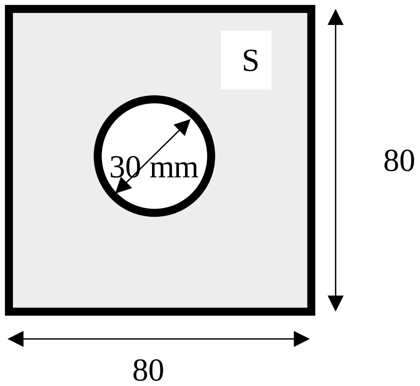


Figure 35: Scheme and dimensions of the piston bottom area.

Due to the calculation of the bottom part of the piston area, the area of the drainage hole had to be deducted, and thus the area of the press piston S (m^2) was expressed as follows (Equation 12):

$$S = 5{,}700\ \mathrm{mm}^2 = 57 \cdot 10^{-4}\ \mathrm{m}^2 \qquad \text{Eq. 12}$$

After achieving such results, the operation pressure P (MPa) developed by the investigated manual low–pressure briquetting press was able to be stated, and thus the following calculations were made (Equation 13 and 14).

$$P = \frac{F}{S} \qquad \text{Eq. 13}$$

where: F – force (N), S – area of the bottom part of the piston (m^2)

$$P = \frac{F}{S} = \frac{2{,}941{,}18\ \mathrm{N}}{57 \cdot 10^{-4}\ \mathrm{m}^2} = 51.6\ \cdot 10^4\ \mathrm{Pa}\ = 0.516\ \mathrm{MPa} \qquad \text{Eq. 14}$$

The observed values are further discussed in the following chapters related to the evaluation of the produced bio-briquette samples.

4.4.4. Low-pressure bio-briquette fuel

The most important findings originating from experimental testing of bio-briquette sample production by using a low-pressure briquetting press were related to the specifications of feedstock materials preparation and its suitable form which differed from the commonly used processes with high-pressure briquetting technology. Primarily, feedstock materials must occur in a wet state and must be mixed with water or other fluids. The mixing of feedstock material with external binding agents was also found to be necessary; the ratio of feedstock material and binding agent is an important factor influencing the final efficiency of the densification process. By using those two facts, the feedstock materials can be properly prepared for low-pressure briquetting. Therefore, the final products were produced with a high moisture content, which indicated that the subsequent drying process (before their utilization for combustion purposes) was also necessary. Within that, the suitability of the drainage system was also demonstrated; a hole in the middle of the final product helps with briquette samples drying and improves the porosity and combustion properties of briquette samples due to better oxygen flow. Also, the fibrous materials (waste coconut fibres, bamboo fibre) expressed their suitability for low-pressure briquetting technology.

Based on the observed results, it can be stated that the developed design of low-pressure briquetting press can be useful for small briquette manufacturers in rural areas. Its simple and cheap operation and construction can serve as an improvement of proper waste management practices and be a relevant alternative for adequate waste biomass utilization. Particularly with respect to poor levels of waste management in target areas resulting in a significant amount of potential feedstock materials, it can be a very feasible technology. Within experimental verification of the manufactured manual presses, the bio-briquette samples from different ratios of feedstock materials:binder (2:1, 1:1) were produced and described. The mixture of coconut fibre (feedstock material), waste paper (binder) and water (wet mixing environment) was used as a feedstock material. Bio-briquette samples were produced by using a square-shaped pressing chamber; thus, it occurred in the form of blocks with the following dimensions expressed in Table 20.

Table 20: Dimensions of produced low-pressure bio-briquette samples.

Bio-briquette samples	Width (mm)	Length (mm)	Height (mm)
1:1	80	80	*
2:1	80	80	*

* values differed during the bio–briquette samples production processes, see Table 21 and Table 22

Briquettes are commonly produced in the shape of a square or rectangle, or it can be produced in the form of lumps or other molded shapes [170]. A variety of shapes are shown in Figure 36.

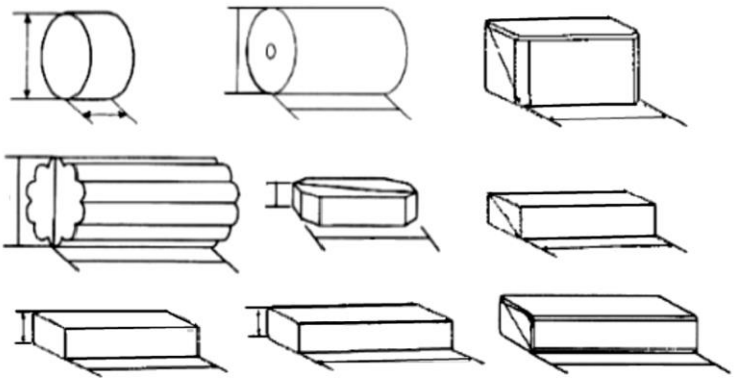


Figure 36: Variety of normalized bio-briquette fuel shapes.

(Source: ISO 17225–1, 2015) [35]

The height of produced bio-briquettes differed before and after the drying process, which was performed directly after bio-briquette sample production in order to determine their initial moisture content after production (due to the use of water as the binding environment).

As described in the methodology chapter, several types of bio-briquette samples were produced. The variance was at a different ratio of feedstock materials (coconut fibre) and external binder (waste paper). Mechanical parameters and dimensions of such samples are noted in Tables 19 and 20, while their different appearances can be compared in Figures 37 and 38.

Briquetting technology uses a process of densification and operates with production factors as a compacting pressure, compacting heat and feedstock material properties without using any binders. All those factors can influence the quality of the final products (briquettes) and thus overall efficiency of briquette production [51]. Absence of binders can negatively influence final briquette quality [171]. Binding effect can be substituted and achieved by using mixed feedstock containing various amounts of materials and/or additives which substitutes missing binder. Production of mixed briquettes is common practice because using additives improves feedstock properties, thus increasing mechanical durability of briquettes.

Table 21: Mechanical parameters of produced low-pressure bio-briquette samples of different feedstocks ratio (1:1).

1:1 (waste paper:coconut fibre)				
	Height (mm)	Weight (g)	Density ($kg \cdot m^{-3}$)	Moisture content (%)
Wet form[1]	34.39 ± 5.56	143.03 ± 17.91	729.78 ± 38.88	69.19 ± 1.03
Dry form[2]	42.66 ± 4.61	44.05 ± 5.52	181.15 ± 7.73	–

[1]directly after bio-briquette sample production, [2]after drying process

Figure 37: Produced low-pressure bio-briquette samples of feedstocks ratio 1:1 (waste paper:coconut fibre).

The main monitored and evaluated parameters of such biofuel were their initial moisture content M_c and density ρ. The level of initial moisture content A_c indicated the energy which must be invested into the drying process before such biofuel can be used for direct combustion. In both cases, the level was extremely high but comparable. In respect to the purpose of such fuel, it can be stated that the subsequent drying process (electrical or sun energy) is an integral part of the process of low-pressure briquetting technology.

Table 22: Mechanical parameters of produced low-pressure bio-briquette samples of different feedstocks ratio (2:1).

2:1 (waste paper:coconut fibre)				
	Height (mm)	Weight (g)	Density ($kg \cdot m^{-3}$)	Moisture content (%)
Wet form[1]	35.88 ± 1.81	158.35 ± 14.48	774.15 ± 44.35	65.82 ± 1.33
Dry form[2]	42.79 ± 3.71	54.14 ± 5.42	222.32 ± 14.36	–

[1]directly after bio–briquette sample production, [2]after drying process

Figure 38: Produced low-pressure bio-briquette samples of feedstocks ratio 2:1 (waste paper:coconut fibre).

The technical standard related to the briquette fuel density ρ is mandatory only for commercially produced briquette fuel; thus, its requirements were not decisive in evaluating the produced bio-briquette samples. The levels of density ρ differed in the case of samples after production (wet form) and after post-production processing (dry form) in consequence to the change of their weight and dimensions. Nevertheless, both types of bio-briquette samples indicated similar levels of density ρ; thus, it can be concluded that the difference between investigated feedstock:binder ratio did not influence the result of mechanical quality of produced low-pressure bio-briquette fuel.

Nevertheless, the need of binder during low-pressure briquetting is indispensable, thus, for such technology would be suitable (or necessary) to use mixed feedstock materilals. Such mixed feedstock materials (mixed waste biomass) works with the properties of all mixed feedstock materials and uses them to improve the final quality of the mixture. The ratio of mixed feedstock materials indicates if it is mixed waste biomass or pure waste biomass kind with additive [172]. The type or amount of additives is not generally defined and both are carefully chosen according to specific chemical (lignin content) or mechanical (particle size) properties to achieve the highest improvement of briquette quality [171]. Lignin leaves cell structures during pressing and act like a glue to bind different components of material into the form of a briquette. It implies that additives are finding between materials with high lignin content [146].

An example of a frequently used additive for mixing with other feedstock materials is sawdust, which presents a suitable combination of lignin content and small particle size [68; 95; 146; 171]. Countless representatives of commonly used additives can be found between plant origin material [39], animal origin material and chemical or mineral substances [68; 96]. Selection of appropriate additives and their ratio in feedstock was scientifically investigated in many previous studies. It is important to realize that every specific feedstock material suits different additives added in a certain ratio which forms a unique mixture, leading to improvement of final briquette quality. Consequently, all briquettes produced from a unique mixed feedstock must be subjected to tests to define overall appropriateness of additives and a suitable ratio for use in feedstock. Many varieties of different additives and their influences were investigated in previous research. Research which studied the influence of cassava starch and wood ash additives on final quality of briquettes produced from tropical hardwood sawdust concluded that the highest improvement was exhibited by briquettes with cassava starch additive [39]. Other papers analyzed, for example, the lignite additive in palm sawdust feedstock [96] or denatured rice husk additive added in various biomass feedstocks. One study focused on dry cow dung additive in briquettes made from raw mango and acacia leaves and saw dust exposed the best mechanical durability of combination with 10 % of dry cow dung additive [68]. The mentioned randomly selected additive materials reflect the wide scope of additive utilization in briquette production in an attempt to improve the quality of final products across various manufacturing sectors.

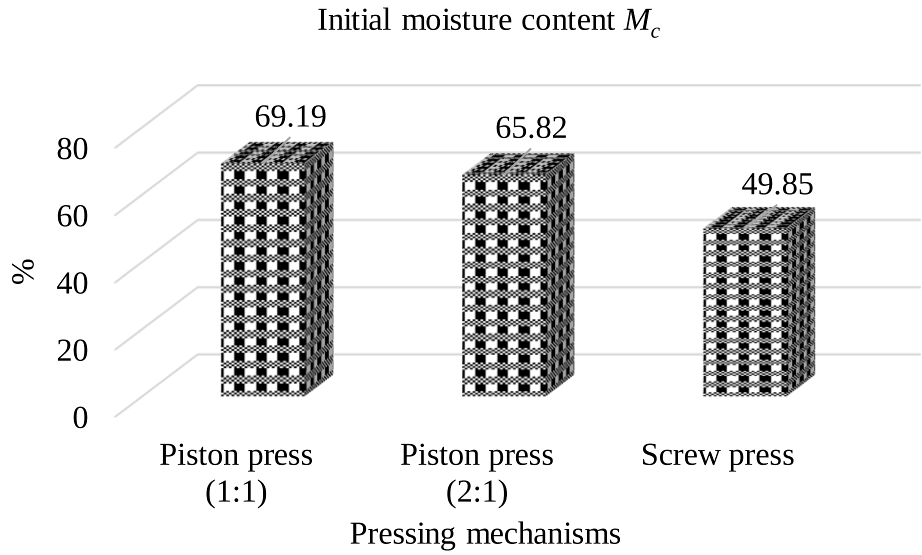


Figure 39: Comparison of different technologies of low-pressure bio-briquetting (initial bio-briquette samples moisture content M_c) [Authors data; 131]

Different pressing units (piston, screw) were used for feedstock material compression, as well as the used pressure (see Table 21), could influenced both the levels of moisture content M_c and density ρ of produced bio-briquette samples. The comparison of the mentioned two parameters within different pressing units are clearly expressed in Figures 39 and 40. As can be observed, the screw press led to better results than the piston press, even when a lower level of pressure was used.

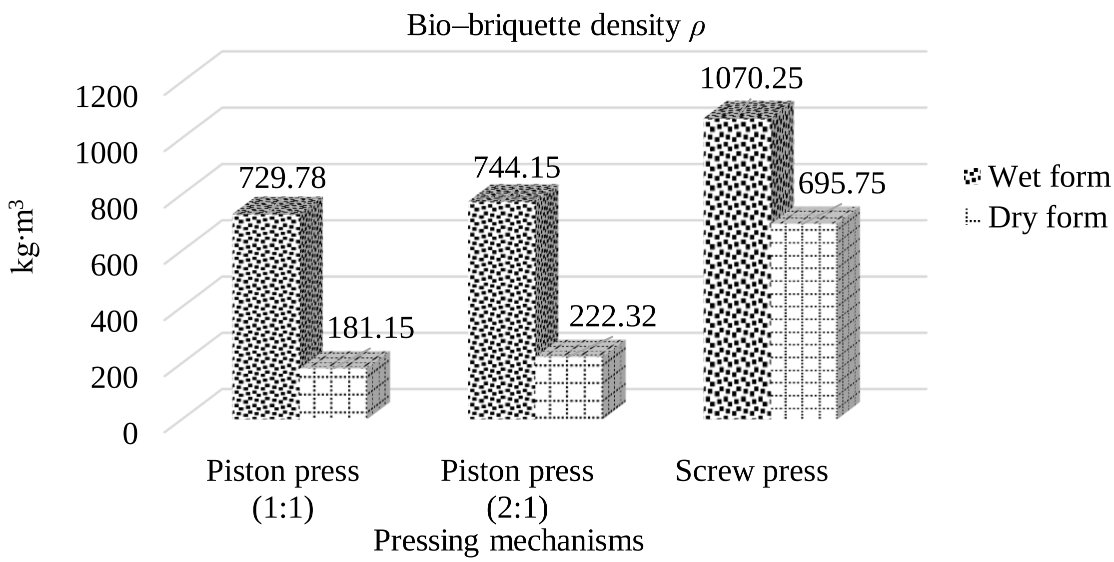


Figure 40: Comparison of different low-pressure briquetting technologies [Author's data; 131].

To monitor the relations between loaded pressure and achieved density ρ, the Table 23 was created to summarize previously published papers related to the efficiency of the low-pressure briquetting technology.

Table 23: Comparison of low-pressure presses and produced bio-briquette fuels.

Feedstock material	Country	P (MPa)	ρ ($kg \cdot m^{-3}$)	Reference
Rice husk + bran	USA	4.2	426.85	[130]
Sawdust	NGA	1.1	310.00	[173]
Tannery solid wastes	NGA	3.9	661.67	[174]
Mixed biomass*	RSA	0.9 – 1.8	695.75	[131]
Rice straw		0.2 – 1.0	207.48	
Banana leaves	IND	0.2 – 1.0	179.69	[15]
Teak leaves		0.2 – 1.0	227.53	

*32 % spent coffee grounds, 23 % coal fines, 11 % sawdust, 18 % mielie husks, 10 % waste paper, 6 % paper pulp

P – operation pressure, ρ – bio–briquette density, USA – United States of America, NGA – Nigeria, RSA – Republic of South Africa, IND – India, IDN – Republic of Indonesia

As can be seen in Table 23, the level of density ρ is not always higher if a higher pressure is used. Clearly, there are several more factors which influence the final level of a produced bio-briquette, such as type of used binder and feedstock, the ratio of binder and feedstock, pressing unit and similar.

The achieved operation pressure occurred at a relatively low level if compared with other published results (as shown in Table 23); nevertheless, the equipment was able to produce bio-briquette fuel, and thus its viability was demonstrated. As measured after bio-briquette sample production, the level of their density ρ also occurred at a lower level (if compared with figures in Figure 40). Such a limitation could be eliminated by using a longer lever which would cause a higher operation pressure P. Moreover, due to the variability of such investigated presses, their different construction must be considered.

The selection of the investigated feedstock material was found to be successful. It contained fibrous material (coconut fibre) in combination with waste paper which was shredded into strips; hence, their mixing created a fixed bond between materials. As a consequence, the utilization of fibrous materials is recommended for low-pressure briquetting technology.

4.4.5. Comparison of briquetting quality technologies

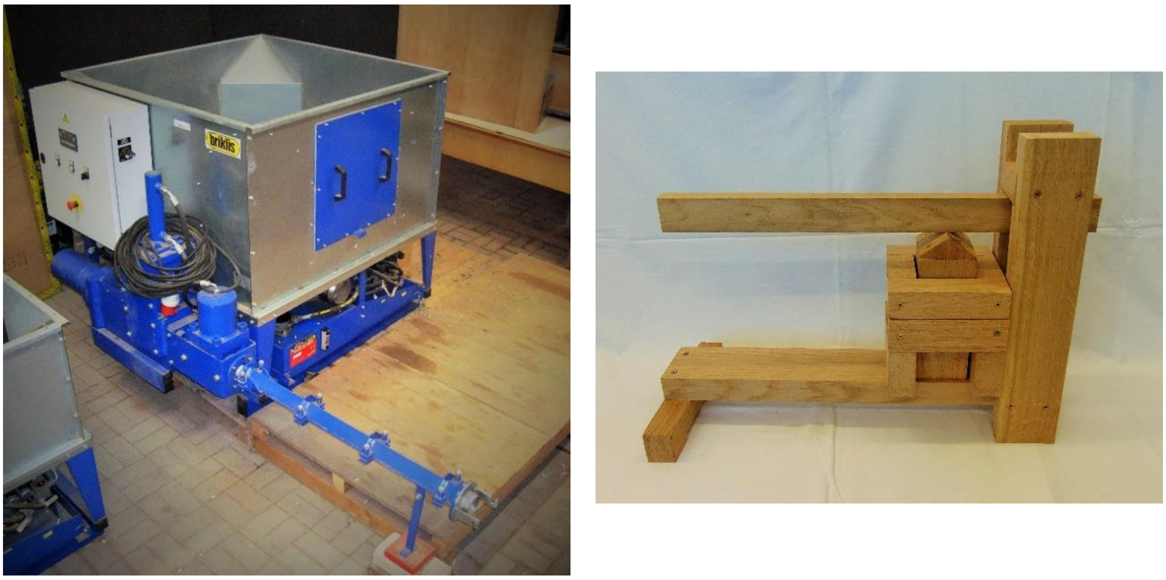
Manufacturing and utilization of a low-pressure briquetting press resulted in production of bio-briquette samples, the mechanical quality parameters of which were the point of interest, as well as the efficiency and suitability of such a press. After obtaining the necessary information, the comparison of both used briquetting presses was complete, namely, high-pressure and manual low-pressure briquetting presses. The results of such investigation in terms of differences between the two mentioned pieces of equipment are provided in Table 24. A particular emphasis has been placed on the suitability of specific equipment for different production conditions and on user friendliness.

Table 24: Comparison of specific used high- and low-pressure technologies.

	Properties	Press type	
		High-pressure press	**Low-pressure press**
Machine properties	Operation pressure	80 – 100 MPa	< 5 MPa
	Pressing chamber	Cylindrical	Square
	Pressing unit	Piston	Piston
	Power	Electricity	Man
	Power consumption	4.4 kW	–
	Size	2.91 m^3	0.07 m^3
	Weight	780 kg	± 10 kg
	Price	± 335 000 CZK	± 475 CZK*
	Productivity	30 $kg{\cdot}h^{-1}$	< 5 $kg{\cdot}h^{-1}$
Bio-briquette properties	Shape	Cylindrical	Block
	Diameter	40 mm; 50 mm	80 mm
	Weight	116.64 g	49.10 g
	Height	56.67 mm	42.72 mm
	Moisture content	9.11 %	67.50 %
	Density	1094.64 $kg{\cdot}m^3$	201.73 $kg{\cdot}m^3$
	Post-production treatment	None	Drying
	Storage	Yes	Hermetically sealed
Feedstock requirements	Moisture content	7 – 15%	> 50 %
	Particle size	< 10 mm	< 50 mm
	Need of binder	No	Yes

*price of wooden version of press manufactured in Republic of Indonesia (2016) and Socialist Republic of Vietnam (2018)

If considering all obtained information, differences were found in almost every monitored parameter of the selected technologies. However, such differences did not indicate unsuitability of specific briquetting technologiey these differences indicated that each briquetting technology is suitable and advantageous in different conditions. Thus, the efficiency of a specific briquetting press depends on the precise requirements of each press' production conditions. Between the main monitored parameters contained the question of target area (developing vs. developed country), the level of desired press development (commercial vs. individual production), the mechanical fuel requirements (need of fuel storage vs. direct utilization), financial investment issues or availability of properly trained operators. The most visible difference between such technologies were observed during visual inspection, see Figure 41.



a) b)

Figure 41: Comparison of used presses within different briquetting technologies: a) high-pressure briquetting press, b) low-pressure briquetting presses.

Several main parameters must be considered, such as price and size of the presses. Also, the need for electricity for the press work, requirements of the feedstock material and most importantly the quality of produced biofuel represented by the bio-briquette density ρ. Thus, the possible user or owner of such equipment must firstly define their own possibilities, such as expectations regarding the press' efficiency and the ability to ensure the requirements of the press. When all such issues are clarified, the chosen type of briquetting technology will fit into the conditions and satisfy those expectations.

5. Conclusion

In general, this thesis has found that the reuse of all investigated waste materials (i.e. waste biomass kind) is highly recommended with respect to their origin (biological residues) in order to maintain principles of appropriate waste management and follow the 'three R's' of waste management: 'Reduce – Reuse – Recycle'. If any material was not found to be appropriate for the investigated briquetting technology itself, some other possibility of its reuse is highly recommended.

The performed overall analysis of investigated waste biomass kinds represents important knowledge related to the topic of solid biofuel production and covers the absence of such analysis. The literature tends to focused only on one or a few specific waste materials and their suitability for bio-briquette production, but the overall evaluation and characterization of specific waste biomass kinds has been missing in the available theoretical background. Thus, the statement of each waste biomass kind's parameters extends the field in a theoretical manner, as well as in practice. The following parameters for specific waste biomass kinds were demonstrated:

- **Wood** – high level of chemical quality indicators, lower (but still satisfactory) level of mechanical quality indicators. Nevertheless, suitable for the investigated purpose in all cases.
- **Herbaceous** – average satisfactory level of chemical quality indicators (quality requirements achieved) and excellent level of mechanical quality of bio-briquette fuel
- **Fruit** – suitable for process of direct combustion (extremely high energy potential, satisfactory ash content), but low level of bio-briquette mechanical quality – need for the use of a binder, other additive or mixing with other waste biomass kind
- **Aquatic** – unsuitable properties for process of direct combustion (low energy potential, high moisture and ash contents); thus, not suitable for bio-briquette fuel production
- **Mixed** – it would be misleading to generalize this area; results depend on the content of mixed waste biomass. Nevertheless, such waste biomass kind represents a significant advantage in combining different waste materials with specific properties, which (in the right case) leads to elimination of negative properties of bio-briquette fuel and increasing their positive properties.

Nevertheless, determination of such statements was accompanied with problems and complications due to the obtained values' generalization within specific waste biomass kinds, insomuch as extending occasional differences between results for specific waste materials. Despite such differences, prevalent quality indicators occurred at the same level within specific waste biomass kind, and thus a statement regarding their quality parameters was possible and successful.

In the end, it can be concluded that the investigated biological residues originated from agriculture crops which are not cultivated for energy production purposes, but a significant part of them were found to have high potential for energy generation (by direct combustions).

The research partly focused on development and verification of a manual low-pressure briquetting press manufactured from wood components. The representative of a low-pressure briquetting technology was successful within the entire process of equipment design, manufacturing, operation and bio-briquette sample production. However, a limitation was observed in operation pressure, which occurred at a very low level; thus, changes in the design (lengthening of the lever) of the equipment are recommended in order to increase the operation pressure P and therefore also the mechanical quality of the produced bio-briquette fuel (namely, the density ρ).

The overall evaluation of the investigated equipment's applicability in practice indicated that it is a suitable technology for energy generation and waste management in rural areas in developing countries due to its simplicity and intelligibility.

By combination of all observed primary data related to the chemical parameters of various kinds of waste biomass, their energy potential and the mechanical parameters of various kinds of bio-briquette fuel, combined with the observed knowledge of low-pressure briquetting, was performed and monitored, experimentally investigated and evaluated for a wide range of applications of various briquetting technologies for clean renewable energy generation and appropriate waste management in different developed and developing areas.

6. References

[1] Goldemberg, J., Coelho, S.T. 2004. Renewable energy–traditional biomass vs. modern biomass. *Energy Policy* 32(6), 711–714.

[2] Fullerton, D.G., Bruce, N., Gordon, S.B. 2008. Indoor air pollution from biomass fuel smoke is a major health concern in the developing world. *Transactions of the Royal Society of Tropical Medicine and Hygiene* 102(9), 843–851.

[3] Bapat, D.W., Kulkarni, S.V., Bhandarkar, V.P. 1997. Design and Operating Experience on Fluidized Bed Boiler Burning Biomass Fuels with High Alkali Ash. In Proceedings of the 14th International Conference on Fluidized Bed Combustion, New York: Vancouver ASME 1997, 165–174.

[4] UNEP (United Nations Environmental Programme). 2017. Waste Agricultural Biomass. Global Partnership on Waste Management. Accessed 27th of January, 2017. Available online: http://web.unep.org/gpwm/what-we-do/waste-agricultural-biomass

[5] Suzuki, K., Tsuji, N., Shirai, Y., Hassan, M.A., Osaki, M. 2016. Evaluation of biomass energy potential towards achieving sustainability in biomass energy utilization in Sabah, Malaysia. *Biomass and Bioenergy* 97, 149–154.

[6] Owusu, P.A., Asumadu-Sarkodie, S., 2016. A review of renewable energy sources, sustainability issues and climate change mitigation. *Cogent Engineering* 3(1), 1167990. https://doi.org/10.1080/23311916.2016.1167990

[7] Lozano, F.J., Lozano, R., 2018. Assessing the potential sustainability benefits of agricultural residues: Biomass conversion to syngas for energy generation or to chemicals production. *Journal of Cleaner Production* 172(20), 1462-4169.

[8] Werther, J., Saenger, M., Hartzge, E.U., Ogada, T. & Siagi, Z. 2000. Combustion of agricultural residues. *Progress in Energy and Combustion Science* 1(26), 1–27.

[9] Li, J.F., Hu, R.Q. 2003. Sustainable Biomass Production for Energy in China. *Biomass and Bioenergy* 25, 483–499.

[10] Purohit, P., Tripathi, A.K., Kandpal, T.C. 2006. Energetics of coal substitution by briquettes of agricultural residues. *Energy* 31(8–9), 1321–1331.

[11] Zeng, X., Ma, Y., Ma, L. 2007. Utilization of straw in biomass energy in China. *Renewable and Sustainable Energy Reviews* 11, 976–987.

[12] Ben–Iwo, J., Manovic, V., Longhurst, P. 2016. Biomass resources and biofuels potential for the production of transportation fuels in Nigeria. *Renewable and Sustainable Energy Reviews* 63, 172–192.

[13] UN (United Nations). 2017. Affordable and clean energy: Why it matters. Available online:http://www.un.org/sustainabledevelopment/wp-content/uploads/2016/08/7_Why-it-Matters_Goal-7_CleanEnergy_2p.pdf

[14] Bhattacharya, S.C., Leon, M.A., Rahman, M., 2000. A Study on Improved Biomass Briquetting. In *Proceedings of the International Conference on Biomass–based Fuels and Cooking Systems* (BFCS 2000). Pune, India, 20–24.

[15] Agyeman, K.O.G.; Oldham, J.H. 1986Utilization of cocoa by-products as an alternative source of energy. *Biomass* 10, 311–318.

[16] Brand, M.A., Jacinto, R.C., Antunes, R., da Cunha, A.B., 2017. Production of briquettes as a tool to optimize the use of waste from rice cultivation and industrial processing. *Renewable Energy* 111, 116–123. doi:10.1016/j.renene.2017.03.084.

[17] Demirbas, M.F., Balat, M., Balat, H., 2009. Potential contribution of biomass to the sustainable energy development. *Energy Conversion and Management* 50(7), 1746–1770.

[18] Nonhebel, S., 2007. Energy from agricultural residues and consequences for land requirements for food production. *Agricultural Systems* 94, 586-592.

[19] Scarlat, N., Martinov, M., Dallemand, J.F., 2010. Assessment of the availability of agricultural crop residues in the European Union: potential and limitations for bioenergy use. *Waste Management* 30(10), 1889–1897.

[20] Ahuja, A. & Tatsutani, M. 2009. Sustainable energy for developing countries. *S.A.P.I.E.N.S.* 2(1), 1–16.

[21] Lantin, R. 1999. Rice: Post–harvest Operations. INPhO–Post–harvest Compendium. Report Food and agriculture Organization of the United Nations.

[22] Food and Agriculture Organization of the United Nations (FAO). 2018. Available online: http://www.fao.org/faostat/en/?#data/QC (accessed on 21st April 2018).

[23] Samsuri, A. & Zoveidavianpoor, M. 2014. Does the maturity of Jatropha curcas L. affect the quality and quantity of the yield of oil for biodiesel production. International *Journal of Green Energy* 11, 193–205.

[24] Joshi, Ch. & Khare, S.K. 2011. Utilization of deoiled Jatropha curcas seed cake for production of xylanase from thermophilic Scytalidium thermophilum. *Bioresource Technology* 102(2), 1722–1726.

[25] Singh, R.N., Vyas, D.K., Srivastava, N.S.L., Narra, M. 2008. SPRERI experience on holistic approach to utilize all parts of Jatropha curcas fruit for energy. *Renewable Energy* 33(8), 1868–1873.

[26] Minowa, T.; Kondo, T.; Sudirjo, S.T. 1998. Thermochemical Liquefaction Of Indonesian Biomass Residues. *Biomass Bioenergy* 14, 517–524.

[27] Mohammed, M.A.A.; Salmiaton, A.;Wan Azlina,W.A.K.; Mohamad Amran, M.S.; Omar, R.; Taufiq-Yap, Y.H.; Fakhru'l-Razi, A. 2012. Gasification of oil palm empty fruit bunches: A characterization and kinetic study. *Bioresour. Technol*. 110, 628–636.

[28] Moral, M.N.A., 2000. Briquetting of biomass in Bangladesh. In *World renewable energy congress* 6(4), 2402–2405. ISBN: 0-080-43865-2.

[29] Stolarski, M. J., Szczukowski, S., Tworkowski, J., Krzyzaniak, M., Gulczyński, P., Mleczek, M., 2013. Comparison Of Quality And Production Cost Of Briquettes Made From Agricultural And Forest Origin Biomass. *Renewable Energy* 57, 20–26. ISSN 0960-1481. doi: 10.1016/J.Renene.2013.01.005

[30] Chou, Ch.S., Lin, S.H., Peng, Ch.Ch., Lu, W.Ch. 2009. The optimum conditions for preparing solid fuel briquette of rice straw by a piston-mold process using the Taguchi method. *Fuel Processing Technology* 90(7–8), 1041–1046.

[31] Eissa, A. H. A., Gamea G. R., El Saeidy E. A., El Sisi, S. F. 2013. Quality Characteristics For Agriculture Residues To Produce Briquette. In: *Trends in Agriculture Engineering*. Praha: Czech University of Life Sciences, Prague, 156–162

[32] Bilgili, F., Kocak, E., Bulut, U., Kuskaya, S., 2017. Can biomass energy be an efficient policy tool for sustainable development? R*enewable and Sustainable Energy Reviews* 71, 830-845.

[33] UN (United Nations). 2017. Affordable and clean energy: Why it matters. Available online: http://www.un.org/sustainabledevelopment/wp-content/uploads/2016/08/7_Why-it-Matters_Goal-7_CleanEnergy_2p.pdf

[34] Anggono, W.; Suprianto, F.D.; Sutrisno Kasrun, A.W. 2016. Investigation on Biomass Briquette as Energy Source. *JIRAE,* 1, 11–14.

[35] EN ISO 17225–1 (2015): Solid biofuels – Fuel specifications and classes – Part 1: General requirements; ISO: Geneva, Switzerland, 2018.

[36] Garrido, M.A., Conesa, J.A., Garcia, M.D., 2017. Characterization and Production of Fuel Briquettes Made from Biomass and Plastic Wastes. *Energies* 10, 850. doi:10.3390/en10070850.

[37] Tumuluru, J.S., Sokhansanj, S., Wright, Ch. T., Boardman, R.D., Yancey, N. 2011. A Review on Biomass Classification and Composition, Co-Firing Issues and Pretreatment Methods. *Biofuels Bioproducts and Biorefining* 5, 683–707.

[38] EN ISO 17225–1 (2015): Solid Biofuels - Fuel Specifications and Classes – Part 1: General Requirements; ISO: Geneva, Switzerland, 2018.

[39] Emerhi, E.A., 2011. Physical and combustion properties of briquettes produced from sawdust of three hardwood species and different organic binders. *Advances in Applied Science Research* 2 (6), 236–246. ISSN: 0976–8610.

[40] Loo, S.V., Koppejan, J. 2004. The Handbook of Biomass Combustion and Co-Firing. Earthscan, London. 1–443. ISBN: 978-1-84407-249-1.

[41] Obernberger, I., Thek, G. 2004. Physical Characterisation and Chemical Composition of Densified Biomass Fuels with Regard to Their Combustion Behaviour. *Biomass and Bioenergy* 27(6), 653–669.

[42] Kirsten, C., Lenz, V., Schröder, H.W., Repke, J.U. 2016. Hay Pellets — The Influence of Particle Size Reduction on Their Physical – Mechanical Quality and Energy Demand During Production. *Fuel Processing Technology* 148, 163–174.

[43] Husain, Z., Zainac, Z., Abdullah, Z. 2017. Briquetting of Palm Fibre and Shell From the Processing of Palm Nuts to Palm Oil. *Biomass and Bioenergy* 22(6), 505–509.

[44] Munjeri, K., Ziuku, S., Maganga, H., Siachingoma, B., Ndlovu, S. 2016. On the Potential of Water Hyacinth as a Biomass Briquette for Heating Applications. *International Journal of Energy and Environmental Engineering* 7, 37–43.

[45] Rodriguesa, A.J., Oderob, M.O., Hayombec, P.O., Akunod, W., Keriche, D., Maobef, I. 2017. Converting Water Hyacinth to Briquettes: A Beach Community Based Approach. *International Journal of Sciences: Basic and Applied Research* 32(1), 358–378

[46] Picchi G., Silvestri S., Cristoforetti A. 2013. Vineyard residues as a fuel for domestic boilers in Trento Province (Italy): Comparison to wood chips and means of polluting emissions control. *FUEL* 113, pp. 43-49.

[47] Obi, O.F., Okongwu, K.C.H. 2016. Characterization of fuel briquettes made from a blend of rice husk and palm oil mill sludge. *Biomass Conversion and Biorefinery* 6, 449–456.

[48] Romallosa, A.R.D., Kraft, E. 2017. Feasibility of Biomass Briquette Production from Municipal Waste Streams by Integrating the Informal Sector in the Philippines. *Resources* 6(1), doi:10.3390/resources6010012

[49] Rezania, S., Fadhil, M., Fatimah, S. 2016. Evaluation of water hyacinth (Eichhornia crassipes) as a potential raw material source for briquette production. *Energy* 111, 768–773. ISSN 0360-5442. doi:10.1016/j.energy.2016.06.026

[50] Nasrin, A. B., Ma, A. N., Choo, Y. M., Mohamad, S., Rohaya, M. H., Azali, A., Zainal, A. Z., 2008. Oil Palm Biomass as Potential Substitution Raw Materials for Commercial Biomass Briquettes Production. *American Journal of Applied Sciences* 5(3), 179–183 ISSN 1546-9239.

[51] Mitchual, S.J., Frimpong-Mensah, K., Darkwa, N.A., 2013. Effect of species, particle size and compacting pressure on relaxed density and compressive strength of fuel briquettes. *International Journal of Energy and Environmental Engineering* 4(1), 1–6.

[52] Tabarés, J.L.M., Ortiz, L., Granada, E., Viar, F.P., 2000. Feasibility study of energy use for densificated lignocellulosic material (briquettes). *Fuel* 79(10), 1229-1237, ISSN 0016-2361, doi: 10.1016/S0016-2361(99)00256-2

[53] Resch, H., 1982. Densified wood and bark fuels. Energy from Forest Biomass. *Holzforschung und Holzverwertung* 34(4). 69-74. ISSN : 0018-3849.

[54] Zavrazhnov & Syasin. (2014). Research process for producing fuel briquettes from waste uprooting orchards. *Michurinsky State Agrarian University Bulletin* 2, (46–49).

[55] Živković, M., Živković, M., Urošević, S. O., Mićo, O., Gligorević, K., Zlatanović, I., Koprivica1, R. (2013). Aspects Of Using Potential Energy Products Of Biomass After Pruning Fruit And Grape Plantations In The Republic Of Serbia. *Agriculture & Forestry* 59(1), 167–182.

[56] Bilandzija, N., Voca, N., Kricka, T., Matin, A. & Jurisic V. (2012). Energy potential of fruit tree pruned biomass in Croatia. *Spanish Journal of Agricultural Research* 10(2), 292–298.

[57] Niedziółka, I., Szpryngiel, M. 2014. Assessment of energy consumption of pellets and briquettes production in compressing devices. *Agricultural Engineering* 2(150), 145–154.

[58] Tumuluru, J.S., Tabil, L.G., Song, Y., Iroba, K.L., Meda, V. 2015. Impact of process conditions on the density and durability of wheat, oat, canola, and barley straw briquettes. *BioEnergy Research* 8(1), 388–401.

[59] Kim, S., Dale, B.E. 2004. Global potential bioethanol production from waste crops and crop residues. *Biomass and Bioenergy* 26, 361–375.

[60] Guo, L., Tabil, L. G., Wang, D., Guanghui, W., 2015. Briquetting of wheat, barley, canola and oat straw. In: *ASABE International Meeting*. American Society of Agricultural and Biological Engineers, 25–26. doi:10.13031/aim.20152181098

[61] Stasiak, M., Molenda, M., Bańda, M., Wiącek, J., Parafiniuk, P., Gondek, E. 2017. Mechanical and combustion properties of sawdust – Straw pellets blended in different proportions. *Fuel Processing Technology* 156, 366–375.

[62] Kaliyan N., Morey R.V., 2009. Factors affecting strength and durability of densified biomass products. *Biomass and Bioenergy* 33(3), 337–359. Doi: 10.1016/j.biombioe.2008.08.005

[63] Adetogun, A.C., Ogunjobi, K.M., Are, D.B. 2014. Combustion properties of briquettes produced from maize cob of different particle sizes. *Journal of research in forestry, wildlife and environmental* 6(1), 28–38.

[64] Riga Technical University 2013. Non-Woody Biomass Briquettes. Fuel Analysis and Combustion Tests. In: E*nergy Efficient and Ecological Housing 'Ecohousing' Project Report*, Riga, June 2013.

[65] Muazu, R.I., Stegemann, J.A. 2015. Effects of operating variables on durability of fuel briquettes from rice husks and corn cobs. *Fuel Processing Technology* 133, 137–145.

[66] Sellin, N., de Oliveira, B.G., Marangoni, C., Souza, O., de Oliveira, A.P.N., de Oliveira, T.M.N., 2013. Use of Banana Culture Waste to Produce Briquettes. *Chemical Engineering Transactions* 32, 349–354.

[67] Panwar, V., Prasad, B., Wasewar, K. L., 2011. Biomass Residue Briquetting and Characterization. *Journal of Energy Engineering* 137(2), 108–114. doi:10.1061/(ASCE)EY.1943-7897.0000040

[68] Birwatkar, V. R., Khandetod, Y. P., Mohod, A. G., Dhande, K. G. 2014. Other Energy Source, Technology Dapoli, Farm Machinery a Technology Dapoli, Physical and thermal properties of biomass briquetted fuel. *Indian Journal of Scientific Research* 2(4), 55–62.

[69] Gravalos, I., Xyradakis, P., Kateris, D., Gialamas, A.T. 2016. An Experimental Determination of Gross Calorific Value of Different Agroforestry Species and Bio-Based Industry Residues. *Natural Resources* 7, 57-68.

[70] Al-Widyan, M. I., Al-Jalil, H. F. 2002. Physical durability and stability of olive cake briquettes. *Canadian Biosystems Engineering* 44, 341-345.

[71] Wilaipon, P., 2011. Durian Husk Properties and its Heating Value Equation. American *Journal of Applied Sciences* 8(9), 893-896. doi:10.3844/ajassp.2011.893.896

[72] Nurianaa, W., Martanaa, N.F. 2014. Synthesis Preliminary Studies Durian Peel Bio Briquettes as an Alternative Fuels. In *Conference and Exhibition Indonesia Renewable Energy & Energy Conservation. Energy Procedia* 47, 295–302. doi:10.1016/j.egypro.2014.01.228.

[73] Suryaningsih, S., Nurhilal, O., Yuliah, Y., Mulyana, C. 2017. Combustion quality analysis of briquettes from variety of agricultural waste as source of alternative fuels. In International Conference on Biomass: Technology, Application, and Sustainable Development. *Earth and Environmental Science* 65, 1-6. doi:10.1088/1755-1315/65/1/012012.

[74] Wilaipon, P., 2009. The Effects of Briquetting Pressure on Banana-Peel Briquette and the Banana Waste in Northern Thailand. *American Journal of Applied Sciences* 6(1), 167-171. ISSN 1546-9239.

[75] Scheffer, M. 1998. Ecology of shallow lakes. *Population and community biology* 22.

[76] Smart, R.M., Doyle, R.D. 1995. Ecological theory and management of submersed aquatic plant communities. *Aquatic Plant Control Research Program* (Vicksburg: U.S. Army Engineer Waterways Experiment Station)

[77] Pancho, J.V., Soerjani, M. 1978. Aquatic Weeds of Southeast Asia. *BIOTROP*, Indonesia: Bogor, 130.

[78] Nasution, Z. 2003. Land and Forest Management in the Lake Toba Catchment Area. *Universiti Sains Malaysia*.

[79] Nasution, M.I.T., Awal, S.M.S, Permana, D.M. 2016. The Methods of Preventing Water Hyacinth as Aquatic Pollution in Lake Toba Caused by Agricultural Waste. *International Journal of Environmental Science and Development* 7(8), 630–633.

[80] Langeland, K.A. 1990. Hydrilla: A continuing problem in Florida waters. University of Florida Circular No. 884 (Gainesville: University of Florida).

[81] Rahman, I.A., Saad, B., Shaidan, S., Sya Rizal, E.S. 2005. Adsorption characteristics of malachite green on activated carbon derived from rice husks produced by chemical–thermal process. *Bioresource Technology* 96, 1578–1583.

[82] Kannan, R.R., Rajasimman, M., Rajamohan, N., Sivaprakash, A.B. 2010. Equilibrium and kinetic studies on sorption of malachite green using Hydrilla Verticillata biomass. *International Journal of Environmental Research* 4(4), 817–824.

[83] Tjitrosemito, S. 1994, Integrated management of paddy and aquatic weeds in Asia. In: Proceedings of the International Seminar "Biological Control and Integrated Management of Paddy and Aquatic Weeds in Asia" J., *Asian and Pacific Council*., Tsukuba, Japan.

[84] Little, E.C.S. 1968. Handbook of utilization of aquatic plants. *Plant Production and Protection,* Division Rome, FAO, 123.

[85] Ling, S.W. 1960. Control of aquatic vegetation. In: Third International Inland Fisheries Training Centre Rome, FAO. 12.

[86] Bagnall, L.O. 1971. Processed aquatic plants for animal nutrition. *Annu.Res.Rep.Inst.Food Agric.Sci.Univ.Fla*. 49.

[87] Aswathy, U.S., Rajeev, K., Sukumaran, G., Devi, L., Rajasree, K.P., Singhania, R.R., Pandey, A. 2010. Bio-ethanol from water hyacinth biomass: an evaluation of enzymatic saccharification strategy. *Bioresource Technology* 101, 925–930.

[88] Annachhatre, A.P., Khanna, P. 1987. Methane recovery from water hyacinth through whole-cell immobilization technology. *Biotechnology and Bioengineering* 29, 805-818.

[89] Ighodalo, O.A, Zoukumor, K., Egbon, C., Okoh, S., Odu, K. 2011. Processing Water Hyacinth into Biomass Briquettes for Cooking Purposes. *Journal of Emerging Trends in Engineering and Applied Sciences* 2(2), 305–307.

[90] Munjeri, K., Ziuku, S., Maganga, H., Siachingoma, B., Ndlovu, S. 2016. On the potential of water hyacinth as a biomass briquette for heating applications. *International Journal of Energy and Environmental Engineering* 7(1), 37–43.

[91] Rodrigues, A.J., Omondi, M., Hayombe, P.O., Akuno, W., Kerich, D., Maobe, I. 2014. Converting Water Hyacinth to Briquettes: *A Beach Community Based Approach* 4531, 358–378.

[92] Young, P. & Kennas, S., 2003. Feasibility and Impact Assessment of a Proposed Project to Briquette Municipal Solid Waste for Use as a Cooking Fuel in Rwanda. *Consultancy Report to the Business Linkages Challenge Fund* (BLCF).

[93] Zhang, X.Y., Chen, M.Q., Huang, Y.W., Xue, A.F., 2016. Isothermal Hot Air Drying Behavior Of Municipal Sewage Sludge Briquettes Coupled With Lignite Additive. *Fuel* 5(171), 108–115. ISSN 0016-2361. doi:10.1016/J.Fuel.2015.12.052.

[94] Olorunnisola, A. 2007. Production of Fuel Briquettes from Waste Paper and Coconut Husk Admixtures 9, 1–11.

[95] Lela, B., Barišić, M., Nižetić, A. S., 2016. Cardboard/sawdust briquettes as biomass fuel: Physical-mechanical and thermal characteristics. *Waste Management* 47, 236–245. ISSN 1879-2456. doi:10.1016/j.wasman.2015.10.035.

[96] Saptoadi, H., 2008. The Best Biobriquette Dimension and its Particle Size. *Asian Journal on Energy and Environment* 9(3), 161–175.

[97] Jasinskas, A., Kucinskas, V., Arak, M., Olt, J. 2013. Research of Physical-Mechanical Properties of Sawdust Fuel Briquettes with the Additives. In: *Rural Development 2013: Proceedings* 6(3). Lithuania, 55–59.

[98] Sengar, S.H., Patil, S.S.A., Chendake, D. 2013. Economic Feasibility of Briquetted Fuel. Global Journal Of Researches in Engineering, *Chemical Engineering* 13(1), 21–26.

[99] Johansson, L.S., Leckner, B., Gustavsson, L., Cooper, D., Tullin, C. & Potter, A. 2004. Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets. *Atmospheric Environment* 38(25) 4183–4195.

[100] Gürdil, G.A.K., Selvi, K.C., Malaťák, J., Pinar, Y. 2009. Biomass Utilization for Thermal Energy. *Ama, Agricultural Mechanization in Asia, Africa and Latin America* 40(2), 80–85.

[101] Brožek, M. 2001. Briketování nekovového odpadu. In *Sborník mezinárodní vědecké konference XIV. DIDMATTECH 2001*. Radom, Politechnika Radomska. 84–87. ISBN 83–7204–221–7.

[102] Brožek, M. 2001. Briketování kovových odpadů. In *Sborník mezinárodní konference Trendy technického vzdělávání 2001*. Olomouc, Univerzita Palackého 2001. 38 – 41. ISBN 80–244–0287–4.

[103] Seifi, M. R., Alimardani, R. 2010. Comparison of moisture-dependent physical and mechanical properties of two varieties of corn (Sc 704 and Dc 370). *Australian Journal of Agricultural Engineering* 1(5):170-178 (2010). ISSN:1836-9448

[104] Altuntas, E., Yıldız, M. 2007. Effect of Moisture Content on Some Physical and Mechanical Properties of Faba Bean (Vicia faba L.) Grains. *Journal of Food Engineering* 78 (1): 174-183. DOI: 10.1016/j.jfoodeng.2005.09.013

[105] Yahya, A., Hamdan, T. A. I., Suryanto, H. 2013. Physical and Mechanical Properties of Jatropha curcas L. Fruits from Different Planting Densities. *Journal of Applied Sciences* 13: 1004-1012.

[106] Repsa E., Kronbergs E., Pudans E. Durability of compacted energy crop biomass. *Engineering for Rural Development*, vol. 13, 2014, pp. 436-439.

[107] Alakangas E., Wiik C., Lensu T. CEN 335 – Solid biofuels, Feedback from market actors, *EUBIONET report – VTT Report* VTT-R-00430-07, Jyväskylä, 2007, 71 p.

[108] EN ISO 16559 (2014): Solid biofuels. Terminology, definitions and descriptions; ISO: Geneva, Switzerland, 2018.

[109] Holm-Nielsen J. B., Al Seadi T., Oleskowicz-Popiel P. 2009. The future of anaerobic digestion and biogas utilization. *Bioresource Technology* 100, 5478-5484.

[110] Temmerman, M., Rabier, F., Jensen, P. D., Hartmann, H., & Böhm, T. (2006). Comparative study of durability test methods for pellets and briquettes. *Biomass & Bioenergy*, 30(11), 964-972. DOI: 10.1016/j.biombioe.2006.06.008

[111] Mani, S., Tabil, L.G., Sokhansanj, S. 2003. An overview of compaction of biomass grinds. *Powder Handling Processing*, 15 (3) (2003), pp. 160-168.

[112] McMullen, J., Fasina, O.O., Wood, C.W., & Feng, Y. (2005). Storage and handling characteristics of pellets from poultry litter. *Applied Engineering in Agriculture*, 21(4), pp. 645-651.

[113] ISO 17225–1 (2015): Solid biofuels – Fuel specifications and classes – Part 1: General requirements; ISO: Geneva, Switzerland, 2018.

[114] ISO 17225–3 (2015): Solid biofuels – Fuel specifications and classes – Part 3: Graded wood briquettes; ISO: Geneva, Switzerland, 2018.

[115] ISO 17225–7 (2014): Solid biofuels – Fuel specifications and classes – Part 7: Graded non–woody briquettes; ISO: Geneva, Switzerland, 2018.

[116] EN 18134–1 (2015): Solid biofuels - Determination of moisture content - Oven dry method - Part 1: Total moisture - Reference method; ISO: Geneva, Switzerland, 2018.

[117] EN 18134–2 (2015): Solid biofuels – Determination of moisture content – Oven dry method – Part 2: Total moisture – Simplified method; ISO: Geneva, Switzerland, 2018.

[118] EN ISO 18122 (2015): Solid biofuels – Determination of ash content; ISO: Geneva, Switzerland, 2018.

[119] ISO 18847 (2016): Solid biofuels – Determination of particle density of pellets and briquettes; ISO: Geneva, Switzerland, 2018.

[120] ISO 18125 (2017): Solid biofuels – Determination of calorific value; ISO: Geneva, Switzerland, 2018.

[121] EN ISO 16948 (2016): Solid biofuels – Determination of total content of carbon, hydrogen and nitrogen; ISO: Geneva, Switzerland, 2018.

[122] ISO 16994 (2015): Solid biofuels -- Determination of total content of sulfur and chlorine; ISO: Geneva, Switzerland, 2018.

[123] FCCC (Framework Convention on Climate Change), 1999. Mechanisms pursuant to Articles 6, 12 and 17 on the Kyoto Protocol. *Plan for capacity-building under decision* 7/CP.4: an initial framework.

[124] Bhattacharya, S.C., Kumar S., 2000. Dissemination of renewable energy in developing countries: Experiences of a regional project in Asia. Energy Program. *Asian Institute of Technology*. Thailand.

[125] Bhattacharya, S. C., Salam P. A., 2001. Energy for cooking: Cool biomass options for the developing countries. *Energy Program. Asian Institute of Technology*. Thailand.

[126] Kaygusuz, K., 2012. Energy for sustainable development: A case of developing countries. *Renewable and Sustainable Energy Reviews* 16(2), 1116-1126.

[127] Lohri, Ch. R., Sweeney, D., Rajabu, H. M., 2015. Carbonizing urban biowaste for low-cost char production in developing countries - A Review of Knowledge, Practices and Technologies. *Joint Report by Eawag*, MIT D-Lab and UDSM.

[128] Abakr, Y.A., Abasaeed, A.E., 2006. Experimental evaluation of a conical screw briquetting machine for the briquetting of carbonized cotton stalks in Sudan. *Journal of Engineering Science and Technology* 1, 212- 220.

[129] Ngusale, G. K., Luo, Y., Kiplagat, J. K., 2014. Briquette making in Kenya: Nairobi and peri-urban areas. *Renewable and Sustainable Energy Reviews* 40, 749–759. Doi:10.1016/j.rser.2014.07.206.

[130] Yank, A., Ngadi, M., Kok, R., 2016. Physical properties of rice husk and bran briquettes under low pressure densification for rural applications. *Biomass and Bioenergy* 84, 22-30. Doi:10.1016/j.biombioe.2015.09.015.

[131] Pilusa, T.J., Huberts, R., Muzenda, E., 2012. Low Pressure Binder-Less Densification of Fibrous Biomass Material usin g a Screw Press. *International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering* 6(8), 657–660.

[132] Balasubramani, P., Anbumalar, V., Nagarajan, M.S., Prabu, P.M. 2016. Biomass briquette manufacturing system model for environment. *Journal of Alloys and Compounds* 686, 859–865. doi:10.1016/j.jallcom.2016.06.233.

[133] Hood, A. H., 2010. Biomass Briquetting in Sudan: A Feasibility Study. Women's Refugee Commission. *United States Agency for International Development* (USAID), 1-95.

[134] Eriksson, S., Prior, M., 1990. The briquetting of agricultural wastes for fuel, FAO, *Agriculture and consumer protection Department*, Rome 8.

[135] ISO 17831–2 (2015): Solid biofuels -- Determination of mechanical durability of pellets and briquettes - Part 2: Briquettes; ISO: Geneva, Switzerland, 2018.

[136] ISO 1928 (2010): Solid mineral fuels – Determination of gross calorific value by the bomb calorimetric method, and calculation of net calorific value; ISO: Geneva, Switzerland, 2018.

[137] EN ISO 18123 (2016): Solid biofuels -- Determination of the content of volatile matter; ISO: Geneva, Switzerland, 2018.

[138] EN 643 (2014): Paper and board. European list of standard grades of paper and board for recycling; ISO: Geneva, Switzerland, 2018.

[139] EN 14918 (2010): Solid biofuels – Determination of calorific value; ISO: Geneva, Switzerland, 2018.

[140] EN ISO 16559 (2014): Solid biofuels -- Terminology, definitions and descriptions; ISO: Geneva, Switzerland, 2018.

[141] EN 15234–1 (2011): Solid biofuels – Fuel quality assurance – Part 1: General requirements; ISO: Geneva, Switzerland, 2018.

[142] Czech University of Life Sciences Prague (CULS). 2013. Model of laboratory briquetting press provided with twin-shell pressing chamber. Inventors: Brožek, M., Nováková, A. Czech Republic. 02. 05. 2013.

[143] Herák, D., Kabutey, A., Divišová, M., Svatoňová, T. 2012. Comparison of the mechanical behaviour of selected oilseeds under compression loading. *Not. Bot. Horti Agrobot. Cluj-Napoc.* 40, pp. 227–232.

[144] Sigalingging, R., Herák, D., Kabutey, A., Mizera, Č., Divišová, M. 2014. Tangent curve function description of mechanical behaviour of bulk oilseeds: A review. *Sci. Agric. Bohem.* 45, pp. 259–264.

[145] Jourabchi, S.A., Gan, S., Ng, H.K. 2016. Comparison of conventional and fast pyrolysis for the production of Jatropha curcas bio-oil. *Applied Thermal Engineering* 99, 160–168.

[146] Karunanithy, C., Wang, Y., Muthukumarappan, K., Pugalendhi, S. 2012. Physiochemical characterization of briquettes made from different feedstocks. *Biotechnology research international* 12. doi:10.1155/2012/165202.

[147] Telmo, C. and Lousada, J. (2011) The Explained Variation by Lignin and Extractive *Contents on Higher Heating Value of Wood. Biomass Bioenergy*, 35, 1663-1667. http://dx.doi.org/10.1016/j.biombioe.2010.12.038

[148] Nasser R.A., Salem M.Z.M., Al-Mefarrej H.A., Abdel-Aal M.A., Soliman S.S. Fuel characteristics of vine prunings (Vitis vinifera L.) as a potential source for energy production. *BioResources* 9(1), 2014, pp. 482-496.

[149] McKendry, P., 2002. Energy production from biomass (part 1): overview of biomass. *Bioresource Technol*., 83: 37–46.

[150] Phichai, K., Pragrobpondee, P., Khumpart, T., Hirunpraditkoon. B. S. 2013. Prediction Heating Values of Lignocellulosics from Biomass Characteristics. World Academy of Science, Engineering and Technology. *International Journal of Chemical and Molecular Engineering.* Vol:7, No:7, 2013. 532.

[151] Syamsiro, M.; Saptoadi, H.; Tambunan, B.H.; Pambudi, N.A. A preliminary study on use of cocoa pod husk as a renewable source of energy in Indonesia. *Energy Sustain. Dev*. 2012, 16, 74–77.

[152] Suryaningsih, S.; Nurhilal, O.; Yuliah, Y.; Mulyana, C. Combustion quality analysis of briquettes from variety of agricultural waste as source of alternative fuels. In *International Conference on Biomass: Technology, Application, and Sustainable Development. Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2017; Volume 65, pp. 1–6.

[153] Wilaipon, P.; Trirattansirichai, K.; Tangchaichit, K. Moderate Die–Pressure Banana–Peel Briquettes. *Int. J. Renew. Energy* 2007, 2, 53–58.

[154] RETSASIA (2005): Results Earlier Reported for Sawdust Briquette and Torrefied Wood. www.retsasia.ait.ac.th/publication/WR ERC2005/RONAST-WRERC05

[155] Jittabut, P. 2015. Physical and Thermal Properties of Briquette Fuels from Rice Straw and Sugarcane Leaves by Mixing Molasses, *Energy Procedia* 79, 2-9. ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2015.11.452.

[156] Lindley, J.A., Vossoughi, M. 1989. Physical properties of biomass briquettes. *Transactions of the ASAE* 32, 361–366.

[157] Obernberger, I., Thek, G. 2004. Physical characterisation and chemical composition of densified biomass fuels with regard to their combustion behaviour. *Biomass and Bioenergy* 27(6), 653–669. doi:10.1016/j.biombioe.2003.07.006.

[158] Wakchaure, G.C., Mani, I. 2009. Effect of binders and pressures on physical quality of some biomass briquettes. *Journal of Agricultural Engineering* 46(4), 24–30.

[159] ÖNORM M 7135 (2000): Preβlinge aus naturbelassenem Holz und naturbelassender Rinde –Pellets und Briketts – Anforderungen und Prüfbestimmungen.

[160] DIN 51731 (1996): Testing of solid fuels, compressed untreated wood. Requirements and testing. Berlin, Germany: Deutsches Institut für Normung.

[161] ISO 13061–2 (2014): Physical and mechanical properties of wood — Test methods for small clear wood specimens — Part 2: Determination of density for physical and mechanical tests; ISO: Geneva, Switzerland, 2018.

[162] ASAE (1996): ASAE S269.4 – Cubes, pellets, and crumbles – Definitions and methods for determining density, durability, and moisture content. ASAE Standards 1996, 477–479. St. Josephs, MI: ASAE.

[163] Theerarattananoon, K., Xu, F., Wilson, J., Staggenborg, S., Mckinney, L., Vadlani, P., Pei, Z. & Wang, D. 2012. Effects of the pelleting conditions on chemical composition and sugar yield of corn stover, big bluestem, wheat straw, and sorghum stalk pellets. *Bioprocess and biosystems engineering* 35(4), 615–23.

[164] Kaliyan, N., & Morey, R. V. (2005). Densification of corn stover. In *2005 ASAE Annual International Meeting.*

[165] Li Y. D., Liu, H. 2000. High-pressure densification of wood residues to form an upgraded fuel. *Biomass and Bioenergy* 19(3) 177-186.

[166] Rajkumar, D. & Venkatachalam, P. 2013. Physical properties of agro residual briquettes produced from Cotton , Soybean and Pigeon pea stalks. International *Journal on Power Engineering and Energy* 4(4), 414–417.

[167] Gentil LV, Vale AT (2015): Energy balance and efficiency in wood sawdust briquettes production. *FLORESTA*, 45 (2), 281–288.

[168] Mewes E (1959): “Verdichtungsgesetzmassigkeiten nach presstopfversuchen (Compression relationships as a result of experiments in pressure chambers),” *Landtechnische Forschung* 9 (3), 68–76.

[169] Lequeux P, Carré J, Hébert J, Lacrosse L, Schenkel Y (1990): Energie et biomasse, la densification, Les presses agronomiques de Gembloux, Belgium, 188.

[170] Alexander R., Digestate utilization in the U.S., BioCycle [Online], 53 (1) (2012) 56, http://www.biocycle.net/2012/01/digestate-utilization-in-the-u-s/: Accessed 2018-05-03.

[171] Kaliyan N, Morey RV. 2010. Natural binders and solid bridge type binding mechanisms in briquettes and pellets made from corn stover and switchgrass. *Bioresource Technology* 101: 1082–1090.

[172] Kratzeisen, M. Starcevic, N., Martinov, M., Maurer, C. & Müller, J. 2010. Applicability of biogas digestate as solid fuel. *Fuel* 89(9), 2544–2548.

[173] Sotannde, O.A., Oluyege, A.O., Abah, G.B. 2010. Physical and combustion properties of charcoal briquettes from neem wood residues. *Int. Agrophysics* 24, 189–194.

[174] Onukak, I.E., Mohammed-Dabo, I.A., Ameh, A.O., Okoduwa, S.I., Fasanya, O.O. 2017. Production and Characterization of Biomass Briquettes from Tannery Solid Waste. *Recycling* 2, 17.

[175] Saikia, M., Baruah, D. 2013. Analysis of Physical Properties of Biomass Briquettes Prepared by Wet Briquetting Method. *International Journal of Engineering Research and Development* 6(5), pp. 1

7. List of Annexes

Annex A: Manual low-pressure briquetting press components handbook

Annex B: Manual low-pressure briquetting press construction and use handbook

Annex C: Interactive 3D model of manual low-pressure briquetting press

Annex D: List of authors publications

Annex E: Published article in open access scientific journal *Energies* (Impact Factor: 2.262 (2016); ISSN 1996-1073)