Renewable Energy in Agriculture in Egypt

Technological Fundamentals of Briquetting Cotton Stalks as a Biofuel

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Ehab Abd El Aziz El Seaidy

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Units

Symbol	Unit	Designation
A	fe, ha	Area
a	%	Briquette durability
C_A	LE/fe	Specific costs
C_E	LE/kWh	Specific costs
C_m	LE/t	Specific costs
F	kN	Force
f	MHz, GHz	Frequency
H	MJ/kg	Heating value
l	mm, cm, m	Length
m	g, kg	Mass
$\dot{m}_P$	kg/h	Production
$\dot{m}_T$	t/h	Throughput
P	kW	Power
p	MPa	Pressure
p_R	N/mm^2	Radial compressive strength
T	^0C, K	Temperature
t	min., s, h	Time
U	%	Moisture content
V	cm^3, m^3	Volume
$\dot{V}$	l/min	Flow rate
v	m/s, mm/min	Linear velocity
v_R	rpm	Radial velocity
W	kWh, GJ, PJ	Energy
w_i	%	Initial moisture
w_f	%	Final moisture
$W_{spez,m}$	kWh/t	Specific energy demand
$W_{spez,A}$	kWh/fe	Specific energy demand
X	-	Moisture degree
Y	t/ha	Yield
ρ	kg/cm^3	Density

ρ_G	kg/cm^3	Boundary density
$\rho_{G,e}$	kg/cm^3	End density
ρ_0	kg/m^3	Primary density

Abbreviations	**Meaning**
ASAE	American Society of Agricultural Engineers
ATB	Institut für Agrartechnik, Bornim, e.V.
BMFT	Bundesministerium für Forschung und Technologie
CAPMAS	Central Agency for Public Mobilization and Statistics
CAPS	Cooperative Agriculture Pest Survey Program
DDT	Dichlorodiphenyl -Trychloroethane
DIN	Deutsche Industrie Norme (German Industrial Standards)
DM	Dry Matter
e.V.	Eingetragener Verein (Registered Association)
FAO	Food and Agriculture Organization
Fig.	Figure
FNR	Fachagentur Nachwachsende Rohstoffe e.V.
IDSC	Information and Decision Support Center
KTBL	Kuratorium für Technik und Bauwesen in der Landwirtschaft
LE	Egyptian Pound
MALR	Ministry of Agriculture and Land Reclamation
M.C.	Moisture Content
MS	Microsoft
No.	Number
OECP	Organization for Energy Conservation and Planning
ppm	Part per million
P.T.O.	Power take-off
Rev	Revolution
TA-Luft	Technische Anleitung zur Reinhaltung der Luft (Technical Rules for Air Pollution Control)
UCIMP	University of California, Integrated Pest Management Project
UNEP	United Nations Environment Program
USA	United States of America

Measures

feddan	4201 m^2 = 0.42 ha
1GJ	278 kWh = 23.5 kg oil equivalent

Chemical Symbols

CO_2	Carbon dioxide
NO_x	Nitrogen oxide
SO_2	Sulphur dioxide
S	Sulphur

Exchange rate

1 € = 7.13 Egyptian Pound (Central Bank of Egypt, 22.10.2003)

1 Problem and objective

Energy is considered the basis for the progress and prosperity of nations and societies. It is also the cornerstone of economic and social development. In many developing countries energy from biomass continues to be the main source of energy, mostly in its traditional forms designed to meet the demands of domestic use (Hall and Rosillo, 1998). In industrialized countries, the use of biomass for energy production has been increasingly proposed as a substitute for fossil fuels. The limited availability of fossil fuels and the growing awareness of the detrimental environmental consequences resulting from greenhouse gas emissions have reinforced the importance of biomass as an energy resource in developed and developing countries.

In Egypt, crop residues are considered to be the most important and traditional source of domestic fuel in rural areas. These crop residues are by-products of common crops such as cotton, wheat, maize and rice. The total amount of residues reaches about 16 million tons of dry matter per year. Cotton residues represent about 9% of the total amount of residues. These are materials comprising mainly cotton stalks, which present a disposal problem. The area of cotton crop cultivation accounts for about 5% of the cultivated area in Egypt (MALR, 2002).
The energy equivalence of these energetically usable residues of the main Egyptian crops is approximately 112 PJ/year. These residues can represent about 4.2 % of national primary energy resources. This means that these residues can be used as a source of renewable energy in rural areas, which may suffer from a lack of fossil energy.

Previously farmers used these residues as fuel resources for the traditional mud ovens in which their families cooked and baked. For this purpose, farmers stored these residues on the roofs of their houses or on the fields. This traditional way of handling these residues caused several problems because

- the residues formed a good habitat for insects, mice and snakes that developed in the pile,
- they promoted insect infestation by pests such as the pink bollworm, which reduces the quantity and the quality of cotton fibres,
- such storage increased the risk of destructive fire in the villages.

In accordance with Rule No. 1472 for the year 1994, as of 1999 the Egyptian Ministry of

Agriculture obliged farmers to burn their cotton residues on the fields immediately after the harvest operation. The burning operation kills the insects and disease carriers that can develop in the residues and attack the nearby or following crops (MALR, 1996). This is, however, an environmentally unfriendly practice. It results in huge amounts of harmful gases and clouds of smoke covering the sky over Cairo and the surrounding regions. These emissions lead to environmental pollution and adverse effects for human health. As a result, also in the year 1999, the Ministry of the Environment applied law No. 4 for year 1994 which prevented the farmers from burning these residues on their fields (EEAA, 1994). Nowadays farmers are once again storing these residues or burning them illegally on the fields in the evening.
To solve this problem a new technology needs to be developed to handle these residues easily and safely, in particular to protect crops against the harmful disease carriers.

The objective of this study is to develop the fundamentals of a technology for energetic utilization of cotton stalks to reach the following targets:

- Solving the problem of harmful storing and burning of cotton stalks in Egypt and preventing the smoke clouds caused by this
- Handling of these residues via a phytosanitary method that is safe for both the environment and agriculture
- Producing a cheap, easily storable, and environmentally sound biofuel for rural areas in Egypt
- Contributing to job creation and rural development.

The key process of this technology is briquetting. During this process the harmful insects are hopefully killed and the huge volume of residues can be reduced to a practicable and easily storable form. Furthermore, the burning properties of the raw materials can be improved and the emissions caused during combustion reduced.

The technological, scientific and economic problems to be solved in order to reach these targets are how to process and press the cotton stalks, what temperature is needed to kill the cotton bollworms, and last but not least, what the costs of briquetting are. Since there is no experience of cotton stalk briquetting available and only little knowledge of briquetting similar materials, it was necessary to conduct our own investigations and experiments.

Therefore, within the framework of this research, the following tasks had to be performed:

- Determine the minimum pressure and the optimum moisture content for obtaining stable briquettes.
- Study the influence of the press diameter and particle size on the density and stability of briquettes.
- Determine the minimum temperature that kills the bollworms.
- Study the behaviour of the moisture content of cotton stalks in the field.
- Study the combustion behaviour of briquettes and measure the environment-relevant emission during combustion.
- Evaluate the costs of the briquettes compared with commercially available fuel.

Because of the limited availability of cotton stalks in Germany where the work was to be done, some experiments had to be conducted with comparable materials such as poplar, hemp and rye straw.

2 Review of literature

2.1 Definitions, benefits and problems

2.1.1 Biomass

The recent changes in global environmental conditions and the increase in atmospheric concentration of carbon and sulphur compounds are stimulating studies geared to finding alternatives to the use of fossil fuels. It is understood that fossil fuels have a limited potential and detrimental consequences for the environment. Climate experts are therefore warning against excessive use of fossil energy due to the pollution induced by greenhouse gases. The main damage caused by greenhouse gases has direct effects on agriculture, horticulture, and forestry because of its contribution to global warming and climate change in the form of:

- more extreme weather situations
- rise in temperature (2-3 °C in 50 years)
- rise of sea water level (0.8 m in 50 years)
- growing desertification.

In this context, biomass appears to be an attractive energy resource because it is a domestic and environmentally sound renewable fuel (Bezzon and Cortez, 1999; Strehler, 1998).

The term biomass covers a large number of materials with highly different properties which can be used as fuels. These materials can be classified in a few main categories, each of which can be divided into several types:

- Wood from forestry
- Residues from wood and food industries
- Agricultural residues
- Energy crops (Madsen, 1998).

The fundamental process of biomass accumulation within the context of energy is based on photosynthesis. This is the process by which plants convert solar energy into biomass, as the sun is the source of most renewable forms of energy. The green plant is the only organism able to absorb solar energy with the help of the green pigment, i.e. chlorophyll. It converts this energy into chemical energy of organic compounds with the aid of carbon dioxide and water (Kaltschmitt and Reinhardt, 1997; El Bassam, 1998).

Biomass can be defined as all renewable organic matter including plant materials, whether grown on land or in water, animal products and manure, food processing and forestry by-products, and urban wastes (Kitani and Hall, 1989; The energy educator of Ontario, 1993). Another definition of biomass includes terrestrial plants whose harvest index is principally tons of lignocellulose material per hectare-year. This group is made up of woody and herbaceous plants (Ranny, 1992). Plant components containing lignocelluloses supply thermal energy directly through incineration, or supply gaseous or liquid fuels indirectly after conversion (Sonnenberg and Graef, 1998).

Biomass fuels composed of cellulose and hemi-cellulose are much more highly oxygenated and less aromatic than coals (Hall and Overend, 1987). Biomass materials generally contain a lower percentage of carbon and a higher percentage of oxygen than fossil fuels. The result is a lower heating value per unit mass of biomass compared with fossil fuels. This means that more biomass fuel must be handled and processed to obtain an equivalent unit of usable energy (Unger, 1994).
As presented, biomass can be defined as renewable organic materials that contain energy in a chemical form that can be converted to fuel. It includes the residues from agricultural operations, food processing and energy plants.

The use of biomass as a source of energy is of interest world-wide because of its environmental advantages (Coll et al., 1998). During recent decades, biomass use for energy production has been proposed increasingly as a substitute for fossil fuels. Biomass can also offer an immediate solution for the reduction of the CO_2 content in the atmosphere (Gemtos and Tsiricoglou, 1999). It has two other main advantages: firstly its nearly unlimited availability, and secondly the fact that it can be used without essential damage to the environment (Nendel et al., 1998). In addition to its positive global effect by comparison with other sources of energy, it presents no risk of major accidents, as nuclear and oil energy do (Ghislain, 1994). Biomass is a renewable resource compared with the fossil energy resources. By comparison with the other renewable energy resources such as solar and wind energy, biomass is a storable resource, inexpensive, and with favourable energetic efficiency (BMFT, 1986; Brökeland and Groot, 1995; Scholz, V. and Berg, W. 1998).

Franco et al., (1998) mentioned that the utilisation of biomass for generating heat and power is gaining importance as a feasible alternative to fossil fuels. Its use in energy production could generally be a more advantageous option over fossil fuel. The emission levels of various polluting gases are far lower due to the low amounts of nitrogen (N) and sulphur (S) contained in this fuel. The combustion of biomass such as hay, miscanthus, or hemp generates ashes that can be used as fertilizer. The main nutrients in these ashes are potassium (K) and phosphorus (P) (Hasler et al., 1998). In most developing countries, biomass combustion provides the largest component of total national fuel use. It is burned to provide heat for cooking, crop drying, factory processes etc. (Twidell and Weir, 1986). In rural areas, biomass is likely to be the cooking fuel for many years to come. Many towns and villages throughout the world depend on this fuel. Liquid and gas fuels offer an alternative to biomass fuel in these areas, but at higher cost (El Bassam, 1998).

2.1.2 Solid crop residues

Due to the wide variety of crops cultivated, wide ranges of agricultural residues are produced. These residues may include various plant parts such as stems, branches, leaves, chaff pits etc., depending on the crop and harvest methods. They are divided into field crop residues and arboricultural residues. Field crop residues are derived from crops cultivated such as small grain cereals (wheat, barley, rye, rice and maize), oil crops (sunflowers, rapeseeds, etc.), cotton and tobacco etc. Arboricultural residues are derived from pruning of vines and trees such as apple trees, olive trees etc., as well as from final disposal of old trees. Due to the high energy content, crop residues can present an attractive alternative energy source to fossil fuels. On average 2.5 tons of biomass on a dry basis have an energy potential equivalent to one ton of oil. Therefore biomass can be used for heat and power generation (Panoutsou, 1998). In arid and semi-arid areas, straw for example can be an important basis for animal feed, while under European conditions straw might be important as a fertilizer or for bedding animals (Hall and Overend, 1987).

The term ‘crop residues’ covers the whole range of biomass produced as by-products from growing and processing crops. There are four main categories of agricultural residues:

- woody crop residues such as coconut shells
- cereal residues such as rice, wheat straw and maize stalks
- green crop residues such as groundnut plants and soybean tops
- crop processing residues such as bagasse and rice husks (UNEP, 1991).

Crop residues can be defined as the non-edible plant parts. These residues are left in the field after harvest, are generated by crop packing plants, or discarded during crop processing. The greatest potential biomass resource appears to be formed by the field residues of corn, wheat, soybeans, other grains, sorghum, the processing residues of sugarcane (bagasse) and cotton wastes. Another definition of crop residues stated by Unger (1994) comprises plant materials such as stems and leaves that remain in the field after harvesting of the principal crop products (grain, fibre, nuts, or fruits). These residues usually remain in one place or are distributed over the field. In addition, in many developing countries, crop residues are widely used as fuels for food preparation and heating purposes. These residues are often a substitute for gas, oil and charcoal, which may be too costly or unavailable. In such cases utilization of residues may be of considerable economic value (Kitani et al., 1999).

It can be summarized that crop production generates considerable amounts of residues. These can be divided into field residues and process residues. Field residues are residues that are left in the field after harvesting. Besides being used as an energy source, crop residues are used for several other purposes, such as fodder and manufacturing materials. In some cases they are just burned as waste without any benefit.

2.1.3 Cotton stalks

The cotton plant is a shrubby plant of the genus *Gossypium*, belonging to the *Malvaceae* family. It is considered to be a plant that can be used almost completely. It provides substantial amounts of fibres, oil and several by-products of agricultural and industrial interest (Tharp, 1965; El Khshen, 1978; Bertelsmann Lexikon, 1992).

Cotton stalks are the residues that are left unused for the time being with an average dry matter yield of 4.5 t/ha per year (MALR, 2002). They have the potential for use as biomass for energy production (Gemtos and Tsiricoglou, 1999). The general shape of cotton stalks ranges from columnar through pyramidal to rounded. The shape is determined by the length of the branches. The stems have a moderately thick, tough bark in which bast fibres are prominent. The outer layer of the bark is quite corky. It is of a yellowish-brown colour on the older parts of the stems and greenish to reddish on the younger. The larger side of stems consists of well developed wood structure with prominent wood rays and water carrying vessels (Brown and Ware, 1958; Gad et al., 1987).

The average fibre length of stems is about 1.1 mm. At room temperature cotton stalks contain 10-20% moisture. Their bulk density is about 450 kg/m^3. The material has about 25% lignin, 37.9% cellulose, 20.4% hemi-cellulose, 4% extractives, and 4% ash (Fahmy et al., 2000). The mean diameter of the stalks is about 10.3 mm and the mean height is about 126 cm (Tayel et al., 1988).

El Bassam (1998) stated that the dried cotton stems can be used as a fuel. They consist of a cellulose-rich material, which after pyrolysis and gasification could be a prime material for the industrial and energy sectors. Sumner et al., (1984) also reported that the cotton plant has high-residue yields of cellulose biomass that is well suited for use as a fuel providing thermal energy. They added that the energy value for cotton stalks was 21.3 MJ/kg, so that cotton plant residues were a better fuel than soybean and corn for drying grain in a biomass furnace. This means that cotton residues would be a suitable fuel in the areas where cotton is grown.
Demain (1979) reported that one of the difficulties in cotton production is the need to clear the ground of old cotton stalks after the harvest in order to rid the field of the cotton diseases. Both bacterial and virus diseases can be transmitted from season to season through the stems or debris of stalks which remain in the field.

2.2 Phytosanitary issues concerning the use of cotton stalks

2.2.1 Pink bollworm

The cotton pink bollworm (*Pectinophora gossypiella*), was originally reported in India in 1842. It is one of the most destructive cotton insects wherever it is firmly established. It feeds on cotton, okra, hibiscus, and a few other species of *Malvaceous* plants (Brown and Ware, 1958; Davidson and Peairs, 1966; Abdel Salam, 1993). Its life cycle includes four stages. These are egg, larvae, pupa, and adult.

The first stage is the egg. Female pink bollworm moths lay about 200 to 500 eggs, usually singly or in small groups of 5 to 10. Eggs are small and difficult to see without the use of magnification. Eggs hatch about three to four days after they are laid. Eggs of the first field generation in the spring are often laid on vegetative cotton plants, near to or on the cotton squares. They can also be found under the calyx of bolls or on stems (Frank, 1979).

The second stage in the life cycle is as larvae, which begin to bore into bolls after hatching. In the squares, the larvae complete most of their development before blossoming occurs. In bolls, larvae feed on seeds to complete development before pupation. The pink bollworm larvae are 7 to 10 mm long. Their bodies are ivory with pink bands, and their heads are dark (Figure 2.1). Young larvae are tiny with dark brown heads. When mature they are about 12 mm long and have wide transverse pink bands on their backs. Larvae generally require about 12-15 days to complete their development.

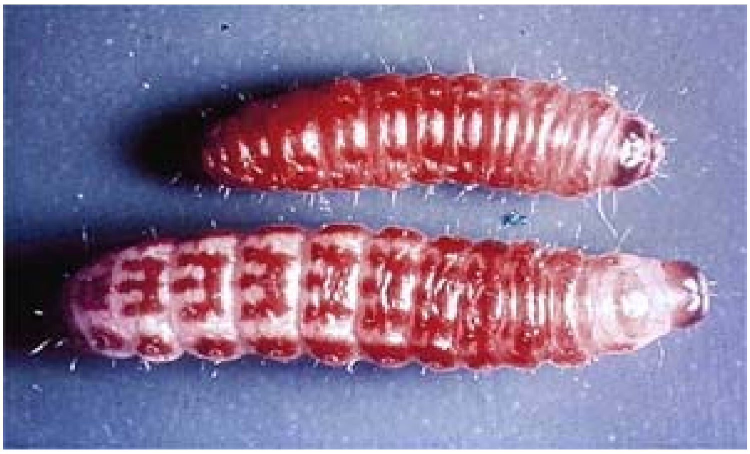


Fig. 2.1: Larvae of the pink bollworm

The pink bollworm overwinters as a fully developed larva, waiting to emerge for pupation. During this period the pink bollworm larva is in a state of arrested development called diapause. This diapause lasts for about 56 to 120 days in the cold winter. There is no feeding or movement during this stage. The larva often spins a loose silken web or cocoon in which it remains until the late winter and spring. In this period the larva may be found in bolls, on the plants which remain unploughed through the winter, or in the soil. Most overwintering occurs in the cotton field, although some may occur wherever cotton debris is deposited.

Pupation is the third stage. This occurs in spring in the top layer of soil beneath cotton plants. Once the diapause is completed, the larva begins to respond to temperature and moisture conditions and ultimately pupates in the spring. The pupa is brown and about 7 mm long. It does not feed or move during the pupal period of seven to eight days.

The last stage is the adult. Adults are small, greyish brown and inconspicuous moths. They emerge from pupae to lay eggs. In summer, the fully developed larvae drop to the soil and pupate for seven to eight days before emerging as second-generation moths. The female moths produce a sex pheromone that assists the male to locate her for mating purposes. Adults move about searching for cotton and are capable of travelling long distances in order to reach susceptible cotton. Most flight occurs at night (especially between midnight and 3 a.m.).

Mating occurs, and a gravid female must lay most of her eggs in about 10 days after emerging. Depending on local conditions, pink bollworm is capable of passing through one to six summer generations. The entire life cycle requires about 32 days from egg to egg (Hammad and Abdel salam, 1985; Abdel salam, 1993; Metcalf, 1993; El Menshawy and Higazy, 2000). The pink bollworm life cycle and its seasonal life cycle are illustrated in Figures 2.2 and 2.3.

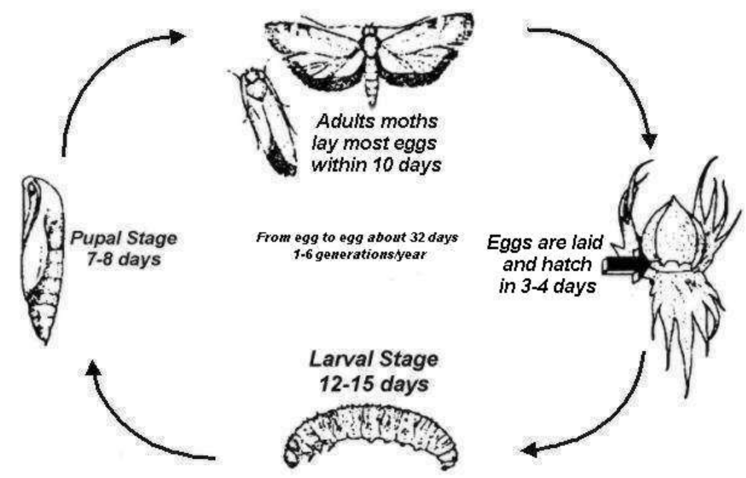


Fig. 2.2: Life cycle of pink bollworm (Ellsworth, et al., 2003)

2.2.2 Damage by the pink bollworm

The pink bollworm is a destructive cotton pest. It prefers cotton, but also feeds on okra and hibiscus. Larvae are the dangerous stage in the pink bollworm's life cycle. They feed inside the growing cotton bolls and destroy them. They begin to bore into bolls immediately after hatching. Larvae feed within one to five seeds to complete development before exiting and dropping to the soil for pupation. They feed from 10 to 14 days. While moving from seed to seed, larvae cause further damage by cutting through the lint with their mouthparts as shown in Figure 2.4. The greatest damage carried out by the pink bollworm is to the lint, seed, yield, and quality. The infested balls are generally immature, have poor lint characteristics, and contribute little or nothing to yield.

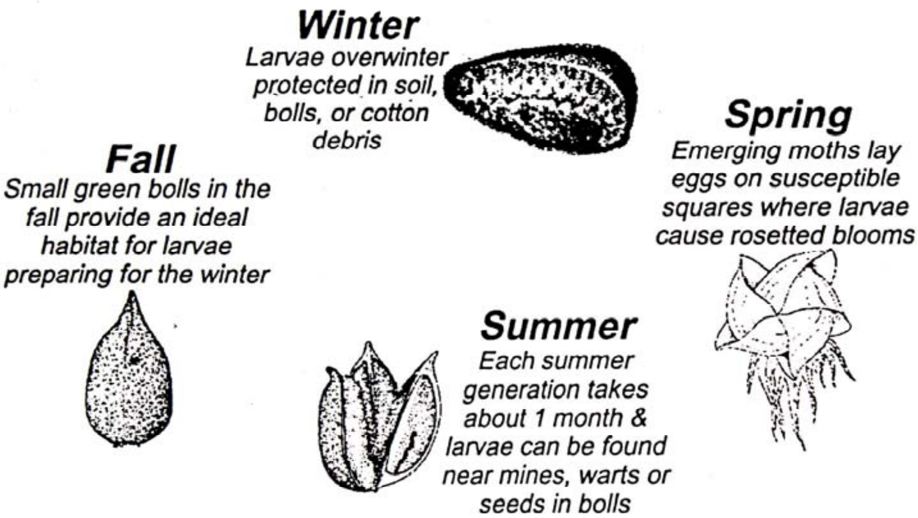


Fig. 2.3: Seasonal Life cycle of pink bollworm (Ellsworth, et al, 2003)

Fig. 2.4: Damage caused by the cotton bollworm (Integrated pest management project, University of California, 2002)

In 1998 the New Mexico Department of Agriculture stated that the burrowing activity stains lint, destroys fibres, and reduces seed weight, vitality, and oil content. In 1966, the loss of yield in San Diego reached about 25-35% (Reynolds and Leigh, 1967). In 1998, the cotton bollworms reduced the total US crop yield of 2.7% (Gianessi and Carpenter, 2003). MALR (1987; 1991) reported that the pink bollworm caused losses in Egypt alone of about 10-20% of cotton crop per year.

2.2.3 Extermination of the cotton bollworm

Chemical insecticides, which were first introduced in the early 1900s, required careful and selective use because of ecological considerations. They appear to be the most effective and efficient means of control (To Africa line, 2002). Applications of DDT were used in more heavily infested areas. The artificial control practice generally consists of observing quarantine regulations. These regulations include seed sterilization, timing of planting and destruction of stalks, and all other field and border debris at a certain date in the fall season (Brown and Ware, 1958). In Texas during the 1960s and 1970s, chemical insecticides including DDT were used in attempts to control the insect. In the 1980s scientists used insect pheromones. Researchers tricked male bollworms into mating with female budworms. Because the genitalia were mismatched, the insects became locked together and died.

To control the pink bollworm now, shredding and ploughing under of the cotton stalks is used to prevent overwintering of the pests (The Handbook of Texas, 2002). The same method was investigated in New Mexico by the New Mexico Department of Agriculture as reported in 1998. The cotton residues were destroyed by shredding, followed by ploughing down to reduce the pink bollworm population seeking to overwinter in the field waste. All plant residues should be buried about 6 inches or more below the soil. Shredding destroys some larvae directly and promotes rapid drying of unharvested bolls. With the help of the high prevailing temperatures, leaving crop debris on the soil surface for two weeks or more after shredding operations destroys more larvae. Eliminating the food supply is another method of control, e.g. cutting off irrigation early enough stop production of green bolls by early September. Winter irrigation can also reduce the population of overwintering worms by as much as 50-70% (UCIMP, 2001).

In Egypt, the extermination of the pink bollworm has always been an important process since the discovery of this destructive insect in the year 1910. Chemical pesticides were used to control the infestation. In the year 1921 Law No. 20 was published. According to this law, cotton ginning must be done before 31 March in Upper Egypt and before 15 April in North Egypt. Cotton seeds must be heated at 55-60 °C for 5 minutes to kill the larvae that may be found in the seeds (Abdel salam, 1993). Rule No. 1472 was published by the Ministry of Agriculture in the year 1994. Because of the environmental problem, this law was applied in 1999. The law obliged farmers to burn cotton residues after the harvest operation (MALR,

1987). The early cultivating of cotton is also one of the important rules. It is applied in order to harvest the cotton in September and October, a time of high infestation.
The microwave oven is one of the great inventions of the 20^{th} century. Microwave ovens are popular because they cook food incredibly quickly. They are also extremely efficient in their use of electricity because a microwave oven heats only the food - nothing else. Microwaves are electromagnetic waves. Their frequency (f) lies between 300 MHz and 300 GHz i.e. between the radio waves and the infrared branch (Rexilius and Wandel, 1987; Von Hörsten, 1995). Radio waves in this frequency range have an interesting property. They are absorbed by water, fats, and sugars. When they are absorbed they are converted directly into atomic motion-heat. Microwaves in this frequency range also have another interesting property. They are not absorbed by most plastics, glass, or ceramics. Metal pans are not used in microwave ovens, where the metal reflects the microwaves. Heat can also be turned off/on instantaneously (Cnovas and Mercado, 1996).

Another application for microwaves within agriculture could be to kill off insects in cereals. Because of the large difference in moisture content between insects (40-80%) and cereals (12-20%), the temperatures lethal for the insects are reached without any impairment of the cereals. This can be realized by optimal choice of the correct application frequency. This process only lasts about 10 seconds. The method is also effective for killing off fungus that can be found in the seeds (Lücke, 1992).

This method can be also used to kill the worms or eggs found still alive or vital after cutting and pressing cotton stalks. The worms are then killed without any damage to the briquettes.

2.3 Technologies of cotton stalk processing

2.3.1 Traditional lines in Egypt

Because of the small size of farms (if owned or rented by the farmer), it is clear that farmer income will hardly cover the family expenditures. Therefore farmers try to use all possible agricultural products and crop residues to minimize expenditures. Consequently it was normal for farmers to use milk products for feeding, manure as a fertilizer and cotton stalks as an energy source of fuel for domestic purposes. The farmer transports these residues to his house. He stores the residues on the roof of his house. His family uses these residues later as energy source for the traditional mud oven. This oven is used for cooking and baking. Figure 2.5 shows a traditional oven in Egypt.

Fig. 2.5: Combustion of cotton stalks in a traditional oven in Egypt

It was found that this method of storage is dangerous for the cotton crop when added to some plants from the *Malvaceous* family. The stalks are an overwintering site for cotton worms such as pink bollworm, which attacks the cotton plants and the nearby crops. These stalks cause ecological and environmental harm, which can damage about 20% of the cotton crop in Egypt (MALR 1987; 1991).

The Egyptian Ministry of Agriculture obliged the farmers to burn these stalks in the fields after the harvest operation in order to kill the pink bollworm, which is a harmful insect for cotton crops, and to prevent further infestation as shown in Figure 2.6.

As a result of this haphazard burning of huge amounts of cotton stalks, clouds of smoke covered the sky above Cairo and surrounding urban areas. This was an environmentally unfriendly practice and caused human health problems. Therefore the Ministry of Environment was against this practice. It published Law No. 4 for the year 1994 which prohibited such burning. This confusion in laws led the farmers to burn stalks illegally on the fields and this still remains a problem in Egypt.

Fig. 2.6: Cotton stalks burning on the fields

2.3.2 Present lines in other countries

In the warmer regions in the USA, cotton plant residues are a great problem as they serve as an overwintering site for insects, and thus must be destroyed. Presently, they are buried (White et al., 1996). In the southern California desert, cotton plants are shred immediately after harvest for pest control. Shredding destroys the pests and insects. Ploughing with a cross disk to a depth of at least 15 cm is also required (Integrated pest management project, University of California, 2002).

Cotton residues are handled by the same method in Greece. The farmers usually chop the stalks after the harvest using a shredder and the residues are then incorporated into the soil by ploughing (Gemtos and Tsiricoglou, 1999). Koroneos et al., (2000) added that in Greece, cotton shanks remain in the fields, shattered and dispersed by the majority of the producers.

Kemp and Matthews (1982) reported that in cotton growing areas of Africa, stalks are either cut at ground level, stalked by hand and burned, or slashed into short lengths (maximum 300 mm), windrowed by a side delivery rake, and burned. When plants are mulched into even shorter lengths the material can be ploughed in.

In the cotton growing region of Sudan, it is a common practice to remove the entire cotton plants from the field or to burn them to control cotton pests and diseases (Sumner et al., 1984). The guidelines for destruction of the cotton residues in Brazil require that the entire plants be incinerated, including the roots (The culture in Brazil, 2002).

The methods of cotton stalk disposal described above are not applied in Egypt yet. They would also be undesirable methods for the Egyptian farmers. Because of the woody structure of cotton stalks, the farmers would have to pay extra costs to rent a tractor with shredding equipment for this process. This must be followed by ploughing. In addition, the farmers would lose a free and essential source of domestic fuel. Therefore, technological fundamentals for recycling these residues are required.

2.4 Briquetting

2.4.1 Principles and technologies

Although there are crops with both higher and lower residue yields, it is reasonable to assume that about 25% of any dry agricultural feedstock consists of residues. These residues are not properly collected or utilized efficiently. The major limitation in utilizing them is their low bulk densities and irregular size, making transportation, handling and storage costs enormous. These limitations can be overcome by compacting and converting the residues into a high density form (FAO, 1990).

Densification is a method of pre-treating loose, bulky biomass materials and bringing them into a form suitable for use in available combustion equipment. The handling characteristics of material for transport, storage etc. are also improved (Hulscher et al., 1992). The density depends mainly on pressure. In the presses, especially in briquetting without binding agents, external compressive forces are applied and transmitted through the aggregate of the particles, compacting them. Increasing this force will increase the density and the binding forces between the particles (Lindley and Vossoughi, 1989; Clauß, 2002).

There are different forms of compressed materials. These forms are cubes, pellets and crumbles. ASAE (1991) defined these forms as follow:

- Cubes: An agglomeration of ungrounded ingredients. The configuration of the agglomeration may take any form
- Pellets: An agglomeration of individual ground ingredients, or mixture of such ingredients, commonly used for animal feed
- Crumbles: Pelletised feed reduced to granulate form

The best known forms of the compressed materials are pellets and briquettes. In general there is no difference in properties between them. The small-length pressed materials are called pellets and the coarse materials are called briquettes. The use of briquetting for the conversion of agricultural residues is comparatively recent. Briquetting makes these wastes easier to transport, to handle and to store. It is efficient to use briquettes as an alternative fuel to coal, and additionally this reduces the volume of polluting gases such as sulphur (S) and phosphorus (P) fumes. Increasing the material density through briquetting will increase the energy density. The briquettes are normally cylindrical in shape with a diameter of about 25-100 mm and a length of about 40-400 mm (FNR, 2000).

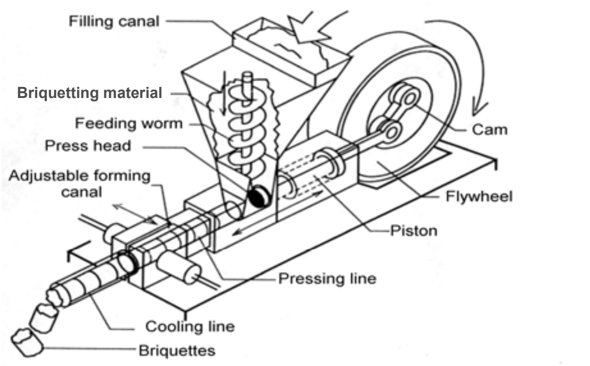
Briquettes can be produced with a density of up to 1.2 g/cm^3 from loose biomass with a bulk density of 0.1 and 0.2 g/cm^3. When using these briquettes for energy purposes, the optimal density is between 0.9 and 1.2 g/cm^3. The briquettes are also affected by the moisture content. Briquettes with a moisture content of less than 18% are constant and durable. The maximum moisture content of wood pellets according to DIN 51731 is 12%. Water in raw materials will prevent the compression of briquettes, and the steam that evaporates will reduce the density. If the briquette then absorbs humidity from the air, the briquette will swell and the density will also decrease. This process can lead to the total disintegration of briquettes (Clauß, 2002).

The compaction of loose combustible material for fuel-making purposes was a technique used by most civilisations in the past. The methods used were no more than simple baling or drying. Industrial methods of briquetting date back to the second part of the 19th century. In 1865, a report was issued on a machine used for making fuel briquettes from peat. Since then there has been widespread use of briquettes made from brown coal, peat, and coal fines.

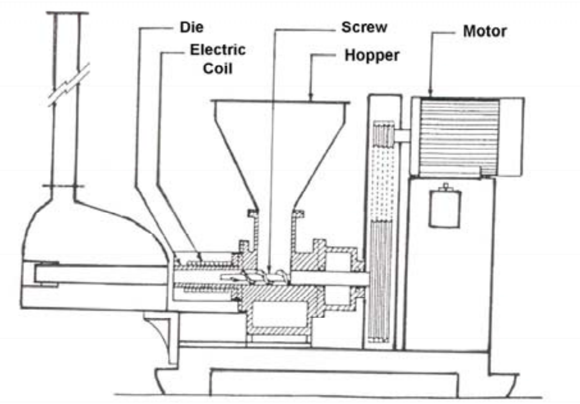
The piston press is one of the main high press technologies used for briquetting. Figure 2.7a shows a piston press. The development of the modern type of mechanical piston press started in Switzerland during World War II, based upon work done in Germany in the 1930s. The piston press acts in a discontinuous mode with material being fed into a cylinder, which is then compressed by a piston into a slightly tapering die. The compressed material is heated by frictional forces as it is pushed through the die. The lignin contained in all woody-cellulose materials begins to flow and acts as a natural glue to bind the compressed material. When the cylinder of material emerges from the die, the lignin solidifies and holds it together, forming cylindrical briquettes which readily break into pieces about 10-30 cm long. The briquettes produced by a piston press are completely solid. The production ($\dot{m}_P$) of these machines is between 25-1800 kg/h, depending on the press canal diameter, the kind of materials pressed, and their properties (FAO, 1990).

The screw press is another type of mechanical press machine. The earliest development work on screw presses was carried out in the USA in the 1930's. In screw presses, material is fed continuously into a screw, which forces the material into a cylindrical die. This die is often heated to raise the temperature to the point where lignin flow occurs. If the die is not heated, then the temperature may not rise sufficiently to cause lignin flow and binding materials may have to be added. These can be molasses, starch, or some cheap organic materials. The briquettes from screw machines are often of higher quality than from piston units. The screw press is usually sized in the range 75-250 kg/h, though larger machines are available. Figure 2.7 b shows the screw press.

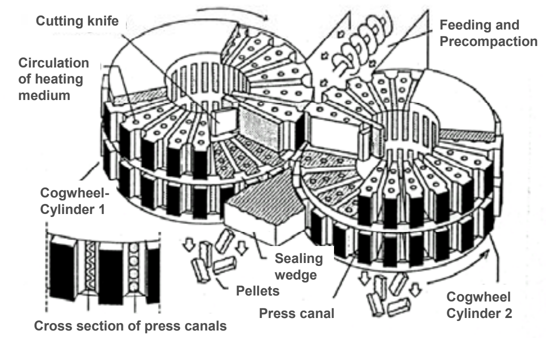
The most standard pellets machines are roller presses with a circular die and cog-wheel pellet principle. The operating principles of a roller press with a circular die and a cog-wheel pellet principle are shown in Figure 2.7 c-d. Such machines were originally developed for the production of animal feedstuffs. These operate by extruding small pellets of diameter 10-30 mm through a die that has many holes. The extruding mechanism is often an eccentric roller that moves inside the large cylindrical or conical die. Its throughput ($\dot{m}_T$) performance depends on various parameters. The most important of these is the fineness of the pressed materials. The size of the die and its holes also plays a major role. With the cog-wheel pellet principle, the pressed materials are pre-compressed, and then pressed and formed in the press canals in the roller coat. The press canals have different cross sections, for instance cylindrical, plate-type or wavy (FNR, 2000; Clauß, 2002). The technical properties of briquetting and pellet machines are presented in Table 2.1



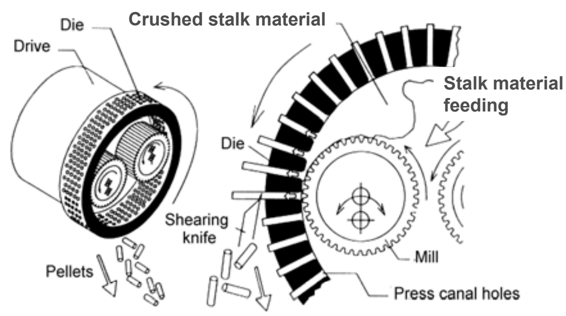
a. Piston press



b. Screw press



c. Roller press with circular die



d. Cog – wheel pellet principle

Fig. 2.7: Operating principles of typical briquette and pellet machines (FAO, 1990; FNR, 2000).

Table 2.1: The technical features of briquetting and pellet machines

Machine type	Common throughput range (t/h)	Specific energy demand (kWh/t)	Bulk density (kg/m^3)
Piston press	0.1-1.8	50-70	300-600
Roller press with circular die	3-8	20-60	400-700
Cog-wheel pellet principle	3-7	20-60	400-600
High pressure piston press	0.04-0.2	508-646	650-750

Nendel et al. (1998) developed a high-pressure compression process for compressing the uncut stalks (especially straw). The principle of the stamp press process presented in Figure 2.8 was used in this work. This process produces a cylindrical form with durable and compact briquettes. The main force of compression works axially. The stalks are pre-compressed by a two-stage band press. Clauß (2002) stated that after the dosage step, the stalks were pressed in a press cylinder under pressure up to 200 MPa without any additional binding materials. Through this process the stalks were compressed to a ratio of about 80:1. The density of the processed briquette was about 0.9 kg/m^3, depending on the processed material. Its technical properties are also illustrated in Table 2.1

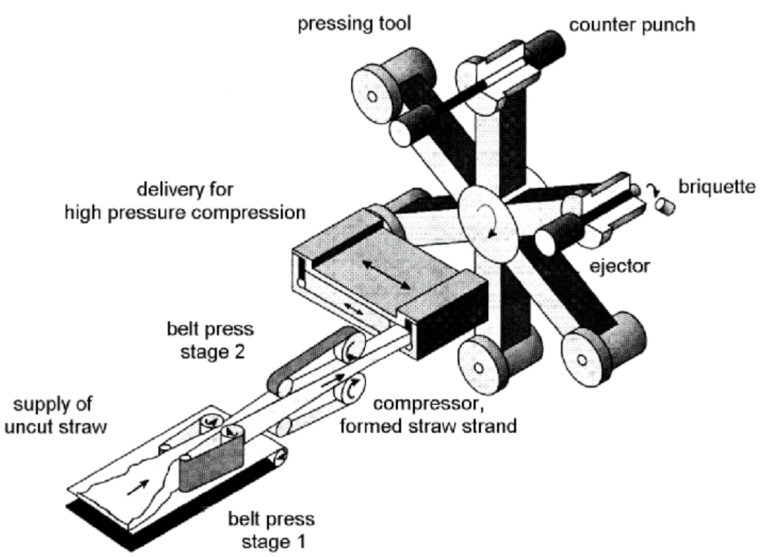


Fig. 2.8: The principle of the high pressure piston press (Clauß, 2002)

2.4.2 Calculation models

Clauß (2002) developed an equation to define the compression factors. It was also stated that when a material is pressed under axial pressing force, a compact briquette will be produced. The primary density of the material (ρ_0) is.

$$\rho_0 = \frac{M}{V} \qquad (2.1)$$

where

M = mass of the material, g

V = volume of the material, cm^3

This primary density depends on:

- the way the material is filled into the press form (loose or pressed by a device),
- the structure of the material (the relation between leaves and stem, the content of roots, the resistance to crack etc.),
- the moisture content and the age of the material.

Clauß (2002) also mentioned that the primary density (ρ_0) is not constant, even when the same mass is weighed and pressed. That is because of the difference in material structure. These factors always affect the material volume, so that after a certain pressure the material reaches the maximum density (ρ_{max}). This is equal to the boundary density (ρ_G) which depends on the density and the moisture of the material. The density cannot be increased by increasing the pressure, but its value can be changed depending on the press machine properties.

After removal of the pressure, the processed briquette tends to elongate and increase its volume until the durability value of the briquette is achieved. This density is the end density and stated as ($\rho_{G,e}$). It depends on the press pressure and the pressed material.
The final form of the equation was presented as.

$$\rho = \rho_G\,(1-e^{-k.\,p}) \qquad (2.2)$$

$$\rho = \rho_{G,e}\,(1-e^{-k.\,p}) \quad \text{after deformation} \qquad (2.3)$$

where

ρ = Density, g/cm^3

ρ_G = Boundary density, g/cm^3

$\rho_{G,e}$ = End density, g/cm^3

k = Constant

This equation is valid for long straw with a moisture content of 8-12% up to a maximum of 16% under a press pressure of up to 250 MPa.

From the models developed it was found that the equations of Busse (1966) are also relevant for use in this study as follows:

$$p_k = e^{[(c_0 + c_1 \frac{U}{100}) + (c_2 + c_3 \frac{U}{100}) p]} \quad (2.4)$$

where

p_k = Pressure, MPa

ρ = Density, g/cm^3

U = Moisture content, %

Busse (1966) considered the press pressure theoretically in the range from 20 to 200 MPa. He examined the press pressure experimentally from the medium to the high pressure range up to 80 MPa. In this range the densification process can also be successful. In his investigation, grass with a moisture content of 22% - 55% in the form of round and square cross sections or long stalks was pressed. In a following study, it was considered theoretically that his equation can be applied for a moisture content of grasses of up to 15%. The coefficients used for grass with a moisture content of 15% are listed in Table 2.2.

Table 2.2: The coefficients used by Busse for grass at a moisture content of 15% (1966)

Coefficient	C_0	C_1	C_2	C_3
1st range	0.98	-5.75	4.05	3.5
2nd range	1.15	-4.6	4.4	1.3

3 Potential of energetically usable farm residues in Egypt

3.1 Quantity of energetically usable farm residues

Historically, Egypt's favourable conditions in the Nile valley and in the Nile delta have given the country a comparative advantage in a number of major food and fibre crops, particularly wheat, rice, maize, and cotton. After the harvest operation is finished, these crops produce huge amounts of residues (leaves, stalks, straw etc.). The total amount of these residues reaches about 16 million tons of dry matter per year. The average yields of the main crops and their residues in Egypt are presented in Figure 3.1. For example, the average yield of cotton stalks is about 4.5 t/ha per year. Cotton stalks represent about 9% of the farm residues in Egypt. About 90% of these residues can be used as energy resources (MALR, 2002).

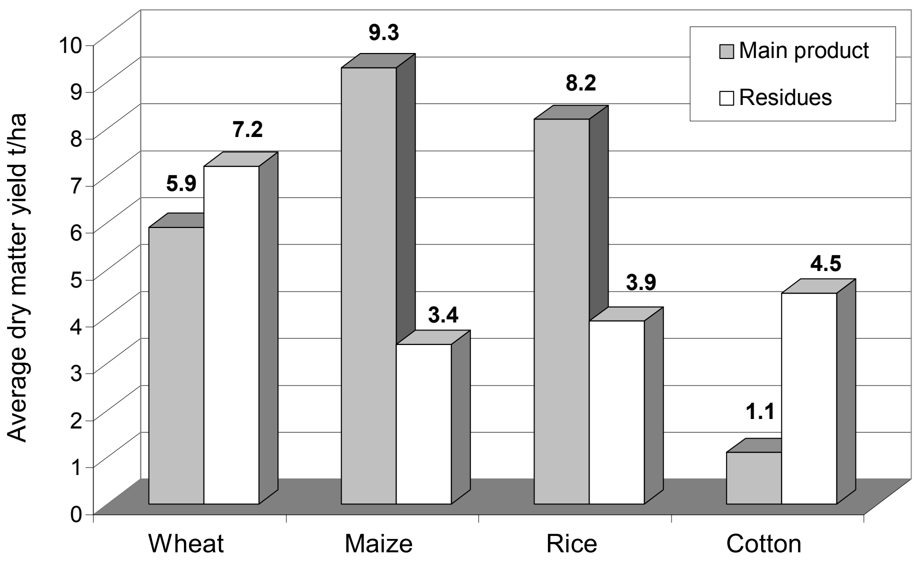


Fig. 3.1: The average yield of the main crops and their residues in Egypt (MALR, 2002)

Previously, farmers stored these residues for domestic purposes. Following the environmental problem of burning cotton stalks, only a small amount is now used illegally by farmers' families for domestic purposes. Figure 3.2 shows the energetically usable and used main crop residues in Egypt. Long straw varieties of wheat are preferred because the straw is of high value (Carig, 1993). Straw is used as animal feed in the summer and for brick-making in the villages of some regions. Therefore it is not used for bioenergy purposes. Rice straw is used mainly for animal feed and bedding. A small amount is used in the paper industry. The annual amount of rice straw is about 3.6 million tons/year. Rice straw was burned on the field at the same time as cotton stalks too. It was also an important factor for the pollution problem. Therefore burning of rice straw on the field was also prevented by Law No. 4 for the year 1994 (EEAA, 1994). This law was applied in 1999, preventing the farmers from burning any crop residues on the fields. On the other hand, the energy equivalent of the energetically usable residues in Egypt reaches about 112 PJ/year (MALR, 2002). These residues can be used as environmentally friendly biofuel if they are well formed and handled.

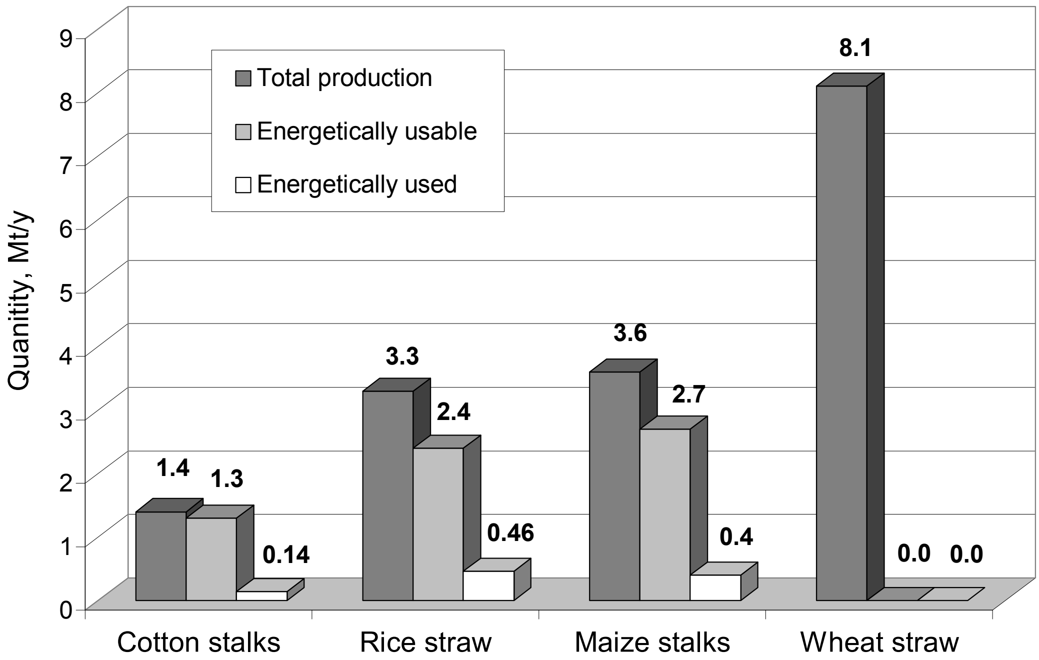


Fig. 3.2: The energetically usable and used main crop residues in Egypt (MALR, 2002)

3.2 Quality of energetically usable farm residues

The use of farm residues for energy purposes requires a study of their physical and chemical properties. This involves analysing these residues and characterizing their differences in use as a fuel. The heating value (H) is one of the most important properties. The heating value describes the energy released upon combustion of a unit mass of fuel. It is an important thermal property for modelling conversion systems. The heating value is reported as higher (gross) heating value or lower (net) heating value. The values are related to the fuel elemental analysis and moisture content. As shown in Table 3.1, farm residues have a high heating value, particularly cotton stalks which have a higher value by comparison with the other residues. The elemental analysis supports this material as good quality for energetic purposes.

Table 3.1: Heating value and compostion of solid biofuels

Type of Fuel	Heating value, MJ/kg (Dry basis)		Elemental Analysis (% by weight, dry matter)								Reference
	Higher	Lower	Volatile	Ash	C	H	O	N	S	K	
Fossil Fuel											
Hard Coal	31.80	-	38.80	6.30	79.40	5.10	6.70	1.50	1.00	0.09	FNR Guide
Biomass Fuel											
Wheat Straw	17.20	-	77.0	5.7 (4.2-8.4)	40.90	5.80	40.90	0.48	0.08	1.00	FNR Guide
Wheat Straw	17.51	16.47	71.3	8.90	43.20	5.00	39.40	0.61	0.11	0.28	Ebling and Jenkis
Barley Straw	17.31	16.22	68.8	10.30	39.92	5.27	43.81	1.25	-	-	Ebling and Jenkis
Rye Straw	17.50	-	76.4	4.8 (3.0-7.2)	46.6	6.00	39.80	0.55	0.08	0.39	FNR Guide
Rice Straw (fresh)	16.28	15.32	69.3	13.42	41.78	4.63	36.57	0.70	0.08	0.34	Ebling and Jenkis
Rice Straw (weathered)	14.56	13.47	62.3	24.36	34.60	3.93	35.38	0.93	0.16	-	Ebling and Jenkis
Maize Straw	17.70	-	79.8	6.7 (5.3-8.3)	45.70	5.3	41.70	0.65	0.12	-	FNR Guide
Cotton Stalks	18.26	17.15	73.3	5.51	47.05	5.35	40.77	0.65	0.21	0.08	Ebling and Jenkis
Poplar	19.38	18.17	82.3	1.33	48.45	5.85	43.69	0.47	0.01	0.10	Ebling and Jenkis
Poplar (with bark)	18.50	-	81.2	1.9 (1.6-2.2)	47.50	6.20	43.10	0.42	0.03	0.26	FNR Guide
Hemp Straw	17.00	-	81.4	4.8 (2.0-9.0)	46.10	5.90	39.20	0.74	0.10	1.50	FNR Guide
Sugarcane Bagasse	17.33	16.22	73.8	11.27	44.80	5.35	39.55	0.38	0.01	0.12	Ebling and Jenkis

4 Energy consumption in Egypt

4.1 National energy consumption

The energy sector plays a major role in Egypt's economic development. Egypt has various forms of conventional energy resources such as petroleum, hydropower, and coal. Petroleum includes crude oil and natural gas. The primary energy resources and production in Egypt are shown in Figure 4.1. It is clear that crude oil represents about 53% of the country's primary energy resources. Since the construction of the High Dam in Aswan, hydropower in the form of electricity has been considered an important source of energy. It accounts for a share of about 5% in these primary resources. Natural gas accounts for about 42% of these resources (NREA, 2002).

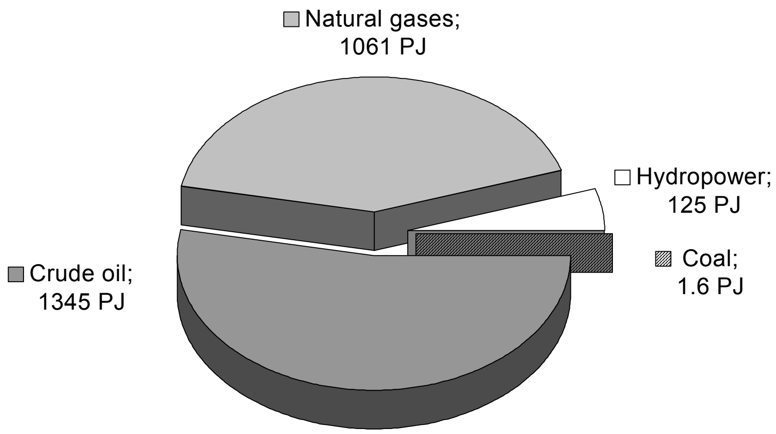


Fig. 4.1: Primary energy resources and production in Egypt (OECP, 2002)

Due to the vital role played by the energy sector, energy demand has increased tremendously to satisfy the technological needs and the development of life styles in Egypt. The demand for energy is increasing directly in line with the increase in population. From the data presented in Figure 4.2 it can be observed that crude oil represents the major part of energy consumption in Egypt with 50.6%. On the other hand, primary production of coal accounts for only 11% of the national consumption of this resource.

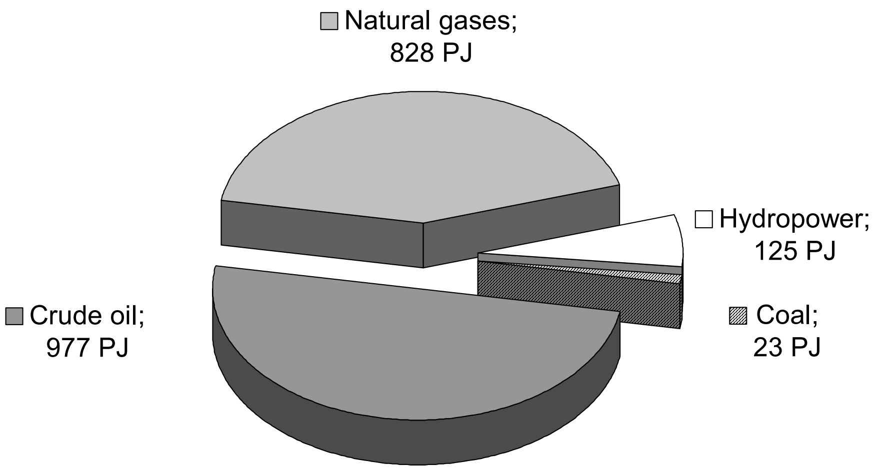


Fig. 4.2: The consumption of primary energy in Egypt (OECP, 2002)

If the energetically usable crop residues are well formed as a biofuel for domestic purposes in Egypt's rural areas, they can contribute about 5.4 % to primary energy consumption in Egypt. The sectoral energy consumption in Egypt is summarized in Figure 4.3. Because of industrial development, the industrial sector accounts for about 46% of energy consumption in Egypt (OECP, 2002).

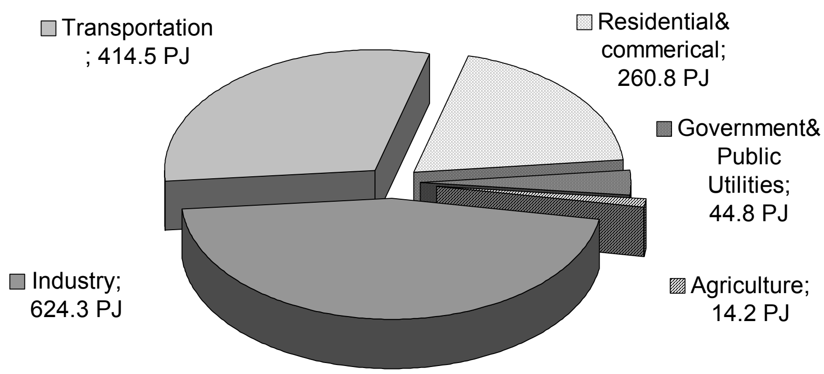


Fig. 4.3: Sectoral consumption of primary energy in Egypt (OECP, 2002)

It is clear that protection and preservation of the environment is one of the most important issues for all scientists. The concern is naturally to minimise the adverse impacts of energy production and use on the environment. The fuels which increase the concentrations of carbon dioxide (CO_2) emissions are petroleum products, natural gas, and coal. Production, transportation, and processing the fuels all contribute to CO_2 emissions.

As a result of the national population growth fuelling a rise in energy consumption, the CO_2 emission has increased to reach about 94 million tons in 1999. This value is about 25% up on the CO_2 emissions in 1990. The CO_2 emission curve is shown in Figure 4.4.

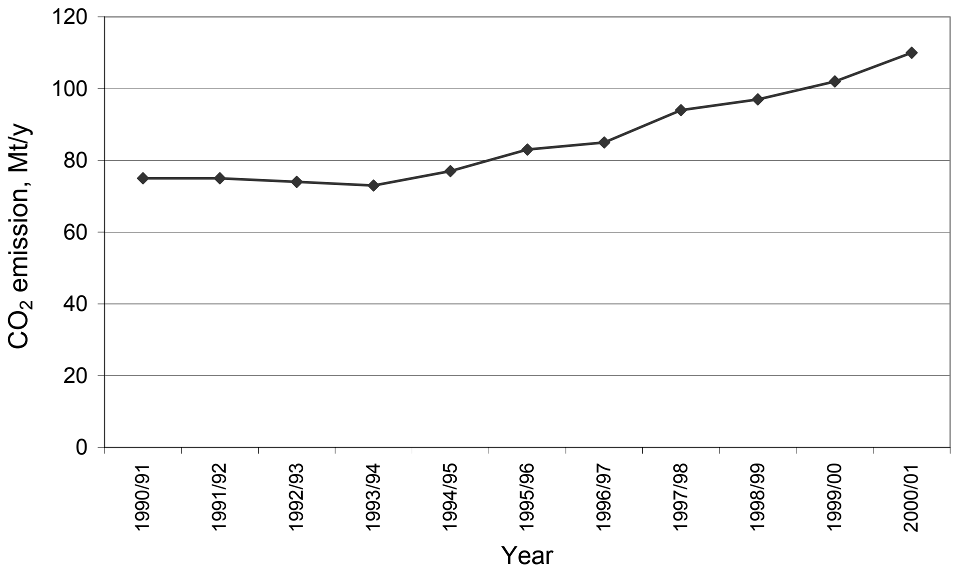


Fig. 4.4: Development of CO_2 emissions in Egypt (OECP, 1998)

4.2 Energy consumption in rural areas

Located in North Africa, Egypt has an area of about one million square kilometres. The country also has a large and rapidly increasing population. According to the last census in 1996, the population was 59 million inhabitants (CAPMAS, 1997). In the year 1999 the Egyptian population was estimated at 63 million inhabitants (MALR, 2000). The inhabited area along the River Nile in the delta and along the northern coast represents only about 5% of the total area of the country. This percentage results in an average population density of 1217 persons per square kilometre with an average annual growth rate of 2.1%. This makes Egypt number four in the list of the countries with the highest rural population density in the world, following Puerto Rico, Oman and Sri Lanka (The World Bank, 2002). As a direct effect of this growth in population, energy consumption has increased too.

The rural population consumes energy from commercial and non-commercial sources. The Egyptian rural areas depend upon biomass resources to meet 50% of their energy needs. Biomass resources are currently used inefficiently due to the poor technology applied, such as direct combustion in open fire stoves in villages. Kerosene and electricity, liquid petroleum and gases are also available to a large extent.
Energy consumption patterns in rural areas are affected by several factors, the most important being:

- Education level
- Per capita income
- Cultural behaviour
- Availability of different energy sources
- Energy pricing and subsidies on different types of fuels (World Energy Council, 2003).

Rural electrification has been a major government initiative in the last 30 years. The rural Electrification Authority was established in 1971 with a mandate to electrify all areas across Egypt except Cairo and Alexandria. In 1994 all schools and clinics had access to electricity, as did 95% of all households. The Egyptian government planned to use access to electricity for land reclamation. A grid supplying electricity to about $5.6x10^5$ ha of arable land is planned to increase agricultural productivity. This provides new job opportunities, maximises the output of agro- industrial projects, and stems migration to large cities.

The annual electricity consumption in El Menoufiya governorate, which is considered as one of the most famous agricultural governorates in Egypt, is 303 kWh/capita. The average household size in the El Menoufiya governorate is about 4.8 persons. Thus the average annual consumption of electricity is about 1455 kWh per household. It costs about 120 LE per year. This electricity is mainly consumed for lighting and water heating, especially in winter, because of the shortage of gas cylinders distribution in the villages (CAPMAS, 1997; IDSC, 1999).

According to the census of 1996 Egypt's rural population reached about 33.8 million. On the other hand, annual crop residue production is about 16 million tons (MALR, 2002). This means that rural families can obtain about 2.27 tons of residues per year. This amount has an average heating value of 38 GJ per year, which is 27 % higher than its annual energy level for domestic purposes (cooking and baking). This access of energy can be used to sustain small industries such as crop drying or heating in the poultry sector.

5 Materials and methods

5.1 Experimental programme

This research was carried out in the energy laboratory of the Department of Post-Harvest Technology in the Institute of Agricultural Engineering Bornim e.V. (ATB), Germany.

An experimental programme was designed for the briquetting experiments. This programme includes the experimental materials which were used in the process. The experimental programme also includes the relevant parameters studied that affected the processed materials. Table 5.1 shows the outline of the programme for a press stamp ∅42.5 mm. As shown in the table, this was a full programme for the poplar experiments. The programme was reduced for the other plants to cover only experiments with the combined parameters that produced the best results. The same programme was also used for a press ∅30 mm after some modifications of the pressure values as listed in Table 5.2.

As an applied process, the experimental materials were briquetted in a commercial hydraulic press machine (SP 45/12). The properties of the briquettes produced were studied and compared with those produced by the laboratory press machine. The moisture content of the cotton stalks on the field before and after harvesting was measured in Egypt. The ambient air temperature and the humidity were also measured. The effect of temperature on the pink bollworm was studied to determine the temperature that kills off the worms as a function of time.

The temperature behaviour of the briquette was studied by measuring the internal temperature of the briquette as a function of time. The dry matter losses of the experimental materials were also measured to determine the maximum temperature needed to heat the briquette and kill off the cotton worms without any losses.

Combustion experiments were carried out to study the features of the experimental materials within this process. The materials were processed as loose materials and as briquettes. A measuring record was also drawn up for all the materials examined. This record includes all the necessary data (see Appendix).

Table 5.1: Experimental program

Press: Lab press with ∅ 42.5 mm, length 400 mm, max. force 10000 kp

Measuring parameters: moisture, bulk density, briquette length, briquette density, radial pressure stability

Moisture (%)		0					5					10					15					20				
Force (Kp)		2000	4000	6000	8000	10000	2000	4000	6000	8000	10000	2000	4000	6000	8000	10000	2000	4000	6000	8000	10000	2000	4000	6000	8000	10000
Pressure (Mpa)		14	28	42	56	70	14	28	42	56	70	14	28	42	56	70	14	28	42	56	70	14	28	42	56	70
Poplar	Fine	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Middle	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Coarse	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Straw	Fine					x					x					x					x					x
	Middle			x	x	x			x	x	x			x	x	x			x	x	x			x	x	x
	Coarse					x					x					x					x					x
Hemp	Fine			x		x			x		x	x	x	x	x	x			x		x			x		x
	Middle	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Coarse			x		x			x		x	x	x	x	x	x			x		x			x		x
Cotton	Fine					x					x					x					x					x
	Middle					x					x					x					x					x
	Coarse					x					x					x					x					x

Remarks:
× completed experiment

Table 5.2: Experimental briquetting programme - ∅ 30 mm
Press: Lab press with ∅ 30 mm, length 400 mm, max. force 10000 kp
Measuring parameters: moisture, bulk density, briquette length, briquette density, radial pressure stability

Moisture (%)		10						15					
Force (Mp)		1.0	3.0	4.9	6.9	8.9	10.0	1.0	3.0	4.9	6.9	8.9	10.0
Pressure (MPa)		14	42	70	98	126	140	14	42	70	98	126	140
Poplar	Very fine chips							x	x	x	x	x	x
	Fine chips							x	x	x	x	x	x
	Middle chips	x	x	x	x	x	x	x	x	x	x	x	x
	Coarse chips							x	x	x	x	x	x
Straw	Fine chips												
	Middle chips	x	x	x	x	x	x						
	Coarse chips												
Hemp	Fine chips	x	x	x	x	x	x						
	Middle chips	x	x	x	x	x	x	x	x	x	x	x	x
	Coarse chips	x	x	x	x	x	x						
Cotton	Fine chips												
	Middle chips	x	x	x	x	x	x						
	Coarse chips												

Remark:
× completed experiment

5.2 Materials

As presented in chapter 2.1.1, biomass is defined as all renewable organic material including plant materials. These materials principally contain lignocelluloses. Plant components containing lignocelluloses supply thermal energy directly through incineration, or supply gaseous or liquid fuels indirectly after conversion (Kitani and Hall, 1989; Ranny, 1992; Sonnenberg and Graef, 1998). There are hardly any differences in the heating values of the biomass sources. They lie between 14 and 18 MJ/kg (Brökeland and Groot, 1995; Mann, 1998). A comparison of these parameters is presented in Table 5.3. This comparison shows that the values of cotton stalks are within the range of the values of the other materials used. Therefore poplar, hemp and rye straw were used as substitute materials for cotton stalks in the experimental work. All of these materials are considered as biomass. They are energy plants (poplar), residues of crop processing (hemp), or crop residues (straw). Figures 5.1 and 5.2 show these materials

Table 5.3: Heating values and compositions of the experimental materials

	Cotton Stalks	Poplar	Hemp	Straw
Heating value MJ/kg	17.15-18.26	18.17-19.38	17.00-18.90	15.32-17.50
Lignin %	25.3	21.6	8-10	35-40
Cellulose %	37.9	48.4	57-60	30-36
Hemi-cellulose %	20.4	18.2	16.4	18-19
Volatile %	73.92	81.2	81.4	76.4
Ash %	5.51	1.9	4.8	4.8

Sources: Kitani, and Hall (1989); Lohmann (1998); Fahmy et al., (2000); FNR (2000) ; Clauß (2002)

In addition to these properties, cotton stalks, poplar and hemp are woody stem materials which consist mainly of the bark, the wood and the mark. The bark is the part in which the bast fibres are prominent. The outer layer of the bark is more or less corky. The wood consists of wood rays and water carrying vessels. The mark is the lowest part of the stem and consists of foamy cells. Figure 5.3 show a cross section of hemp by way of example (Brown and Ware, 1958; Mehlich, J. 1998; Drieling, 1999).

On the other hand, the outer layer of the straw consists of the epidermis cells where the wax is found. The wax protects the stem from soluble penetration (Clauß, 2002).

Fig. 5.1: The experimental materials (raw)

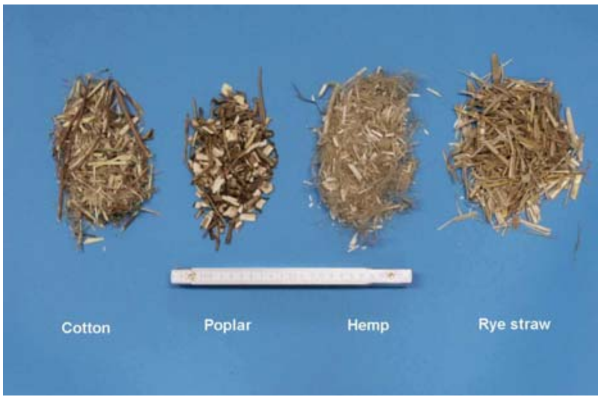


Fig. 5.2: The experimental materials (chopped)

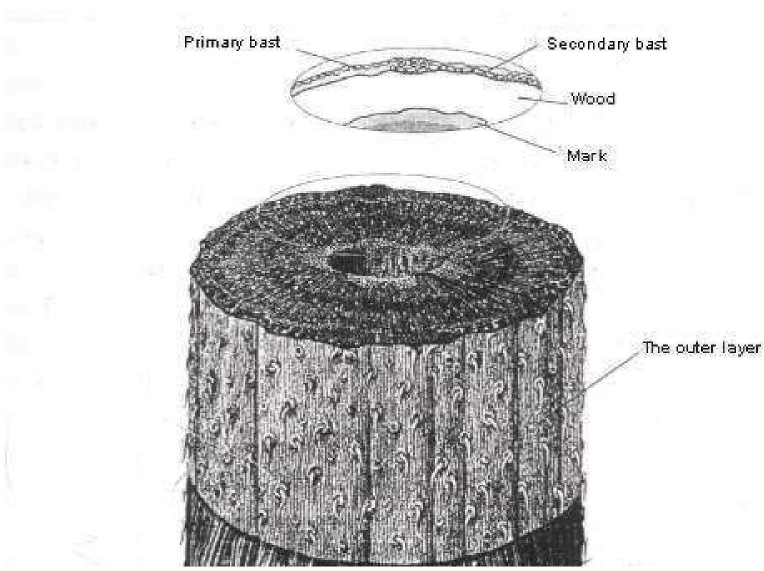


Fig. 5.3: A cross section of hemp stalks (Mehlich, J. 1998; Drieling, 1999).

5.2.1 Poplar

The first experimental series were carried out with poplar plant. Poplar belongs to the family of *Saliaceae*, species *Popoulus*. It is a tree with a capacity for rapid growth. Poplar trees grow to a height of between 30 and 50 m. They are presently used as a short rotation crop and cultivated on biomass plantations to be used for combustion purposes, as briquettes or through gasification in the form of branches, chips or briquettes. Ebeling and Jenkins (1985) studied the heating value of poplar. They reported that the maximum value was 19.38 MJ/kg and the minimum 18.26 MJ/kg. The energetic yield of poplar is very high, between 155 and 167 GJ/ha (Scholz, et al., 1998).

Poplar trees were cultivated in the ATB plantation. Branches between 500 to 1500 mm long with a diameter of up to 20 mm were used in this experiment. These branches were collected from 2 and 4-year-old poplar trees. The branches were chopped in a laboratory wood chopper and divided into 4 categories - coarse, medium, fine and very fine particle lengths. 100 g from each category were weighed and sieved in a sieving apparatus. The sieves had diameters of 1, 2, 3, 4 and 5 mm. The particles under each sieve were collected and weighed. The particles which were coarser than 5 mm were separated by hand. These were divided using a scale into groups of 5-10, 10-15 mm and so on up to 45-50 mm. The other particles that were coarser than 50 mm were separated every 10 mm. All the groups were weighed using a digital balance. The cumulative frequency distribution diagram of poplar is shown in Figure 5.4. The mean chip lengths were 10.1, 6.8, 3.3, and 1.7 mm for coarse, medium, fine and very fine chips respectively.

The median value describes the particle size value of 50% of the particle size amount. This means that 50% of the particle sizes are smaller and 50% are larger than this value. Due to this definition and the ease of reading from the cumulative curve, the median value is frequently used in practice (Zoworka, 2002).

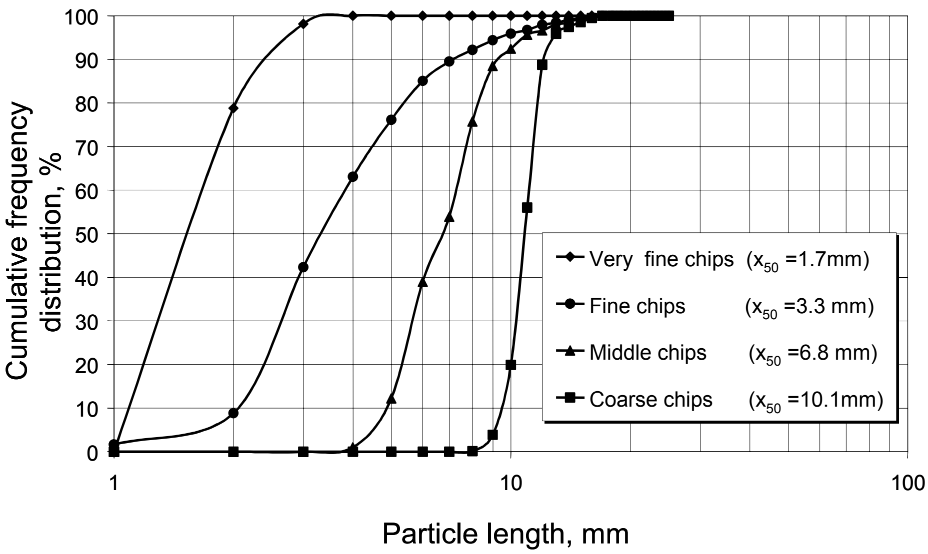


Fig. 5.4: Cumulative frequency distribution of poplar chips

5.2.2 Hemp

Hemp (*Cannabis sative*) is a plant with high and slim stalks. Its length (l) ranges from 115 to 200 cm. The stem can also reach 4 metres and more in height. The top of the plant is covered with leaves. Hemp is produced mainly for its fibres. The stalks consist of 3 essential parts:

1. the bark, where the hemp fibres are found. This is a form of elastic protection for the stem.
2. the wood, which is a material to fill the stem.
3. the mark, which is the lowest part of the stem and consists of foamy cells.

Hemp is an excellent source of high-quality biomass. The cellulose content of the stem is about 57-60%, while the lignin content is about 8-10%. Hemp can also be used as a solid fuel (Drieling, 1999; Gusovius, 2002; Hesch et al., 1996; Mehlich, 1998; Waskow, 1995).

Hemp shives which were used in the experiments are the residues of the hemp fibre resolution machine, which was constructed at ATB. The residues of different stages of fibre cleaning operations were collected. Each stage represents a different category of particle length. The average lengths of the shives used in the experiment were about 4.7, 5.2, and 6.5 mm for the fine, medium, and coarse hemp respectively. There were also some hemp fibres mixed with the hemp shives in an average ratio of 10%. Figure 5.5 shows the cumulative frequency distribution of hemp shives.

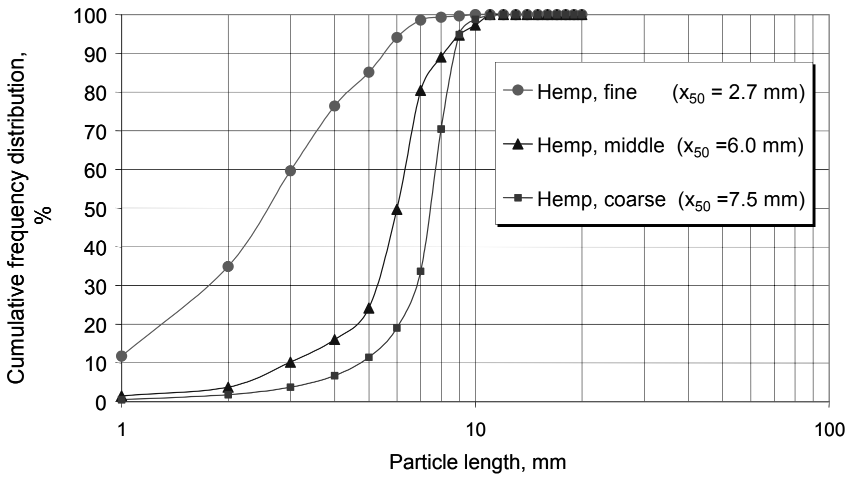


Fig. 5.5: Cumulative frequency distribution of hemp shives

5.2.3 Straw

The straw used in this work was rye straw. Rye (*Secale cereale* L.) is an important feed and bread grain, especially in parts of northern Europe where poor soils and severe winters limit wheat production. In the United States rye is used mainly for grain and as a cover crop to protect soil from erosion (Lyon and Klein, 2003). It can be used for energy purposes. The region of Brandenburg where the ATB is situated is well known for its rye crops. Rye was cultivated in the ATB plantation. It is a versatile crop and harvested for whole crop grain, grain, and silage. It is also used for pasture, or as a cover, green manure, or companion crop. It is a productive crop in many areas where the soil and climate are unfavourable for higher income crops. It has a shorter germination period so that it may be planted later than other grain crops (Briggle, 1959).

Rye straw was chopped in a hammer mill with sieve diameters of 5, 10, and 20 mm. The straw particles were divided into three groups (fine, medium and coarse) depending on the sieve diameter of the hammer mill. The particles in each group were also separated with a sieve apparatus to define the mean length (x_{50}). A cumulative frequency distribution diagram versus the average particle length of the processed materials is shown in Figure 5.6.

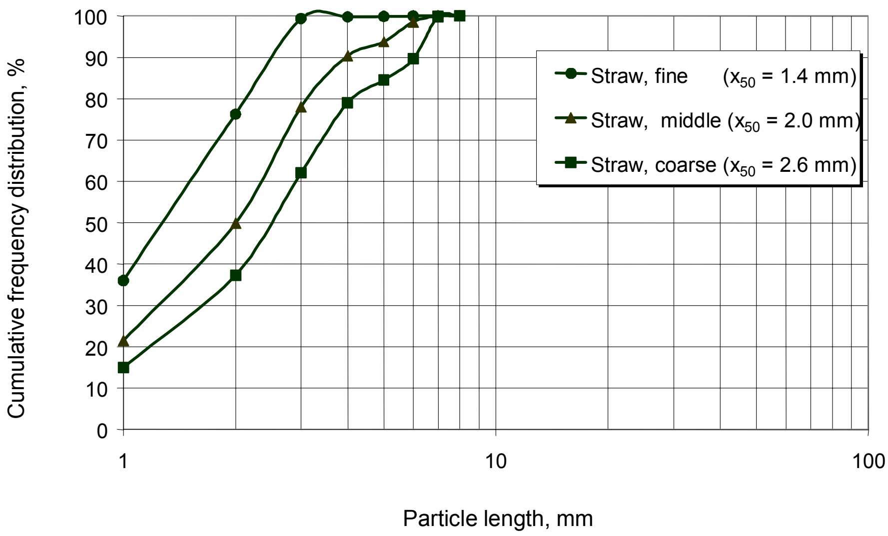


Fig. 5.6: Cumulative frequency distribution of rye straw

5.2.4 Cotton stalks

As the experimental work was performed in Germany, the cotton stalks used in this work were imported from Egypt. The cotton plant was cultivated in the El Menoufiya region in the Nile delta. This region is well known in Egypt for its cotton cultivation. The stalks had an average diameter of 2 mm and a length of 1300 mm. They were chopped in a hammer mill with sieve diameters of 5, 10, and 20 mm. The cumulative frequency distribution diagram of cotton stalks versus the average particle lengths of the processed materials is shown in Figure 5.7.

The stalks also contained some infested bolls which were either immature or had low quality cotton fibres. While chopping the cotton stalks, it was found that some short fibres were mixed with the woody particles. These fibres were not cotton fibres. They were light brown in colour and rough to touch. They were probably a product of chopping the bark. They accounted for about 27% of the processed materials.

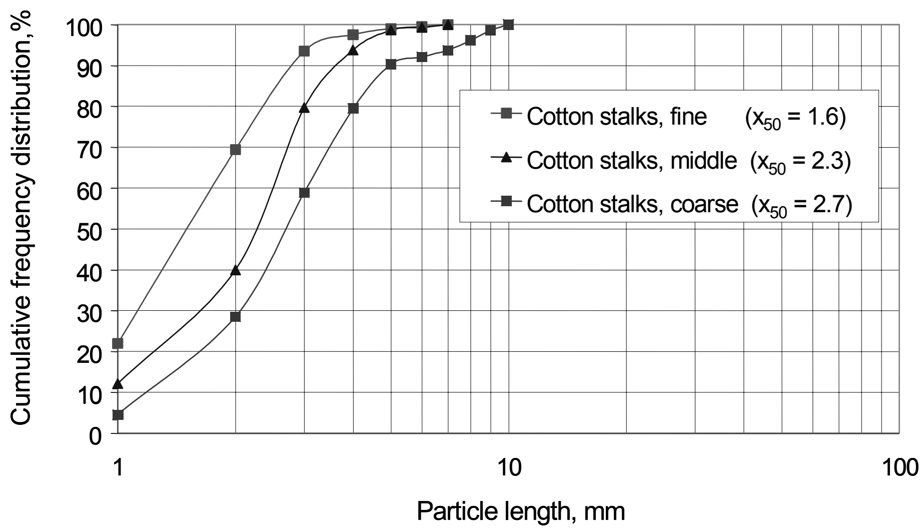


Fig. 5.7: Cumulative frequency distribution of cotton stalks

5.3 Processing

5.3.1 Chopping

Poplar was chopped with a special laboratory chopper consisting of three parts (Figure 5.8). The first part is a transport belt that drives the poplar branches to the squeeze zone. The velocity of this belt can be changed. The branches are pushed towards the squeeze zone, which represents the second part of this machine. This zone consists of two grooved steel cylinders that prepare the branches for cutting and prevent jamming in the cutting zone. The cylinders rotate at the same velocity as the belt. The third part of the machine is the cutting part, which consists of a cylinder. Two knives with the same width of the cylinder are fixed diagonally to perform the cutting operation.

The cutting velocity (v_R) can be changed in different ways to produce a large number of cutting lengths and particle sizes. The cutting cylinder can rotate at 16 velocity degrees. The cylinder velocities were measured using a tachometer. Four cutting velocities were used to cut the poplar branches. These velocities were 304, 474, 665, and 1328 r.p.m. The same instrument was used also to measure the linear velocity (v) of the machine belt. Three linear velocities were used: 0.33 m/s, 0.2 m/s and 0.1 m/s.

Fig. 5.8: The laboratory chopper

Straw and cotton were chopped with the help of a hammer mill, which is shown in Figure 5.9. The materials which entered through the feed opening at the top side of the hammer mill were cut by striking swinging hammers and discharged through sieve holes at the bottom. These hammers are fixed in a rotor, which is powered by an electric motor (16 kW) with a radial velocity (v_R) of 2980 r.p.m. A vacuum fan delivers the particles to the outlet where they are collected.

Fig. 5.9: The hammer mill

5.3.2 Moisture adjustment

The moisture content (U) of a solid is defined as the quantity of water per unit mass (m) of the wet solid. The moisture content of biomass materials is generally variable. The initial moisture content of the experimental material used in this work was generally high. The freshly harvested poplar branches, for example, had a moisture content of about 50%. To define their initial moisture content, a sample of 100 g chopped material was dried in an incubator (Heraeus) for 24 hours at a temperature of 105 °C. The sample was weighed again after drying and then the moisture content was calculated.

Five different moisture content levels were chosen to press the chopped materials. These were: 0%, 5%, 10%, 15%, and 20%. The material was dried to the desired moisture content with help of the following equation 5.1:

$$m_f = m_i \frac{1 - w_i / 100\%}{1 - w_f / 100\%} \tag{5.1}$$

where	m_i	- initial mass, g
	m_f	- final mass, g
	w_i	- initial moisture, %
	w_f	- final moisture, %

To press the materials at 0% moisture content, the material must be pressed directly after drying. Leaving the material in the open air leads to subsequent water absorption. In 30 minutes the moisture content reached 0.5 to 1%. After 2 hours the moisture content reach 2.0 to 2.5%. Figure 5.10 shows the increase in the moisture content after total drying of the experimental materials. All the press materials were pressed within 30 minutes after drying. This means that the moisture content of the materials with 0% moisture content can really be up to 0.5% for straw and hemp and up to 1.0% for poplar. This difference will be neglected.

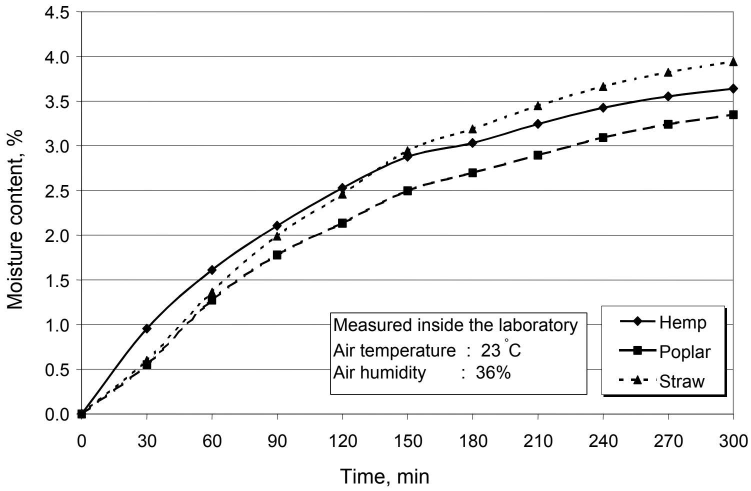


Fig. 5.10: Increasing the moisture content after total drying of experimental materials

5.4 Press experiments

After the moisture content of the materials had been adjusted, they were pressed in a special laboratory press machine that can be used with different pressing instruments. The laboratory press machine consists of three main parts: the base, the press cylinder base, and the press stamp.

Two electric motors supply the machine with motion. The main motor is attached to the base of the machine (1.0 kW) and the smaller one is attached to the back of the press cylinder base (0.2 kW). The base of the machine contains a gearwheel, which takes its velocity from the main electrical motor through a screw. The gearwheel also supplies the press base with velocity through a screw. Three press instruments were manufactured from steel (ST 38) in the ATB workshop. Figure 5.11 shows the construction of the press instruments of the press machine. The instrument consists of two parts. The first part is a hollow cylinder and the second is a solid cylinder that works as a stamp or a piston through the first part. The hollow cylinders have internal diameters of 30 mm, 42.5 mm, and 60 mm. All the cylinders have the same length, 400 mm.

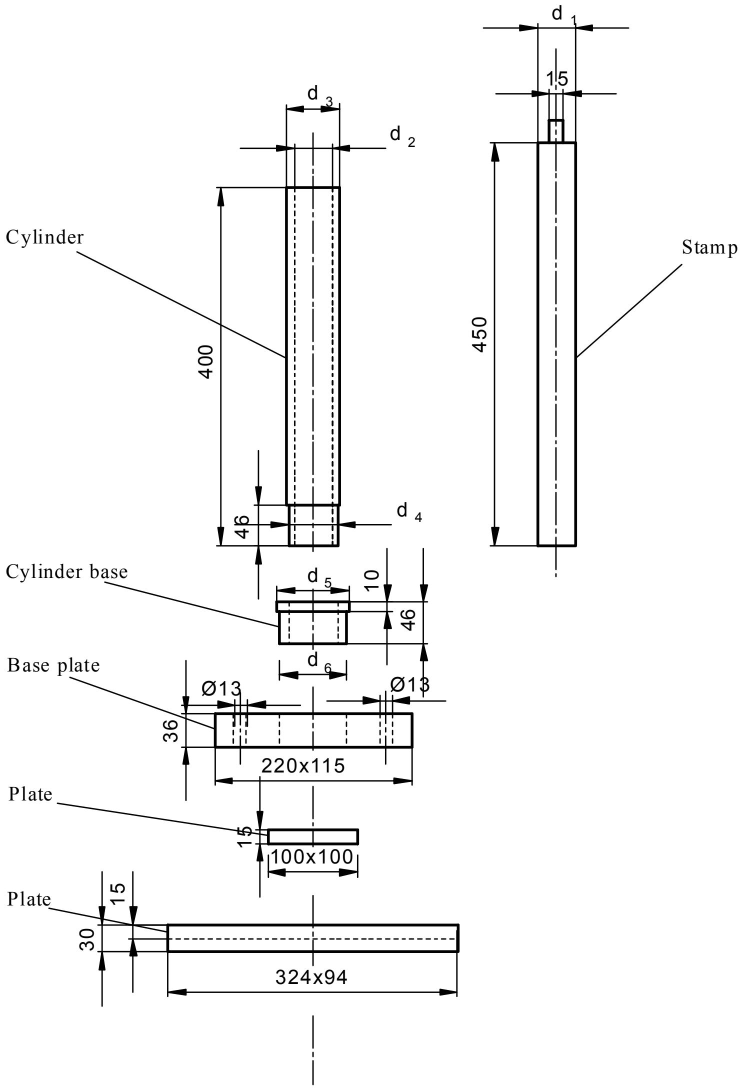


Fig. 5.11: Construction of the press instruments of the press machine

During pressing the press cylinder moves up and down at two velocities. The first velocity is the screw velocity, which takes its motion from the main electric motor, while second is the slow velocity, which is supplied from the small motor (up to 20 mm per min). The velocity can be adjusted by a hand switch. The fast velocity is only used to move the press cylinder up and down when there is no stress. When moving up the press cylinder meets the steel piston (stamp), which is fixed to the upper part of the machine and then presses the material. The pressing force is indicated on a scale. The maximum force of the machine used to press the material is 10^4 kp. Figure 5.12 shows the lab press machine.

Fig. 5.12: Lab press machine (WMF, Leipzig)

The materials acting as substitutes for cotton stalks (poplar, hemp and straw) were also pressed in a commercial hydraulic press machine (SP 45/12) produced by rsn Maschinenbau GmbH. The machine consists of a container into which the materials are placed. In the bottom of the container there is a distributor to spread the materials homogenously in the container and to push them to a screw conveyor. The conveyor pushes the materials to the press zone. A hydraulic press cylinder with a cylindrical press stamp presses the materials to a press canal with a diameter of 60 mm.

The main hydraulic press cylinder presses the materials from the back to form a briquette. A hydraulic motor (7 kW) provides the cylinder with the motion through a hydraulic assembly. The oil pressure (p) on the cylinder is 27.7 MPa. After pressing, the cylinder delivers the briquette to the outlet. The throughput ($\dot{m}_T$) of the machine is between 35-40 kg/h. A cross section of the press zone is shown in Figure 5.13.

Spare parts list

1 press cylinder
2 connecting piece
3 press stamp
4 press die
5 locking plate
6 press canal
7 connecting flange
8 compacting die
9 acryl glass cover
10 switch set
11 press stamp
12 control rod
13 press cylinder
14 screw conveyor
15 flanged bearing
16 discharge arm
17 discharge mechanism
18 sprocket
19 over load clutch

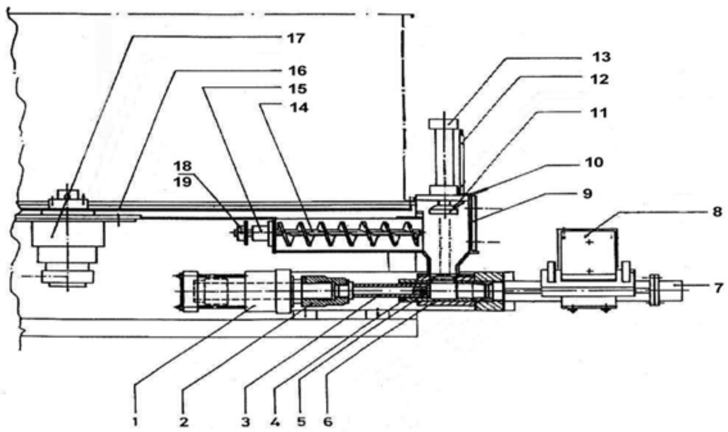


Fig. 5.13: Operating principle of the commercial press machine (SP 45/12)

5.5 Briquette measurements

5.5.1 Briquette density (ρ)

The bulk density of the loose materials used was measured. A cylindrically shaped container with a diameter of 13 mm and a volume of 2000 cm^3 was used for this process. The container was weighed empty to determine its mass. Then it was filled with the material and weighed once more. The measurement was repeated 3-5 times. The bulk density was calculated by dividing the average mass of the material by the volume of the container. After pressing, the briquette density was measured directly. The briquette length was measured and the volume was calculated. The briquette was weighed using a digital balance. The briquette density was calculated by dividing the average mass of the briquette over its volume.

5.5.2 Radial compressive strength (p_R)

The radial compressive strength (N/mm^2) of the briquette was measured directly after pressing. The test machine (Zwick) was used for this process (Figure 5.14). This machine consists of a sensor to measure the breaking force (F) of the briquette up to 2 kN. This sensor is connected to a rectangular block hanging above the machine and to a platform that can be dismantled at the base of the machine. This platform is composed of other parts, which can be varied to suit the diameter of the briquette whose radial compressive strength is to be measured. The rectangular block above the machine hangs directly over the platform at the base and the distance between them is adjustable depending on the diameter of the briquette being tested. The briquette is placed in the middle of the platform and during the motion the press plate breaks the briquette. The width of the plate should be equivalent to half the briquette diameter. When moving up and down the sensor has a velocity of 100 mm per min. The system is connected to a computer program that controls the motion of the sensor and then records the results directly and automatically. The test was repeated 4 times. Figure 5.15 shows an example of the breaking of briquettes.

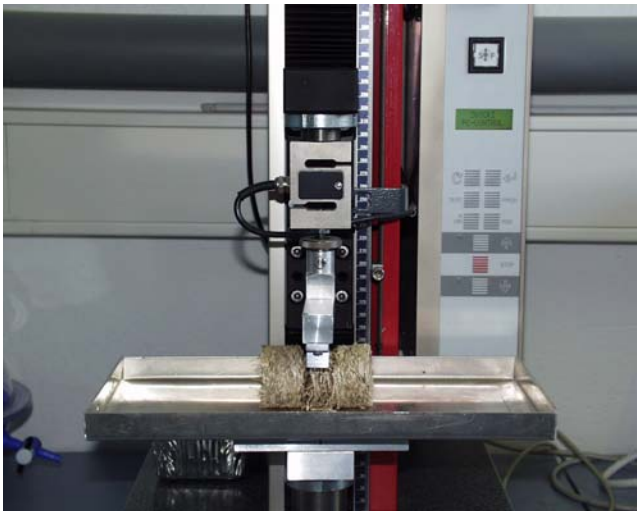


Fig. 5.14: Test machine for measuring the radial compressive strength of briquettes

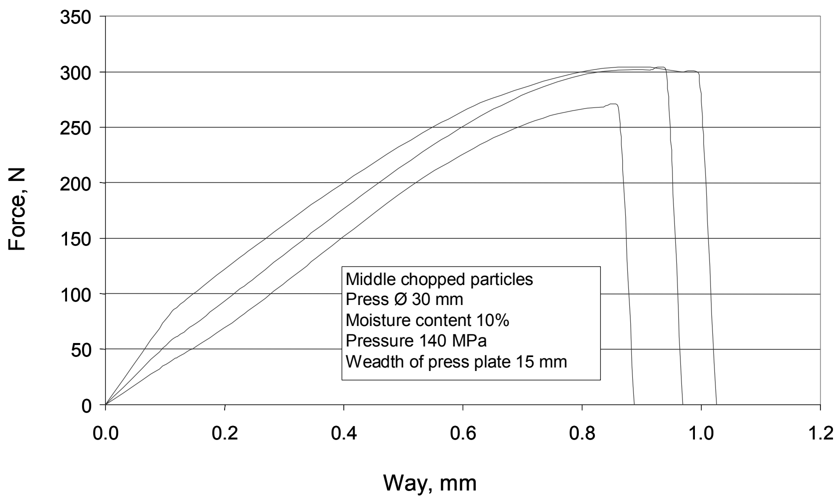


Fig. 5.15: The breaking path of cotton stalk briquettes

5.5.3 Briquette durability

In this study the durability of briquettes (a) was measured according to the standard method of ASAE S269.4, which is intended to assess the durability of Cubes, Pellets and Crumbles. The test was performed in the laboratory of the Institute of Mechanical Engineering and Plastic Technology, Technological University of Chemnitz. Hydraulic pressed briquettes of hemp and poplar were used in this test. A sample of about 500 g briquettes was placed in a dust-tight box. The box was rotated about an axis, which was perpendicular to and centred in the 300 mm side. A 230 mm long baffle was affixed symmetrically and diagonally to a side of the box (300x300 mm). The sample was rotated for 10 min at 50 r.p.m. Figure 5.16 shows the durability test instrument. The durability rating was expressed as the ratio of the original mass of the briquette to the briquette remaining after tumbling in accordance with the following equations,

$$a = \frac{m_a}{m_e}.100 \quad (5.2)$$

$$m_a = m_e - m_p \quad (5.3)$$

where

a = Briquette durability, %

m_a = Briquettes remaining, g

m_e = Original weight, g

m_p = Briquette weight after the test, g

Fig. 5.16: Test machine for briquette durability

5.6 Temperature measurements and experiments

Temperature (T) is an important parameter that affects the pressed materials as loose materials or briquettes. The materials used were dried in an oven at 105 °C for 24 hours to study the effect of temperature on the loss of the dry matter. A sample of 100 g from each dried material was dried directly again in another oven at 120 °C for one hour. The dried material was weighed again and the loss in mass was calculated. The same sample was dried again in the same oven for the same time period after raising the oven temperature by 20 °C. The experiment was performed by drying the sample after increasing the oven temperature by 20 °C for the same time period. The loss in mass was calculated each time. The maximum experimental temperature used was 200 °C. The relation between the temperature and the loss in mass was calculated.

The increase in the internal temperature of a briquette depending on time and ambient temperatures was studied. A briquette of each material with a diameter of 60 mm pressed in the commercial press was drilled through to its centre. A sensor connected to a temperature measuring apparatus via a thermo cable was used to measure the internal temperature of the briquette. The initial temperature was measured, then the briquette was placed in an oven at 70 °C. The change in temperature of the briquette centre was recorded every 5 minutes. The same procedures were applied for other briquettes in the same oven at 105 °C.

The briquette temperature increased because of the friction between the pressed materials and the press stamp wall and also between the pressed particles. The development of the internal temperature of hemp briquettes depending on the operating time of the commercial press was thus studied. The initial temperature of hemp shives was measured with the help of a digital thermometer. The briquette temperature was measured directly after pressing at a depth of 1-1.5 cm.

The effect of temperature on the pink bollworm was also studied to determine the minimum temperature that kills off this worm. Live worms were separated from the infested bolls and placed in an oven at a certain temperature until all the worms were killed. This experiment was repeated several times at increased temperatures. A relation was derived between the temperature and the time needed to kill off the worms.

5.7 Combustion experiments

The combustion experiments were carried out in a combustion boiler with primary and secondary air supply with the experimental materials previously described in the form of loose materials and briquettes produced by the commercial press. The measurements were carried out in the energy laboratory of ATB. Table 5.4 shows the physical properties of the materials used for combustion. A boiler HT 35 (Hager, Forst) was used in this experiment. Its thermal power was 25-35 kW and the combustion chamber capacity was 150 litres (Figure 5.17).

Table 5.4: Physical properties of the materials used for combustion

Parameter		Poplar		Hemp		Rye Straw	
		Branches	Briquette	Stalks	Briquette	Straw	Briquette
Length	mm	305-455	25	320-450	25	100-740	25
Diameter	mm	4-15	62	2-9	62	3-6	62
Moisture content	%	12.5	7	8	11	9.1	8.5
Raw density	g/cm^3	0.58	0.91	1.47	0.98	-	0.87
Bulk density	g/cm^3	0.12	0.67	0.44	0.66	0.05	0.63
Mass	kg	10	10	10	10	10	10

Fig. 5.17 : Combustion test stand of ATB

The boiler was initially fired in accordance with DIN 4702 using wood pieces (7 kg) until it reached a temperature of 60-70 °C. Then the boiler was filled with the tested materials. For the loose materials, the boiler was filled in several stages, then measuring was started. During combustion the boiler temperature was maintained at a constant level of about 68 ± 6 °C.

The flue gas analyser (Visit 02 Eheim) was used to measure the emissions and the flue gas temperature. A gas sensor was installed centrally in the exhaust tube. Different measuring devices and equipment were used to measure the other relevant parameters of technical combustion. These measuring parameters were:

- Time [s]
- Temperature [°C]
- Flow rate [l/min] and thermal power [kW]
- Exhausts and ambient temperature [°C]
- Carbon monoxide CO [ppm, mg/Nm^3]
- Carbon dioxide CO_2 [ppm, mg/Nm^3]
- Oxygen O_2 [%]
- Nitrogen oxide NO [ppm, mg/Nm^3]
- Sulphur dioxide SO_2 [ppm, mg/Nm^3]
- Ash mass [g].

6 Experimental results

6.1 Laboratory press results

6.1.1 Poplar

The effect of pressure on briquette density depending on moisture content was investigated. Figure 6.1 shows the relationship between the parameters studied for medium chopped poplar pressed mechanically in a press of diameter 42.5 mm. Density was taken as dry matter to avoid the effect of water when studying the relationship between the parameters. It was found that there is a correlation between briquette density and pressure for the moisture content levels studied. The moisture acts as both lubricant and binding agent, but above a certain level of moisture the briquetted material could not be compacted, regardless of the pressure level. This could be due to the excess water flooding in the particle surfaces, which causes reduction or even complete loss of the surface tension (Lindley and Vossoughi, 1989). As recommended by Clauß (2002), the most stable briquettes are those with a moisture content under 18%.

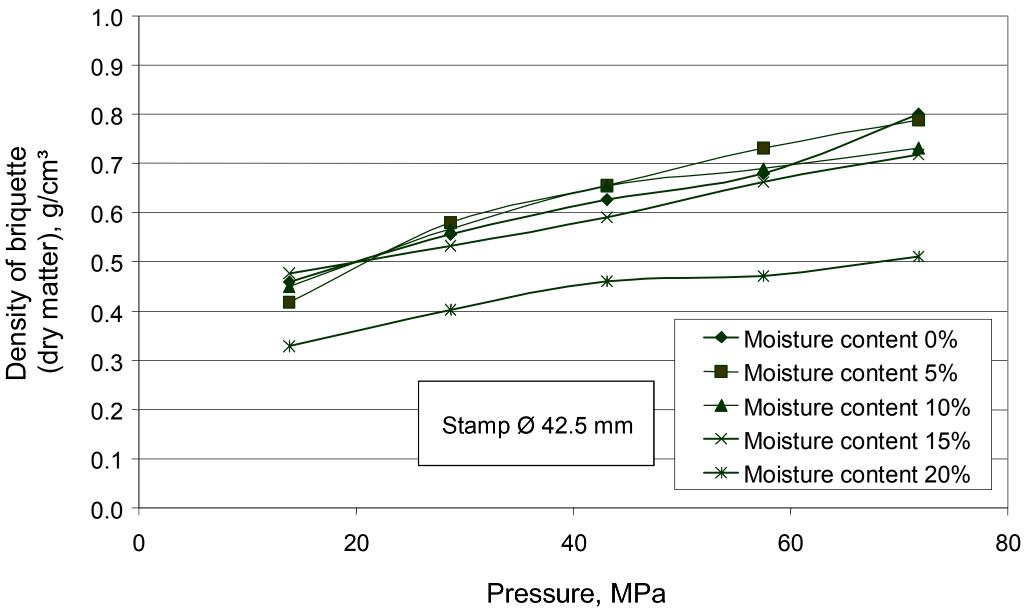


Fig. 6.1: Density of briquette versus pressure for medium-sized chopped poplar (∅ 45.5 mm)

As presented by Lindley and Vossoughi, 1989 and Clauß (2002), the results show that the briquettes processed at 20% moisture content have the lowest density values. It was observed in poplar that some drops of water were expelled from the press while pressing and that this resulted in a reduction in briquette density.

The same relationship between the briquette density and pressure depending on particle size and moisture content was also investigated in a press stamp of diameter 30 mm. A value of 15% moisture content was chosen as representative in the range of the recommended moisture content. A moisture content of 10% for the medium-sized chopped poplar was also studied by way of comparison. The results presented in Figure 6.2 show that the influence of particle size on briquette density is limited, but there is a correlation between density and pressure. The influence of moisture content on briquette density was also observed. For the same particle size and the other parameters studied, briquette density values were higher for moisture contents of 10% than of 15%.

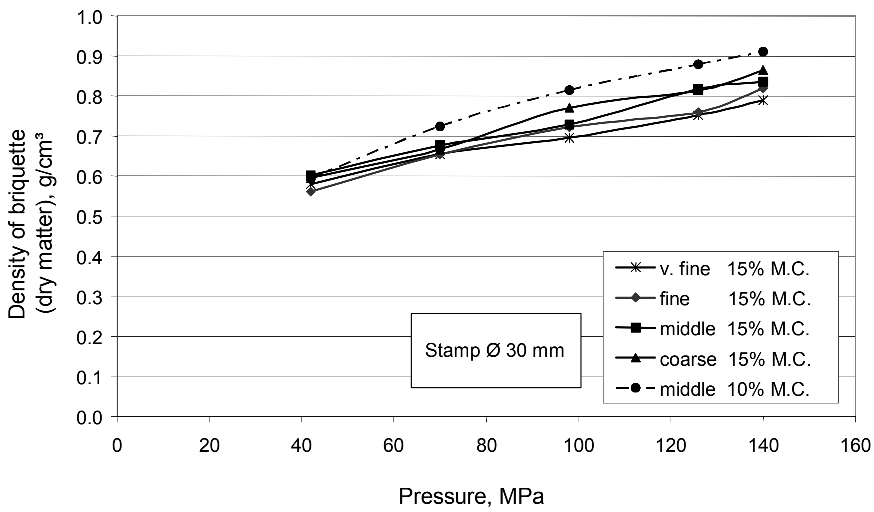


Fig. 6.2: Density of briquette versus pressure for chopped poplar (∅ 30 mm)

6.1.2 Hemp

The relationship between the pressure and the dry matter density of briquettes depending on the moisture content was studied for the medium chopped hemp as shown in Figure 6.3. The particles were pressed mechanically in a press of diameter 42.5 mm. A direct correlation between the parameters studied was observed. 10% moisture content seems to be the optimum moisture level that gives higher briquette density values, although there is no major difference compared with the density values of 5% and 0% moisture content. The Figure shows also that increasing the pressure will significantly increase the density values. Compared with poplar results, the density values of hemp at 10% moisture content were relatively high. Hemp shives used in this work contain hemp fibres in a ratio of about 10%. These fibres are compressible and reduce the briquette volume more than the hard woody particles of poplar.

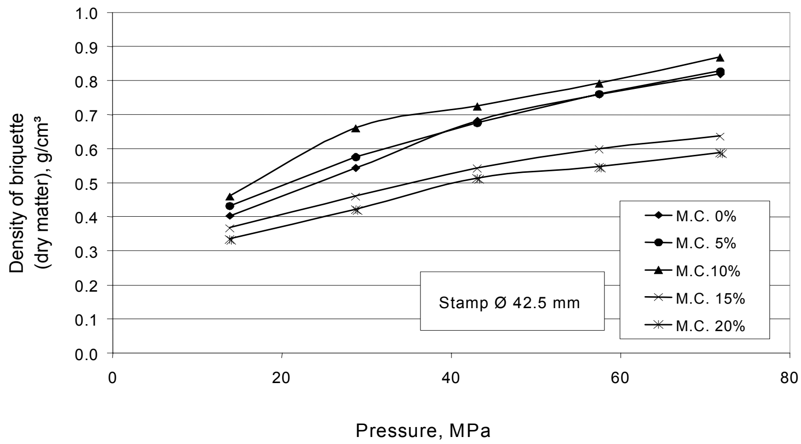


Fig. 6.3: Density of briquette versus pressure for medium chopped hemp (∅ 45.5 mm)

The same relation was studied for hemp pressed mechanically in a press of diameter 30 mm depending on the moisture content and particle size as shown in Figure 6.4. A correlation between the parameters studied was also found. Increasing the pressure above 70 MPa will increase the density digressively. The briquette reaches the plastic stage and resists further pressing, despite the increased pressure. It can be summarized that 70 MPa and 0.8 g/cm^3 values of briquette pressure density are the minimum values for producing a stable and durable briquette.

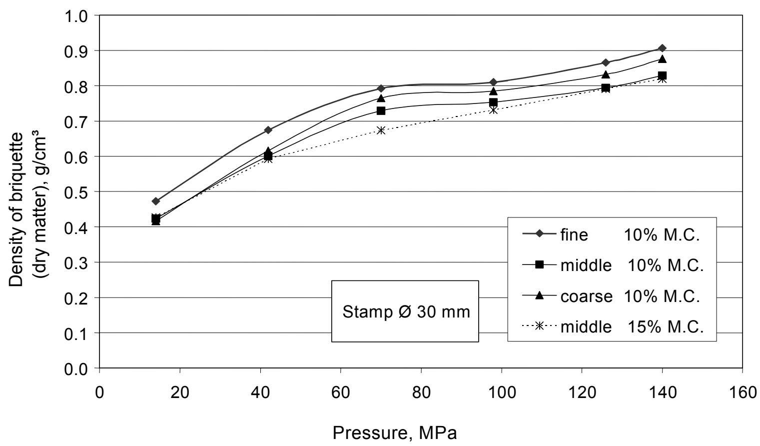


Fig. 6.4: Density of briquette versus pressure for chopped hemp (∅ 30 mm)

The Figure shows also that the particle size has a limited influence on the density although fine particles have higher density values. The fine size particles are more compressible and fill the void spaces better than the coarser particles and thus increase the briquette density. It is also clear that a 10% moisture content has better results for density than a value of 15%.

6.1.3 Straw

The relationship between briquette density and pressure depending on moisture content for straw was also studied. It was correlated and confirmed that 10% moisture content produces the highest briquette density values. The results presented in Figure 6.5 for medium chopped straw pressed mechanically in press of diameter 42.5 mm show that increasing the moisture content above 10% will affect the briquette density negatively. It was found also that the density values of 0 % moisture content were the lowest. It was observed that increasing the pressure above the maximum studied value (70 MPa) may increase density values.

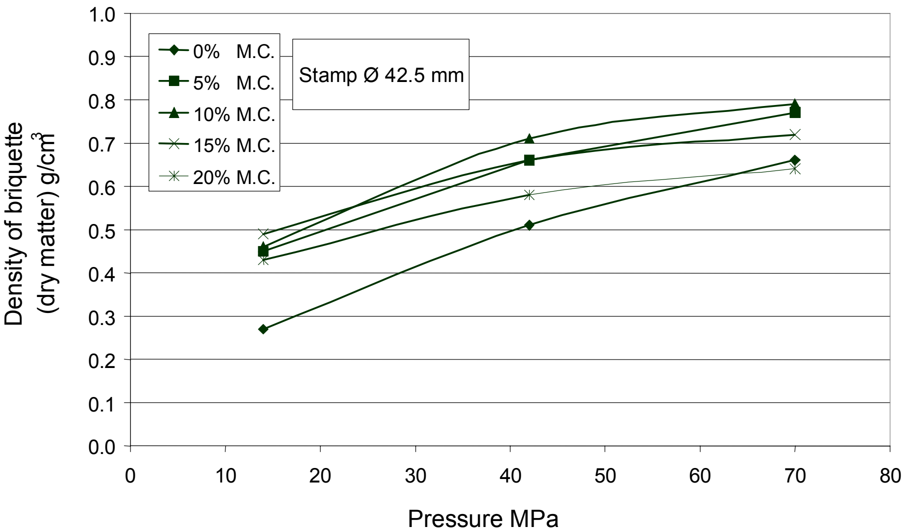


Fig. 6.5: Density of briquette versus pressure for medium chopped rye straw (∅ 45.5 mm)

The same relationship was studied for straw pressed mechanically in press Ø 30 mm at 10% moisture content depending on particle size, as illustrated in Figure 6.6. It was found that there is a correlation between the parameters studied. The density increases digressively until the pressure reaches about 100 MPa. Increasing the pressure above this value will have a limited affect on the density values. The density value then is about 0.9 g/cm^3. It is clear also that the particle size has a limited effect on density value.

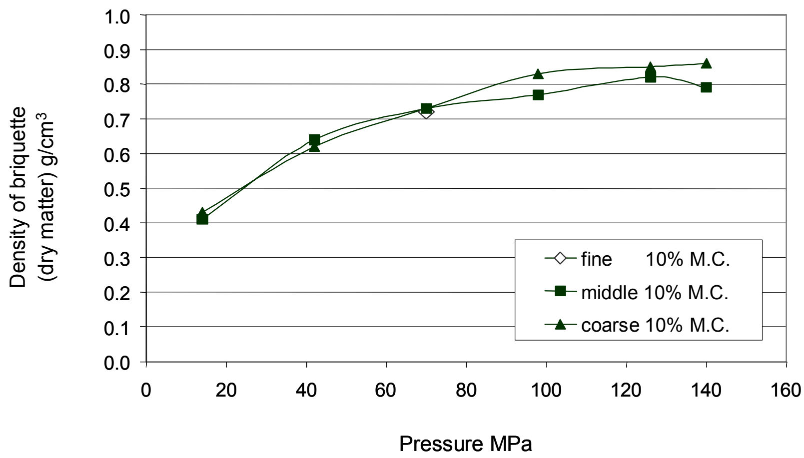


Fig. 6.6: Density of briquette versus pressure for chopped rye straw (∅ 30 mm)

6.1.4 Cotton stalks

The results for cotton stalks set out in Figure 6.7 show the relationship between pressure and density of briquette depending on moisture content. The results show that there is a correlation between the parameters studied pressed mechanically in press Ø 42.5 mm. These results also confirm that 10% moisture content is the moisture content with which the briquettes of highest density can be produced. Increasing the moisture content above this value will result in a decrease in the density values as shown in this figure. The results show also that increasing the pressure above 70 MPa may increase the density values.

The results presented in Figure 6.8 illustrate the same relationship depending on moisture content and particle sizes for stamp Ø 30 mm. The correlation between the pressure and briquette density as dry matter shows that increasing the pressure up to 100 MPa will increase the density values. To continue increasing the pressure up to 120 MPa will significantly affect the density values. After this stage the briquette resists being pressed, despite the increase in pressure. The correlation between the pressure and briquette density agree with the results of the relations for the substitute materials (poplar, hemp, and rye straw).

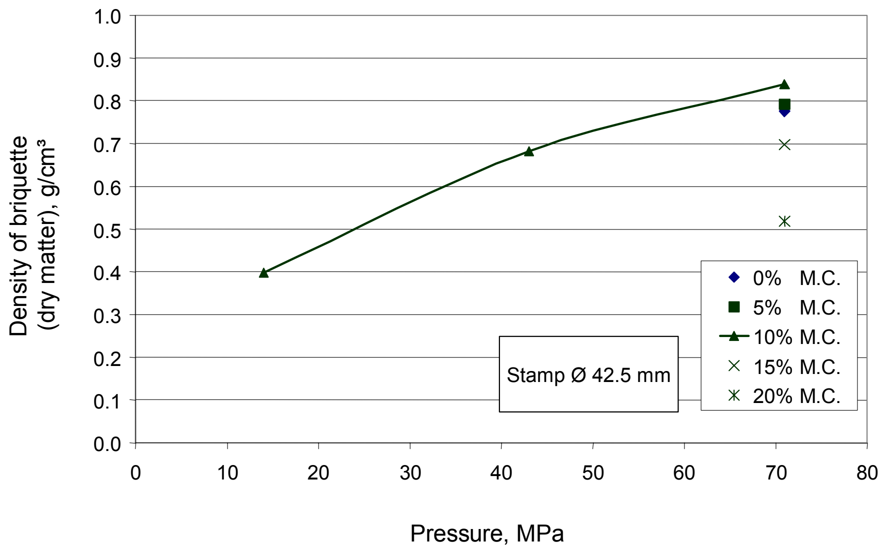


Fig. 6.7: Density of briquette versus pressure for middle chopped cotton stalks (∅ 42.5 mm)

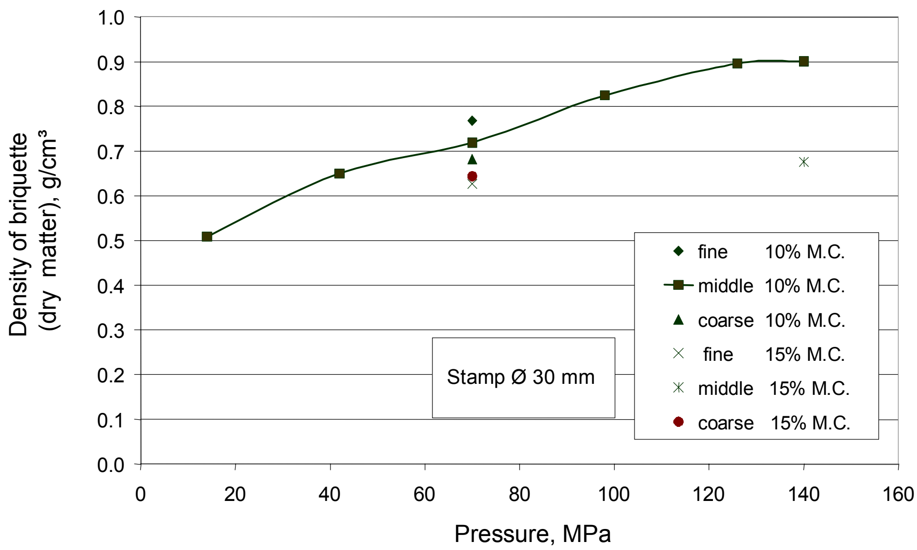


Fig. 6.8: Density of briquette versus pressure for chopped cotton stalks (∅ 30 mm)

6.2 Commercial press results

To apply the results of this work for use in practice, the materials were pressed in a commercial press (SP 45/12) produced by rsn Maschinenbau GmbH to study their behaviour. The physical properties of the processed materials were first studied as presented in Table 6.1. All the parameters were studied directly after pressing (0.5 hour) and after 2 days. The data presented in Table 6.2 show the results of this study. After 2 days, the density of briquettes was reduced to different levels depending on the materials. This reduction is due to the briquette elongation after pressing and thus increased their volume. The reduction in briquette density for hemp was only 2%. This reduction in the briquette density for poplar was only 1% and for straw briquettes was about 2%.

Table 6.1: Physical properties of the experimental raw materials

Parameter	Poplar	Hemp	Straw
Bulk density, g/cm^3	0.16	0.088	0.059
Moisture content, %	7.0	11.0	8.5
Material temperature, °C	14.3	19.1	13.6
Particle size, x_{50} mm	2.5	3.0	3.3

A comparison was made between the briquettes processed in the laboratory and in the commercial press machines. The pressing pressure of the laboratory press was 35 MPa and of the commercial press 27.7 MPa. The briquette diameter of both pressing materials was 60 mm. As also presented in Table 6.2 it was found generally that, the results of briquettes pressed in the commercial press were better than the results of those pressed in the laboratory press. The briquette density was measured for both machines immediately after pressing (0.5 hour) and after 2 days. After 2 days, the density values of the commercial press were higher than those of laboratory press at 39%, 31%, and 44% for hemp, poplar and straw, respectively. The radial compressive strength of briquettes pressed in the commercial press was also studied. Poplar briquettes showed higher radial compressive strength than hemp and straw by the ratios of 34% and 57%, respectively. Depending on the material, the radial compressive strength values were also reduced after storing for 2 days. The reduction rates were 11%, 8%, and 4.5% for poplar, hemp, and straw, respectively.

Table 6.2: Results of the commercial press compared to the results of the laboratory press

Material	Press type	Time	Briquette density (g/cm^3)	Radial compressive strength (N/mm^3)	Briquette temperature, (°C after 0.5 hour)	Stamp velocity, (mm/min)	Machine throughput (Kg/h)
Poplar	SP 45/12	≅ 0.5 hour	0.92	0.52	33.7	220	37.04
		≥ 2 days	0.91	0.46			
	Lab. Press	≅ 0.5 hour	0.70	-	-	< 20	-
		≥ 2 days	0.63	-			
Hemp	SP 45/12	≅ 0.5 hour	1.00	0.34	42.0	193	35.28
		≥ 2 days	0.98	0.31			
	Lab. Press	≅ 0.5 hour	0.75	0.007	-	< 20	-
		≥ 2 days	0.60	-			
Straw	SP 45/12	≅ 0.5 hour	0.87	0.22	44.1	220	26.67
		≥ 2 days	0.85	0.21			
	Lab. Press	≅ 0.5 hour	0.61	-	-	< 20	-
		≥ 2 days	0.48	-			

6.3 Correlation of stability and density of briquettes

The correlation between the stability and density of briquettes was studied to show the effect of briquette density on stability. It was found that there is a correlation between the parameters studied. A trend line was constructed for the medium chopped hemp pressed mechanically in press Ø 42.5 mm to illustrate this relation as shown in Figure 6.9. Hemp briquettes pressed at 10% moisture content were the most stable, as they had the highest density and stability values. It was observed that also increasing the briquette density to more than 0.9 g/cm^3 has a limited effect on the radial compressive strength.

The same relation was investigated for hemp, poplar and cotton stalks. The materials were pressed mechanically in a press stamp of diameter 30 mm. The trend lines which represented this in Figure 6.10 show that there is a correlation between briquette density and stability. It is clear that the hemp briquette pressed at 10% moisture content was the most stable, as it has the highest density and stability values. At the same density value (for example 0.8 g/cm^3) the materials pressed in press with diameter 30 mm have higher stability values than those pressed in the press stamp with diameter 42.5 mm. It is also clear that hemp briquettes are more stable than the processed briquettes of the other materials.

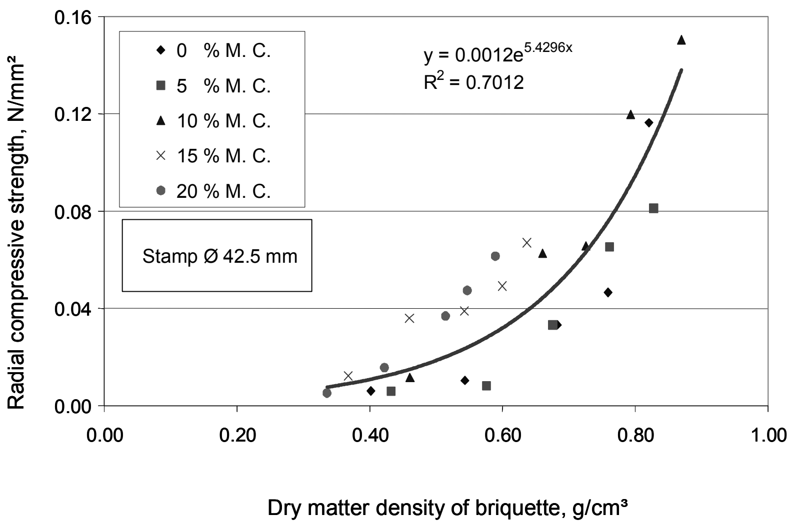


Fig. 6.9: Relation between radial stability and density of briquette from medium chopped hemp (∅ 42.5 mm)

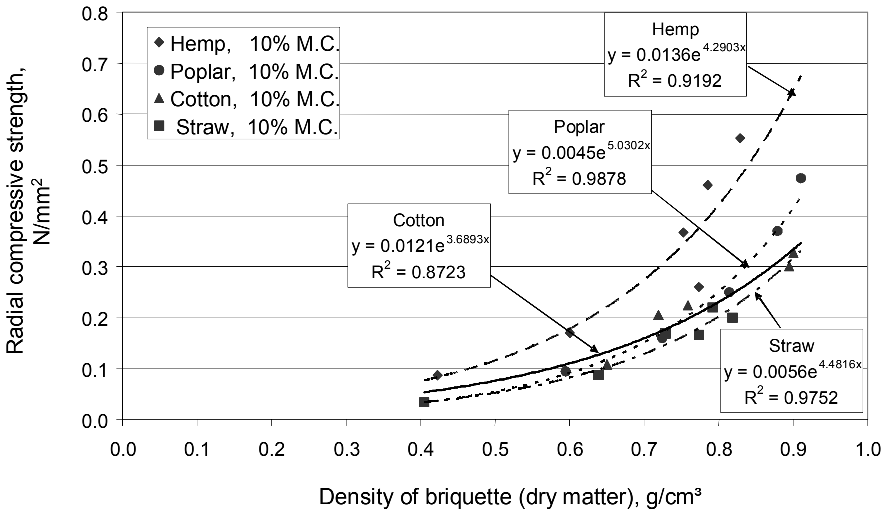


Fig. 6.10: Relation between radial stability and density of middle chopped materials (∅ 30 mm)

This led us to study the influence of the press diameter on the studied relation for the medium chopped hemp. The results presented in Figure 6.11 show that there is a correlation between the parameters studied. The diagram confirmed that the briquettes pressed in the press stamp with a diameter of 30 mm had the highest density and stability values.

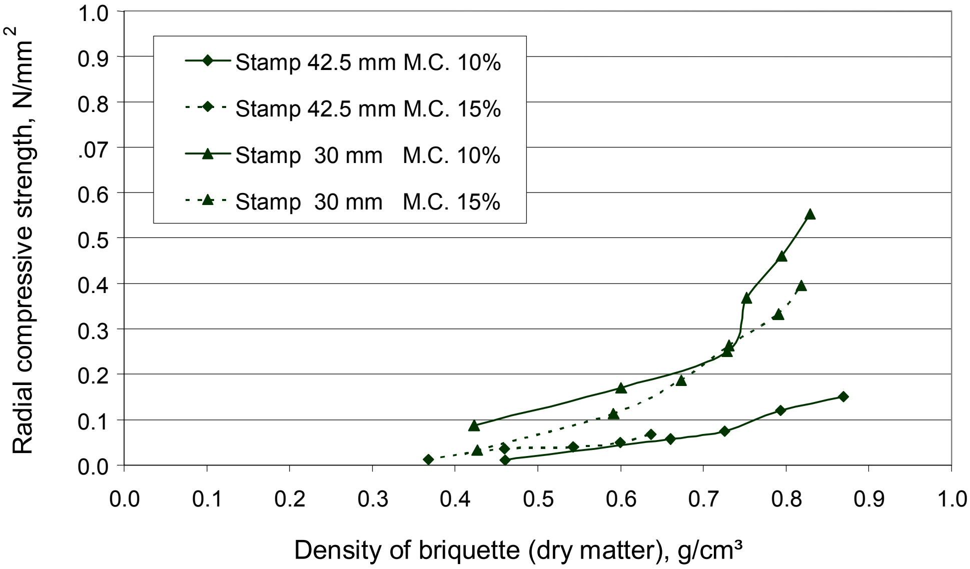


Fig. 6.11: Influence of the press diameter on briquette stability depending on density of briquette of medium chopped hemp

6.4 Briquette durability

The durability of briquettes is a very important factor for transportation processes and feeding combustion equipment. The stability of hemp and poplar (pressed hydraulically) briquettes was tested as presented in 5.1.5.3. Because of the abrasion between the briquettes themselves and between the briquettes and the baffle, some particles of the briquette surface were separated. The rotating motion of the experimental box leads the briquettes to move up and down. This movement leads the briquettes to lose some particles from their surface. The briquette durability was calculated according to the standard equation of ASAE (see 5.1.5.3). It was found that the durability of hemp briquettes was 81%, and of poplar briquettes 75.8%. The average moisture content of the briquettes was 7.8%.

6.5 Moisture content of cotton stalks on the field

Water is one of the most useful agents that are used both as a binder and lubricant. Therefore water is particularly necessary as an aid in briquetting. Several investigations of different materials indicate that the strength and density of briquettes increase with increasing moisture until an optimum level is reached (Lindley and Vossoughi, 1989). They added also that 15% is the optimal moisture content for briquetting saw dust, sander dust and rice husks. They recommended that 10% moisture content is optimal for fireplace log production.

Clauß (2002) stated that the suitable moisture content for producing rigid and stable straw briquettes is under 18%. As presented in chapter 5.2.1, the optimal moisture content for the agricultural residues to be briquetted ranges between 8-15%. Cotton stalks at this moisture content can easily be briquetted in Egypt. The cotton stalks are harvested in October when the average daily temperature is 25 °C and the relative humidity is 60% with no rain (MALR, 2002).

The stalks are left on the field, thus losing about 80% of their moisture in about 5 days. That means the stalk moisture content reaches the recommended range in a time period of less than one week as shown in Figure 6.12. This implies that cotton stalks can be briquetted one week after the harvest operation is finished by a suitable type of briquetting machine without incurring any additional costs for drying.

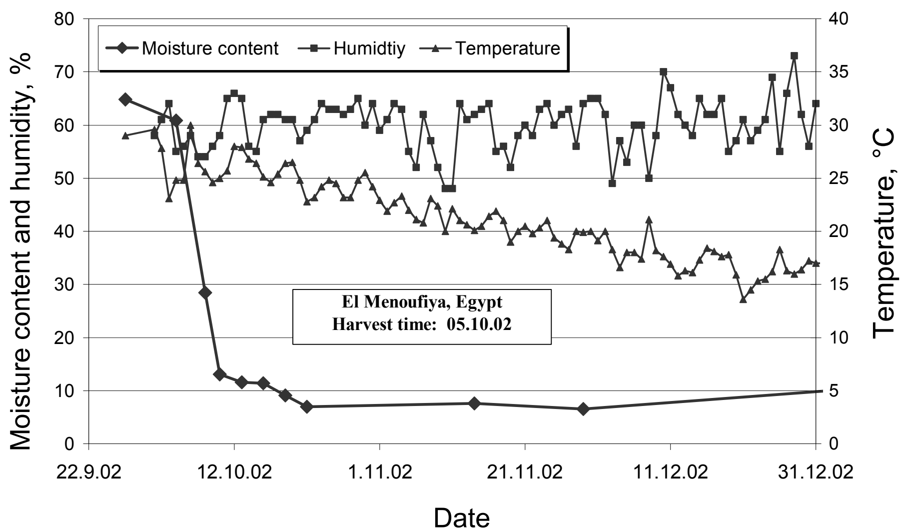


Fig. 6.12: The moisture content of cotton stalks and relevant climate parameters on the field in Egypt

As presented, the moisture content (U) play a major role in the briquetting process. It also has a major influence on the material properties. It is calculated as a ratio of the dry matter to the dry matter plus the moisture content, and this connection is not linear so that for the agricultural sector it is preferable to use the moisture degree (X) as a standard (Kutzbach, 1989). Equation 6.1 illustrates the moisture degree:

$$X = \frac{m_w}{m_s} \qquad (6.1)$$

where

X = Moisture degree

m_w = Moisture mass, g

m_s = Dry matter, g

According to this equation, the preferable moisture degree for pressing cotton stalk is between 0.087 and 0.17.

6.6 Temperature behaviour of cotton bollworms

The pink bollworm is a major pest in cotton world wide. It damages the mature bolls, the damage to bolls being the most serious. The larva burrows into bolls, through the lint to feed on seeds (UCIMP 2001). The infested bolls and seeds are the sources of this worm, so that after the harvest operation is finished, the infested bolls must be collected and eliminated. The method recommended by the Egyptian Ministry of Agriculture of burning the cotton stalks is environmentally unfriendly. After cotton ginning, seeds must be treated by hot air at 55-58 °C for 5 minutes to kill the vitality of the eggs that can be found in the seeds (Muawad, 1991; El Menshawy and Higazy, 2000).

As presented, temperature has a major influence on the elimination of the cotton larvae. An experiment was performed to study the temperature behaviour of cotton bollworms. The pink bollworm larvae were heated in a laboratory oven. The results show that at 70 °C the larvae were completely killed after 2 minutes. Reducing the temperature to 60 °C leads to killing the larvae after 15 minutes. Figure 6.13 shows that increasing the temperature will decrease the time needed to kill the pink bollworm larvae.

It is possible to preheat the processed materials before briquetting to eliminate the worms and eggs that may be found after chopping the processed materials. The other method is to heat the press channel of the press machine to that range of temperatures that kill the harmful worms. Another method is using briquette machines that already have a high temperature.

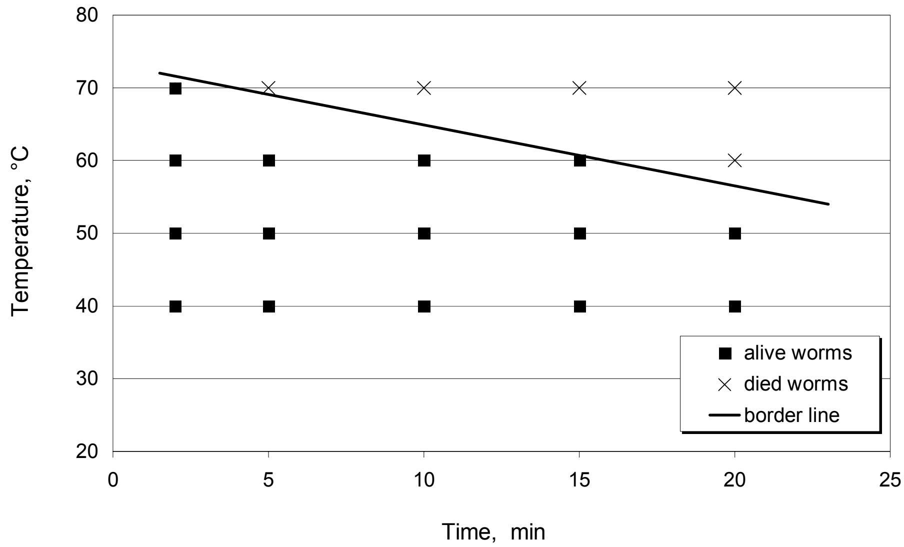


Figure 6.13: The effect of temperature and time on the survival rate of cotton pink bollworms

6.7 Temperature behaviour of briquettes

To study the temperature behaviour of briquettes, hemp shives were pressed in the commercial press machine. The initial temperature of hemp shives was measured with the help of a digital thermometer at a depth of 1-1.5 cm. Briquette temperature was also measured directly after pressing. The results presented in Figure 6.14 indicate that after 5 minutes of operation, the internal temperature of the briquette increased by about 11.1°C above the initial temperature of the processed materials. After 15 minutes, the briquette temperature increased by 20.9 °C above the initial temperature. After 30 minute operating time the briquette temperature was steady at 42.2 °C above the initial temperature.

The temperature produced is due to high pressure and the friction between the processed particles and between the briquette and the press cylinder wall. Scholz and Fürll (1978) confirmed this fact. They stated that the friction and the form of the press instrument play a major role in increasing the temperature of pressed materials. In addition, increasing the temperature (ΔT) reaches 40-60 K depending on the processed material.

However, the heating temperature must not be more than 105 °C. As shown in Figure 6.15 there is a correlation between the temperature and the loss in mass. It was found that after 105 °C release of the volatile materials starts. The figure shows also that straw and cotton stalks are the materials which lose more mass than the others. Above 180 °C the loss of cotton stalks increases drastically as they start to burn.

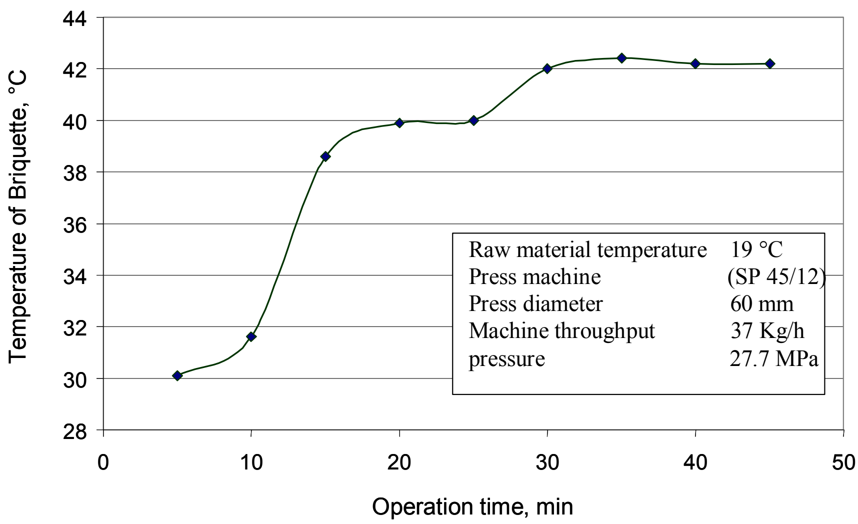


Fig. 6.14: Development of the internal temperature of hemp briquettes depending on the operation time of the commercial press (SP 45/12)

If the temperature of the process does not reach 60 or 70 °C, it is possible to heat the briquettes after pressing by prolongation and/or by heating the press channel. The time needed for heating the briquettes can be calculated with the help of Figure 6.16. There is a correlation between ambient temperature and briquette temperature. At 70 °C, the core temperature of the briquette reaches the level recommended for killing off the pink bollworm after 50 minutes. The temperature remained steady on increasing the time. Increasing the ambient temperature up to 105 °C reduced the time needed to reach the recommended temperature by approximately 75% for straw and 50% for hemp.

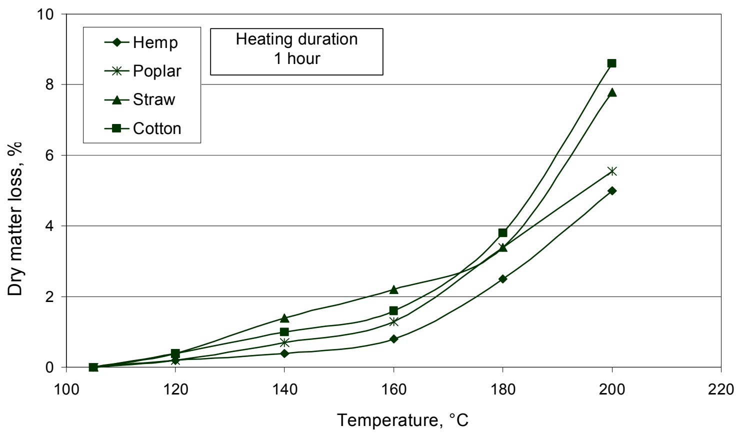


Fig. 6.15: Dry matter loss of the experimental materials after one hour depending on temperature

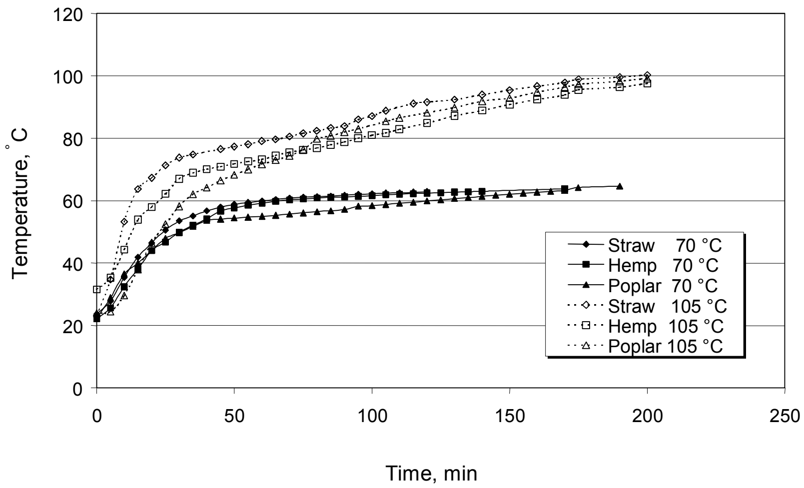


Fig. 6.16: The increase of the internal temperature of briquettes depending on time for various outside temperatures

6.8 Emissions of briquettes during combustion

A main advantage of biofuel is that it can be used without damaging the environment (Nendel et al, 1998). Its advantage lies not only in the contribution to CO_2 mitigation, but also extends to include other elements. Combustion of the experimental materials (poplar, hemp and straw) was undertaken. The materials were burned in the form of both loose materials and briquettes. Figure 6.17 to Figure 6.22 illustrate the course of emission during combustion for each material.

The comparison between the courses of emissions during combustion of the materials studied such as branches and briquettes shows that the emission rates for briquettes were regular. On the other hand, this behaviour in the combustion of branches was quite different. The combustion rates moved up and down drastically. This also indicates that there is more regularity in the energy rate from briquettes than from branches, stalks or stems.

The results of combustion are summarized in Table 6.4. It is clear that CO emission from briquettes (pressed hydraulically) was less than the emission from loose material. CO emission for poplar briquette was lower by 30% than the emission from poplar branches. The corresponding result for straw was 56%. This course of results was also the same for the other emissions (NO_x, SO_2 and Q_N) and the ash content. CO emission for hemp and straw briquette was lower than the emission from their stalks and stems, but the results of the other emissions were converted.

The materials used were also analysed chemically in order to evaluate their use as environmentally friendly fuel. Table 6.5 shows the results of this analysis. The low ash and chlorine content of the straw used was possibly caused by the long storage time. In general, the ash content is 4.2% and the chlorine content is 1600 mg/kg in rye straw (FNR, 2000).

The elementary values of cotton stalks are approximately the same as in the other experimental materials. Although the ash content of cotton stalks is relatively higher than in the other materials, its ratio is in the range of the other biomass materials as found by Ebeling and Jenkins, (1985) and FNR, (2000). The same result was found also for the chlorine ratio.

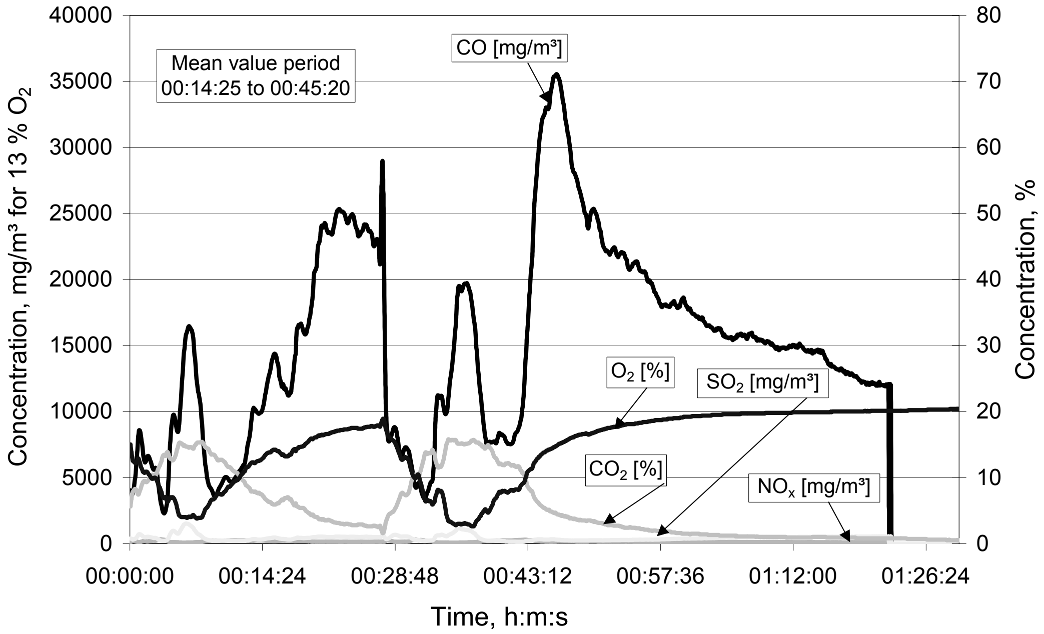


Fig. 6.17: Course of emissions during combustion of poplar branches

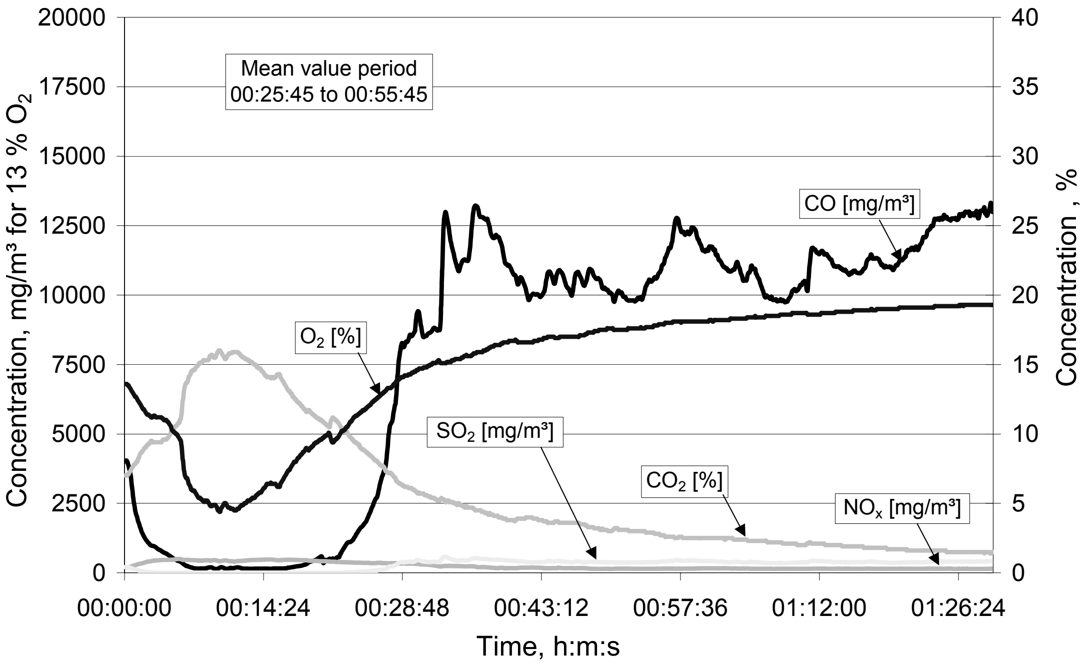


Fig. 6.18: Course of emissions during combustion of poplar briquettes

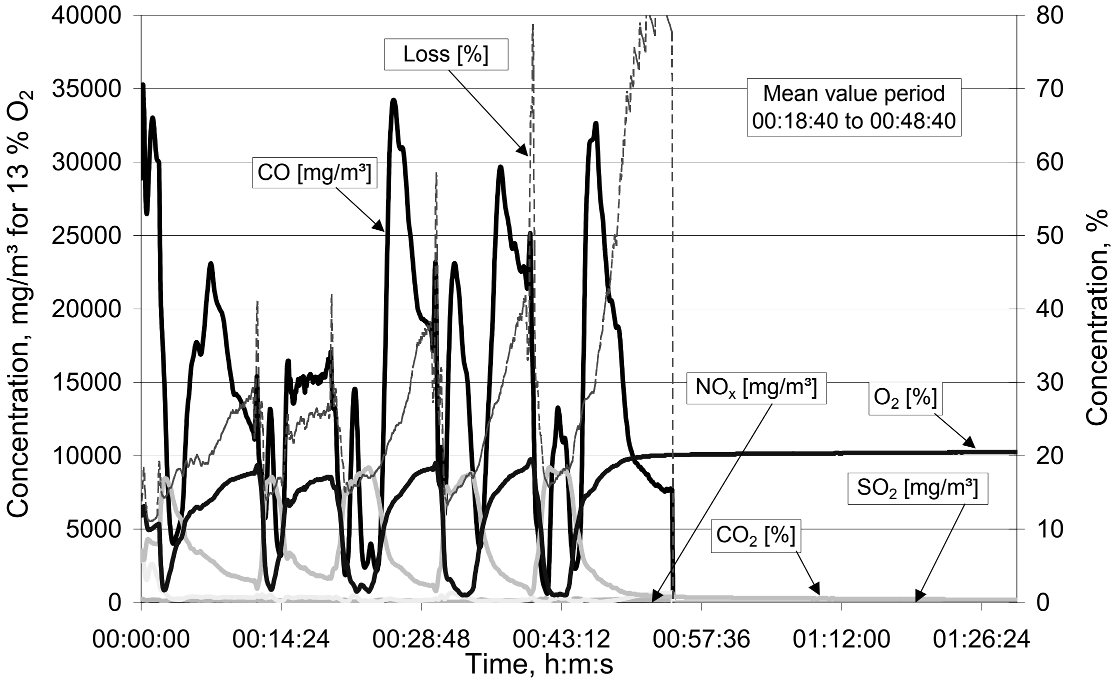


Fig. 6.19: Course of emissions during combustion of hemp shives

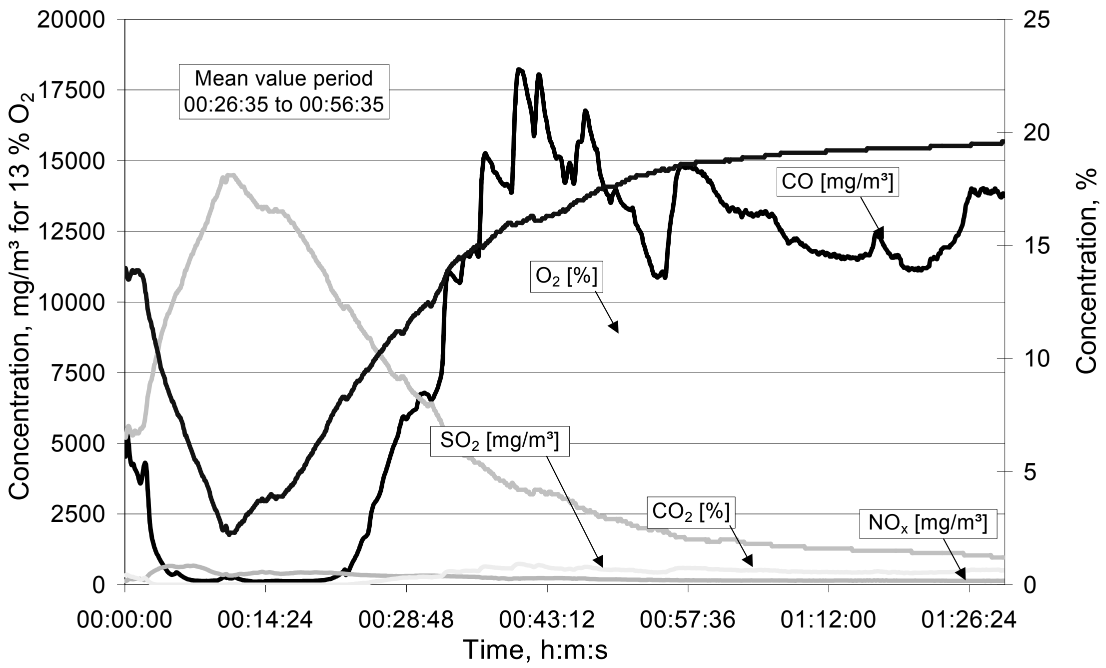


Fig. 6.20 : Course of emissions during combustion of hemp briquettes

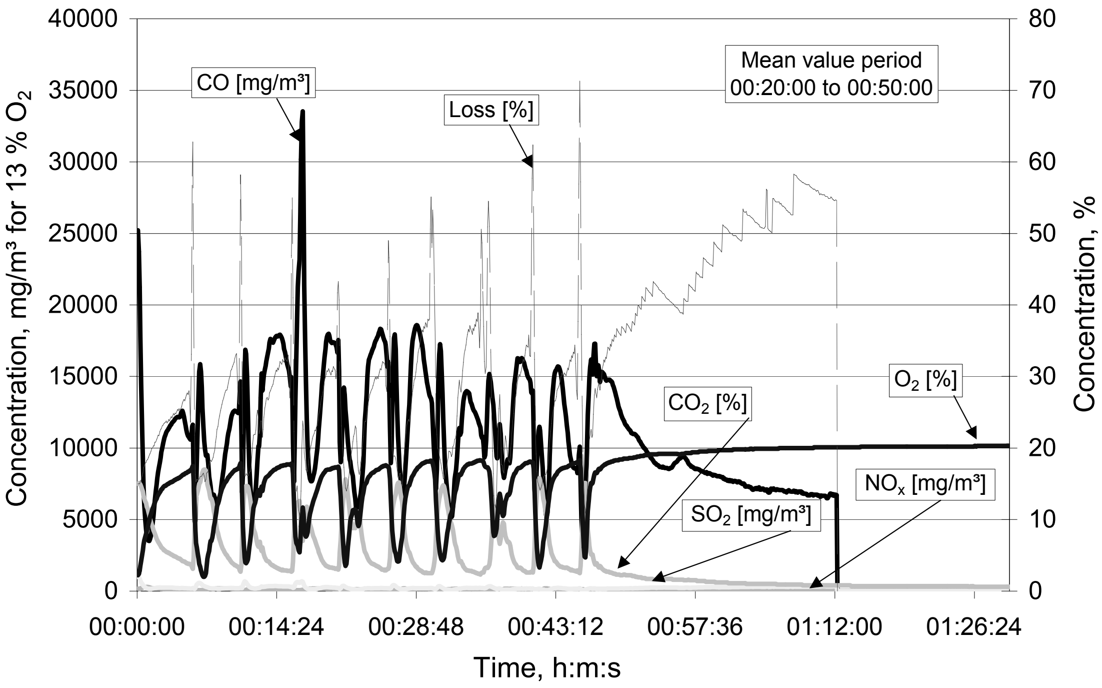


Fig. 6.21: Course of emissions during combustion of straw stalks

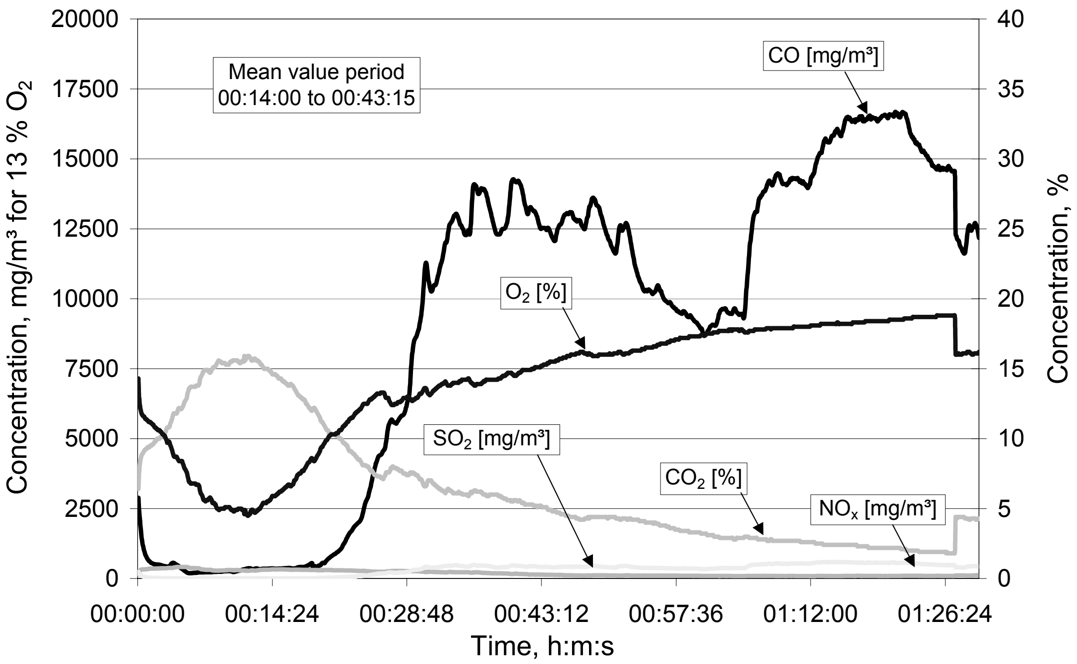


Fig. 6.22: Course of emissions during combustion of straw briquettes

Table 6.4: The results of the combustion experiments

Nr.	Fuel	Emissions and output				
		CO	NO_x	SO_2	Ash	Q_N
		mg/m^3	mg/m^3	mg/m^3	g	kW
1	Poplar branches	15304	171	446	268	24.7
2	Poplar briquettes	9943	211	395	276	24.9
3	Hemp stalks	15911	136	200	321	22.7
4	Hemp briquettes	12400	234	492	596	26.7
5	Straw stems	12444	125	176	290	18.4
6	Straw briquettes	7161	244	248	285	26.4

Table 6.5: Chemical analyses of the experimental materials

Parameter	Units	Analysis Values				Analysing Method
		Poplar wood	Hemp stalks	Rye straw	Cotton stalks	
Ash content, raw	%	1.7	2.5	2.1	4.8	DIN 51 719
Sulphur total, raw	%	0.1	0.1	0.2	0.2	Leco SC 432
Hydrogen, raw	%	5.8	5.7	5.1	4.8	SAA 162
Carbon, raw	%	49.6	45.1	44.5	41.5	SAA 162
Nitrogen, raw	%	0.6	0.7	0.7	0.9	SAA 162
Oxygen, raw	%	37.6	40.1	37.5	36.8	arithmetical
Chlorine, raw	mg/kg	60	300	400	4400	DIN 51 727
Volatiles, raw	%	78.8	74.3	70.3	65.9	DIN 51 720
Heating value, Hu	MJ/kg	19.38	18.6	17.5	18.26	Ebeling and Jenkins (1985), FNR (2000)

7 Discussion of the experimental results

7.1 Influence of material on density and stability of briquettes

The density and the radial compressive strength values of the briquettes depending on pressure and moisture content for various medium chopped materials are listed in Table 7.1. The materials were pressed mechanically in press Ø 30 mm at 10% moisture content. The influence of material on density and stability of briquette was studied on the basis of these data. When comparing the density values of the pressed materials at 140 MPa it was found that the materials have a limited effect on the density of briquettes. As shown in the table, the density values of poplar and cotton stalk briquettes are relatively higher than those of hemp and straw briquettes. When chopping cotton stalks it was found that the pressed materials contained fibres in a ratio of about 27% of the total weight. Hemp shives used in this work also have fibres in a ratio of about 10%. These fibres are more compressible than the woody particle of the other materials. As a result, the density values of the cotton stalk briquettes were higher than the relevant values for the hemp and straw briquettes. The density values of hemp briquettes also were higher than the density values of straw briquettes. This leads us to confirm that the pressed materials that contain fibres produce briquettes of high density values. Increasing the fibre percentage in these materials would increase the briquette density.

Table 7.1: Density and stability of briquettes depending on pressure and moisture content for various medium chopped materials and a stamp diameter of 30 mm

Moisture content %	Pressure MPa	Dry matter density, g/cm^3				Radial compressive strength, N/mm^2			
		Poplar	Hemp	Straw	Cotton stalks	Poplar	Hemp	Straw	Cotton stalks
10	14	-	0.42	0.41	0.51	-	0.09	0.04	-
	42	0.59	0.60	0.64	0.65	0.09	0.17	0.09	0.11
	70	0.72	0.73	0.73	0.72	0.16	0.25	0.17	0.21
	98	0.81	0.75	0.77	0.82	0.25	0.37	0.17	0.22
	126	0.88	0.79	0.82	0.90	0.37	0.46	0.20	0.30
	140	0.91	0.83	0.79	0.90	0.47	0.55	0.22	0.33

The woody particles of poplar are heavier than the hollow stems of straw and the fibres. This affects the briquette density positively, so that density values of poplar briquettes were higher than the others. Straw consists of hollow stalks. This means that the void ratio while pressing is higher than in the other materials. Straw also elongates after pressing and thus negatively affects its briquette density.

On the other hand there is an observable effect of the material on briquette stability measured as radial compressive strength. Generally, the woody materials have greater stability than straw. The lignin contained in all woody-cellulose materials begins to flow and acts as a natural glue to bind the compressed materials (FAO, 1990). The increase of lignin content in cotton stem (about 25.3%) compared with straw (about 18-19%) illustrates the high stability value of cotton briquettes.

7.2 Influence of pressure on density and stability of briquettes

The influence of pressure on the density and stability of briquettes was studied as shown in Figure 7.1. It is clear that there is a correlation between pressure and briquette density. As mentioned by Lindley and Vossoughi (1989), increasing the pressure up to 30 MPa leads to closely packed briquettes due to the plastic deformation of the particles. Furthermore, increasing the pressure leads to further compaction and reduction of the void ratio. Clauß (2002) stated that increasing the press pressure raises the briquette density and its stability As shown in Figure 7.1, increasing the pressure up to 70 MPa increases the briquette density digressively. In addition, increasing the pressure above 70 MPa for cotton, straw and hemp briquettes has a limited effect on density. The briquettes probably reach the plastic stage and resist further pressing. This agrees with Lindley and Vossoughi (1989). After 100 MPa, increasing the pressure increased the briquette density further. This increase is limited for straw and hemp. For cotton, there is an observable digressive increase. The results show also that increasing the moisture content to 15% decreases the briquette density. This leads us to conclude that 70 MPa can be the marginal pressure that produces a well-compacted briquette of cotton and straw, but pressed at 10% moisture content.

As a consequence, the influence of pressure on stability of briquettes was also studied as shown in Figure 7.2. It was found that there is also a correlation between the pressure and briquette stability measured as radial compressive strength of briquettes. For cotton and straw it was found that increasing the pressure up to 70 MPa tends to increase the radial compressive strength up to 70 MPa. From MPa to 100 MPa, the increase in pressure would have a very limited effect on the radial compressive strength.

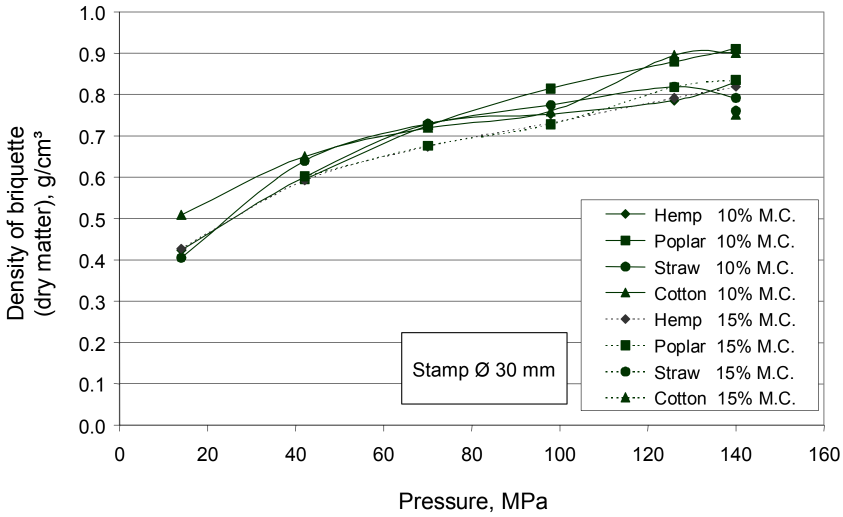


Fig. 7.1: Influence of the pressure on density of medium chopped materials

Increasing the pressure above 100 MPa would increase the radial compressive strength digressively again as presented by Lindley and Vossoughi (1989). For poplar and hemp there was always a digressive increase. This agreed with the results of the effect of pressure on density. This means that increasing the pressure would increase briquette density and its stability simultaneously, thus confirming that there is a correlation between briquette density and stability.

Generally, increasing the moisture content to 15% would also decrease the briquette stability. As shown in Figure 7.2, there is an observable reduction in the briquette stability for all the materials used according to the increase in the moisture content. It can be summarized that 70 MPa is the marginal pressure required to produce a stable briquette for cotton stalks and straw. The optimal moisture content in this case is 10%. Increasing the pressure above 70 MPa would increase the briquette density in a limited range, but would raise its stability.

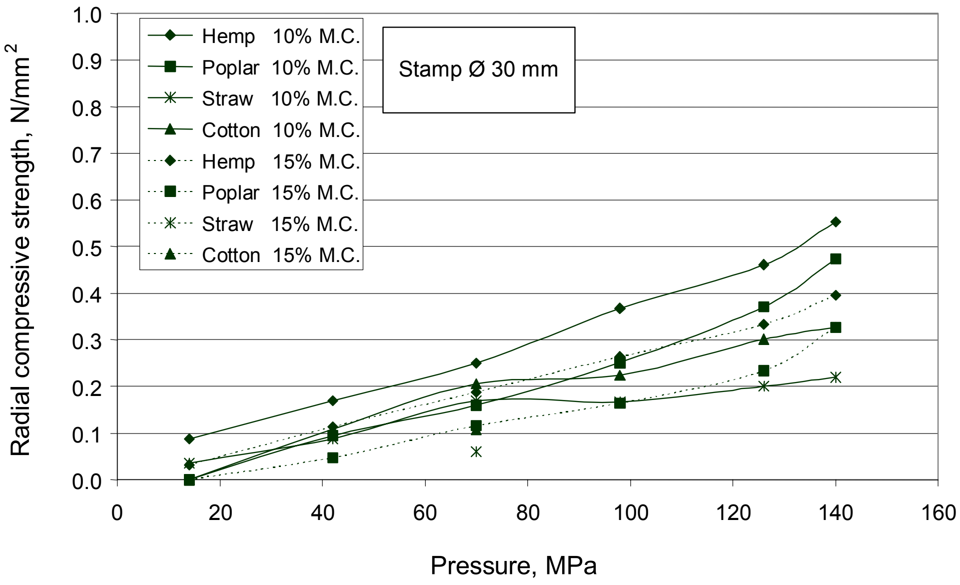


Fig. 7.2: Influence of the pressure on briquette stability

7.3 Influence of moisture on density and stability of briquettes

As reported by Lindley and Vossoughi, (1989) water is particularly suitable as an aid in briquetting. The moisture content is one of the parameters used to determine the quality of the briquette. They added that strength and density of the briquettes increase with increasing moisture content until an optimum level is reached.

The relationship investigated in this study between density of briquette and moisture content is shown in Figure 7.3. It was found that increasing the moisture content above 10% results in a decrease in the density of briquettes. This means that the briquette stability will also be reduced. It was also found that briquettes of 15 % and 20% moisture content were elongated and their volume increased directly after removing the pressure effect. This negatively affects the briquette density. Because the moisture works as a binding material, decreasing the moisture of the materials below a certain limit negatively affects the briquette stability. On the other hand, increasing the moisture over the suitable range also negatively affects the briquette stability. As presented in Figure 7.4, it is generally clear that 10% moisture content is the optimum moisture ratio to produce a stable briquette with the materials used. The high-density and more stable briquettes are produced at this moisture level.

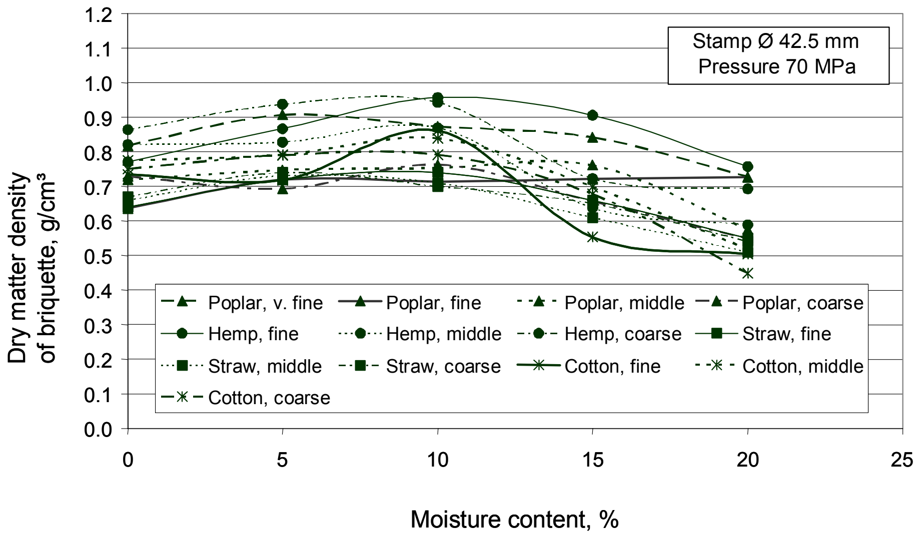


Fig. 7.3: Density of briquette versus moisture content

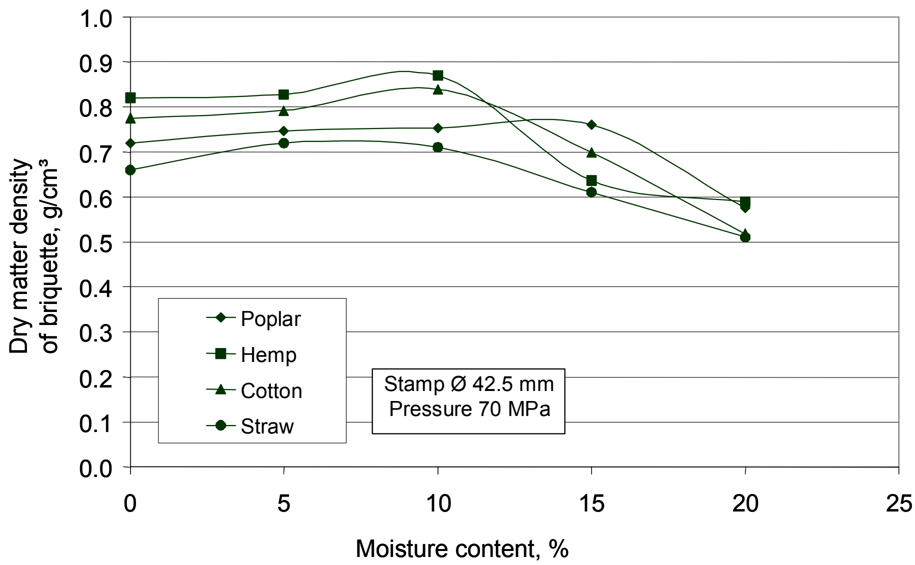


Fig. 7.4: Density of briquette versus moisture content for medium chopped materials

7.4 Influence of particle size on density and stability of briquettes

The influence of particle size on the briquette density and stability was investigated. Lindley and Vossoughi (1989) described the path of pressing operations and illustrated the role of particle size in this process. They mentioned that in briquetting without binding agents, when external compressive forces are applied and transmitted through the aggregate of the particles, a sequence of changes of the particles occurs. Under low pressure (< 1.4 MPa), the particles slide over each other into a tighter packing arrangement and void space between them decreases. With an increase in pressure (up to 30 MPa), closer packing of the particles can only be achieved by fracturing them into smaller particles and by plastic deformation. Further compaction and reduction of void space can then occur by plastic deformation of very small particles by increasing the press pressure over 30 MPa.

As shown in Figure 7.5, the small particle sizes (x50 < 3mm) are more able to fill the interval spaces of the briquettes and that leads to a decrease in briquette volume compared with similar briquettes of coarse particles that resist compression. Therefore this has a limited effect on the briquette density. Consequently the exchange in density values is quite low for the coarse particle size as shown in Figure 7.5.

According to the results for straw it was found that there was a limited effect of particle size on briquette density. Generally, it was observed that the briquette density of the small particles pressed in a press of diameter 42.5 mm was higher. The limited effect of the particle size on the briquette density also leads to a limited effect on the briquette stability for the range of particle sizes studied.

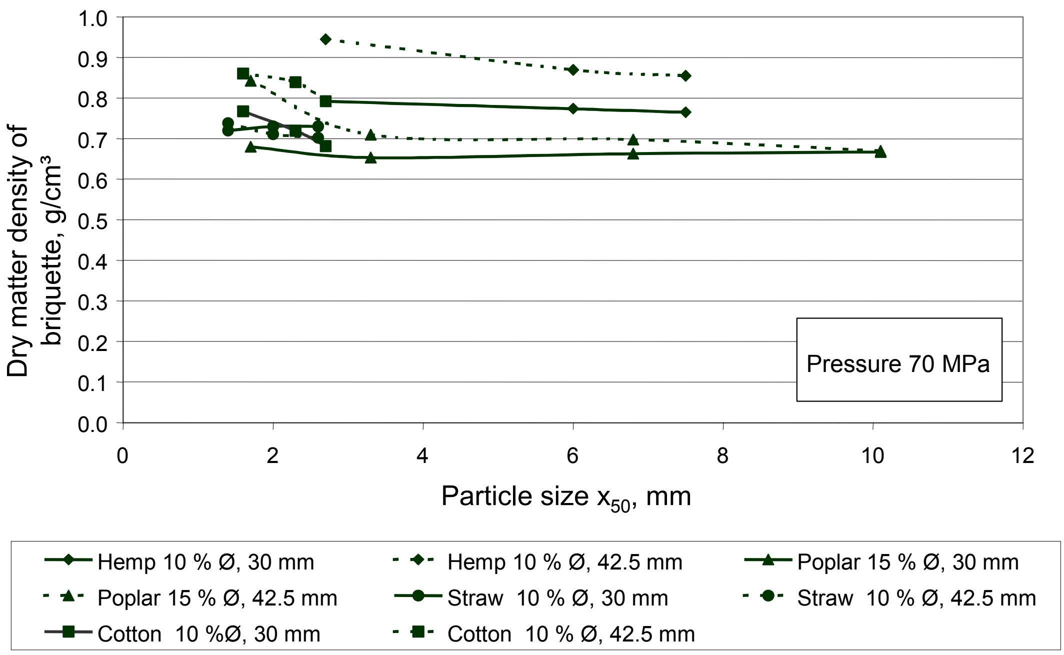


Fig. 7.5: Influence of particle size and stamp diameter on briquette density

7.5 Influence of press diameter on density and stability of briquettes

The influence of the press diameter on density depending on moisture content is presented in Figure 7.6. It was found that the press diameter has an observable influence on the briquette density. The press stamp of diameter 30 mm has a higher effect on the relation (surface area / volume) than a press stamp of diameter 42.5 mm. This means it has higher values of density and radial compressive strength. The major parts of the pressed materials are found in the outer surface. Because of the friction between these parts and the press wall, they are compacted more than the inner parts. In Figure 7.6 it is clear that the density values of the briquettes pressed in a press stamp of diameter 30 mm are higher than the values of poplar briquettes pressed in a press of diameter 42.5 mm. On the other hand, the density values of the hemp and straw briquettes pressed in a press stamp of diameter 42.5 mm are the highest in the maximum range of press pressure studied in a press of diameter 42.5 mm (70 MPa). These results may change if the curve is continued.

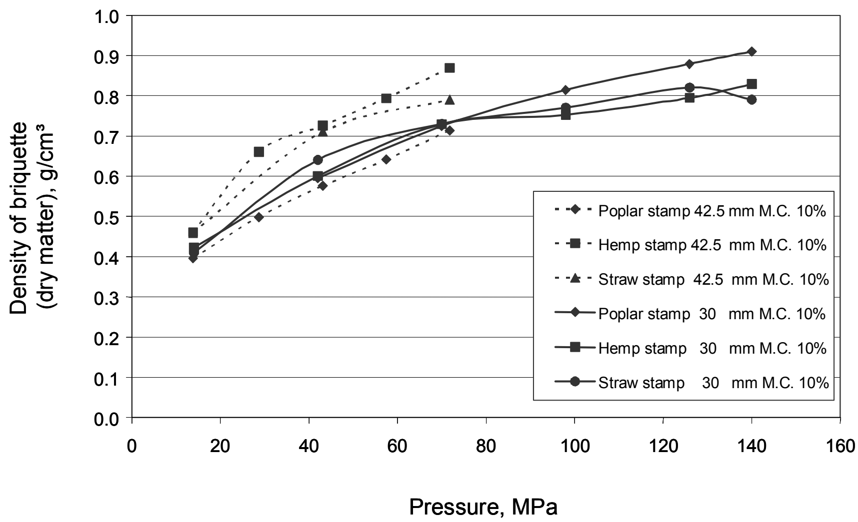


Fig. 7.6: Influence of the press diameter on briquette density of middle chopped materials

The influence of the press diameter on the stability of briquettes was also studied for the medium chopped hemp shives by way of example. The results presented in Figure 7.7 show that briquette stability (measured as radial compressive strength) increases with increasing briquetting pressure. Furthermore, they also show that the briquettes pressed in a press of diameter 30 mm are stronger than those pressed in a press of diameter 42.5 mm with the same moisture content. This confirms the effect of the relation (surface area / volume) illustrated above.

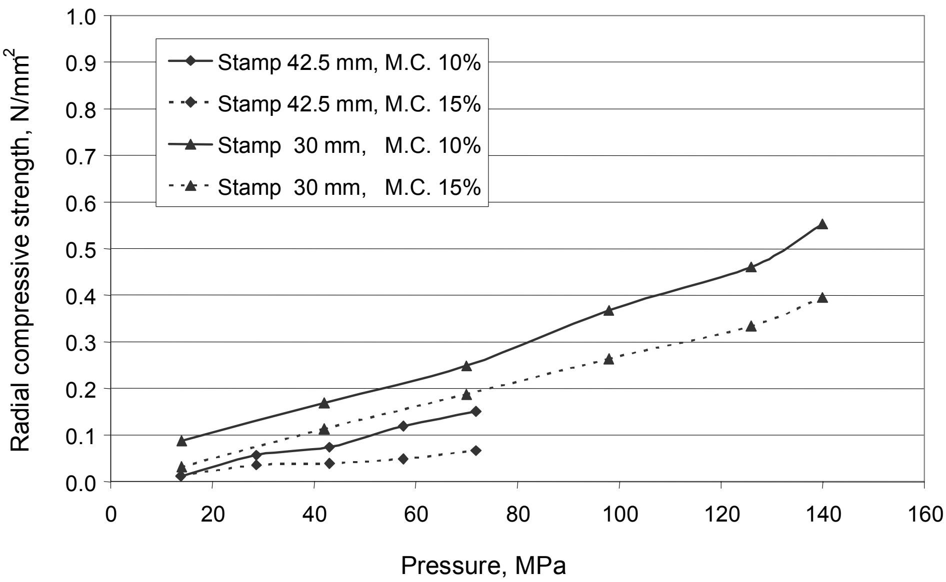


Fig. 7.7: Influence of the press diameter on briquette stability of middle chopped hemp

7.6 Comparison of experimental results with the theoretical model

It was found that the equation developed by Clauß (2002) is suitable for use in this work to compare the experimental results and the theoretical models. According to this equation (2.2), the theoretical diagrams increase digressively in the low press pressure range up to 70 MPa. Then increasing the pressure has a very limited effect on the briquette density until the end density (ρ_{max}) is reached as presented in Figure 7.8. This density is equal to the boundary density ρ_G. That means increasing the pressure will not increase the density of briquette. The diagram in this stage is flat.

These theoretical results agreed with the experimental results for poplar, hemp and straw particles pressed in a press diameter of 30 mm at 10% moisture content. It is clear from this figure that there is a limited difference between the experimental and the theoretical results. The experimental results increase following the same trend, and thus confirm the theoretical results of Clauß (2002).

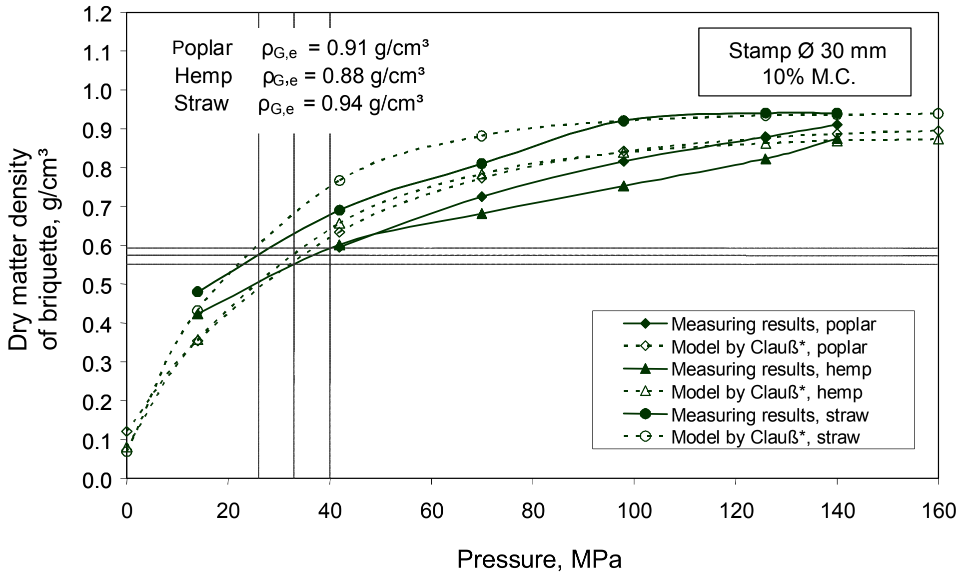


Fig. 7.8: Comparison of experimental and theoretical results for poplar, hemp and straw (10% moisture content)

8 Socio-economic assessments of briquetting cotton stalks

8.1 Introduction

An economic analysis was conducted in order to assess and compare the different alternative ways of producing energy sources. This assessment is important because from the farmer's perspective, the adoption of technologies for producing energy sources depends on their economic competitiveness compared with conventional energy sources.

A comparative cost-analysis approach was chosen to identify the competitiveness of energy carriers made of cotton stalk residues compared with traditional energy sources. The gross margins for each process were also calculated to determine the profits of potential alternatives. From these calculations, the specific energy costs were calculated and used as the main criteria for comparison. The specific energy costs determine the costs of producing one unit of energy (LE/kWh). The analysis compared the costs of the different alternatives to show which would have the lowest economic costs, but it also took into consideration the indirect costs such as the harmful impact of the worms on the harvest and ecological impacts.

8.2 Production lines

In order to perform the required economic analysis, a diagram showing the different energy production technologies was constructed (Figure 8.1). The diagram shows all possible alternatives and the processes involved in them. Four alternatives were chosen for study in this work. These are the most used in addition to the new technological alternatives, which are economically, ecologically, and environmentally friendly.

8.2.1 Stalk burning line

8.2.1-1 Collection of the stalks

After the harvest operation the farmers must prepare the fields very quickly for the next crop. As irrigation water is available all the year round, continuous cropping is practised, with an average of two crops per year. The farmers cut the stalks down (near the roots) using a small axe. Then they collect the stalks in piles on the field by hand. These stalks are transported for storage at the head of the field or on the roof of the farmer's house. They are used later as a domestic fuel for cooking and heating throughout the year.

Production Lines for the energetic use of cotton stalks

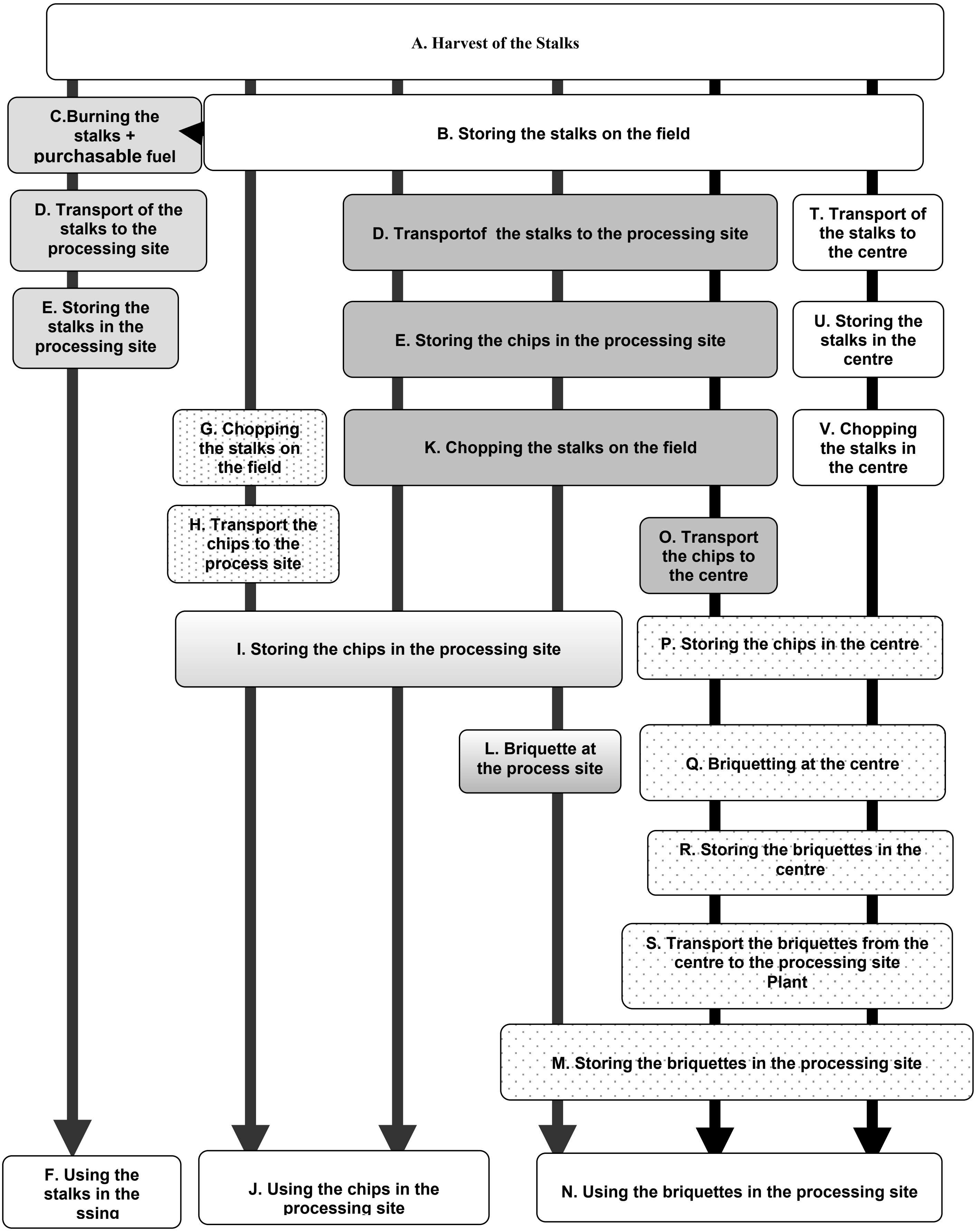


Fig. 8.1: Production lines for the energetic use of cotton stalks

8.2.1-2 Burning of the stalks

Because of the infestation by cotton worms, the stalks were to be burned immediately after the harvest operation according to a law issued by the Egyptian Ministry of Agriculture. The stalks were cut and collected in piles then; the farmer put some drops of kerosene on the pile and burns it with matches. This operation was usually done under supervision of the inspectors of the Ministry of Agriculture.

8.2.2 Stalk storing line

8.2.2-1 Collection of the stalks

See (8.2.1-1).

8.2.2-2 Transporting of the stalks

In former times farmer tied the piles after cutting and transporting them for storage and later use as fuel. Farmers used their own donkey or camel for this operation, renting or borrowing more animals if a huge amount had to be carried or if the field had to be prepared very quickly for the next crop. The stalks were transported to the head of the field, or to the farmer's house.

8.2.2-3 Storing of stalks

Farmers stored the stalks at the head of the field. The storage area was lost to the cultivated area. The other alternative was to transport these stalks and store them on the roof of the house. In both cases these methods of storage were harmful to the environment and human health, and represented an economic loss. Farmers carried out this operation with the help of their family or labourers.

8.2.3 Stalk chopping line

8.2.3-1 Collection of the stalks

See (8.2.1-1).

8.2.3-2 Transporting of the stalks

See (8.2.2-2).

8.2.3-3 Storing of the stalks

See (8.2.2-3).

8.2.3-4 Chopping the stalks

Such work must be performed on the field. It makes transporting of the chips easier and more economical. The machine recommended for this operation is a GSZ 242 produced by SÜDHARZER Maschinenbau (Germany). It is a mounted machine and is driven by the tractor P.T.O. It needs about 12 kW and cuts stems up to 12 cm thick. The chips are then transported and stored for subsequent use as explained in 6.2.2-2 and 6.2.2-3.

8.2.4 Stalk briquetting line

8.2.4-1 Collection of the stalks

See (8.2.1-1).

8.2.4-2 Transporting of the stalks

See (8.2.2-2).

8.2.4-3 Storing of the stalks

See (8.2.2-3).

8.2.4-4 Chopping the stalks

See (8.2.3-4).

8.2.4-5 Briquetting

This operation is the technologically, ecologically and environmentally friendly alternative compared with the other methods of handling cotton stalks. It depends on the use of a mobile hydraulic press machine. This machine is mounted on the tractor. It takes its power from the tractor P.T.O. and the hydraulic system and is preferably operated by the same tractor as the chopping machine. KAHL (Germany) has developed another type of briquetting machine. Depending on the type, briquette diameter, and throughput, the machine needs from 3 to 400 kW power. This machine may be expensive for the farmer, but he can rent it from the machine station.

To collect the empirical data, structured questionnaires were used (see Appendix). The questionnaires employed for the survey have been summarized (see Appendix). The survey was conducted in Egypt. During the survey, the farmers responsible for handling the cotton stalks were the key informants.

For data entry and management, a data bank containing all the information gathered from the interviews was constructed using MS Excel software. The databank was tested and verified to eliminate all errors. This was done by comparing the information entered into the databank with the information in the questionnaires. All other statistical analyses and calculations were also made using the same software.

8.3 Costs

As shown in Figure 8.1 there are several production lines that could be used in order to handle the cotton stalks and produce energy resources. The most potential and important alternatives were chosen for the comparative cost analysis. These alternatives are:

8.3.1 Stalk burning line

This line was chosen because it was the official process used in Egypt, but now it is still used illegal. The Egyptian Ministry of Agriculture prefers this line as it ensures complete destruction of the harmful cotton worms, their eggs and larvae from the last season. This process involves only collection of the stalks from the fields, followed by storing on the field until the time of burning. This operation is also carried out on the field without transportation anywhere else. The cotton stalks are collected in piles on the field by hired labourers and burned. This operation takes about 72 man-hours/feddan. The labour costs 12 LE/day (1.5 LE/hour). The gross margin is –138.00 LE/fe because the production value of this alternative is zero, as it involves no production. The specific energy costs with this alternative are 0.058 LE/kWh. This method prevents the farmer from tapping a free source of energy (about 7500 kWh/fe). As a consequence, the farmer must buy substitute energy from a fossil fuel source.

8.3.2 Stalk storing line

This line is the most favourable for the farmers as it provides a free source of domestic fuel that the farmer's family can use for domestic purposes. It involves the collection of the stalks and transport for storage on the field or on the house roof for later use as a fuel. The farmer's house is usually not far from his field. The maximum distance is about 2 km. This line requires about 20 man-hours/feddan and about 9 m^3 to store the stalks of one feddan. The costs of this operation are about 20-30 LE/feddan. The stalks can also be transported to the operating place by farm animals such as donkeys and camels, which may be owned, borrowed or rented by the farmer. This will then cost 10 LE/day (8 hours).

Storing of the stalks on the field also means a high capital demand. It involves the collection of the stalks, transport, and storage of these stalks. The gross margin is positive (62.87 LE/fe) as the stalks are used for the energy demand of the farmer's family. The specific energy cost is 0.031 LE/kWh. It is the lowest of all.

8.3.3 Stalk chopping line

This line was chosen because it is one of the best alternatives that could reduce the harmful impacts of the worms. It involves the collection of the stalks from the fields, followed by storage on the field. This is followed by chopping these stalks into small chips and then transporting and storing them for subsequent use. The stalks can be chopped by a chopping machine as presented in 6.2.3-4. This costs 10 LE/hour. This operation also takes 9 man-hours/feddan, i.e. three hired labourers for 3 hours per feddan. The total costs of this operation are about 45 LE. After the cutting operation, the farm animals transport the product to the operating place. This operation also takes about 15 hours per feddan. The calculated specific energy cost in this case is 0.045 LE/kWh. The chopping line has a high capital demand compared with other lines in this alternative, as it involves the chopping of the stalks as well as the transport and storage of the chips. The gross margin is still a minus figure (-17.63 LE/fe), but it is higher than that for burning because the chips produced can be used as fuel or an energy resource in the household or for other purposes. The specific energy cost is 0.045 LE/kWh. It is lower than for the burning of the stalks.

8.3.4 Stalk briquetting line

This is one of environmentally and ecologically favoured alternatives, as it will provide many benefits. It will ensure the complete destruction of the worms and provide an environmentally friendly energy resource that can be used by the farmer and his family. It involves the collection of stalks from the fields, followed by storage on the field. This is followed by chopping and briquetting. The briquettes are then transported and stored for subsequent use. The stalks are cut manually and collected by hired labourers, then transported for cutting and pressing. The processed briquettes are transported to the farmer's house, where they can be used as an energy source for domestic purposes. The costs of the different operations such as stalk collection, storage, or transportation are similar to those in the former alternatives. The additional costs here are due to briquetting, which is preferably done by a mounted hydraulic press machine driven by the P.T.O. and the hydraulic system of the tractor. That means this operation is carried out directly on the field. The briquetting line with chopping of the stalks has the highest capital demand compared with other operations. The gross margin is higher than for burning, but still lower than for chopping. The specific energy cost is the highest at 0.062 LE/kWh. It is higher than other lines because it involves the additional operation of briquetting, which requires additional costs.

The costs of each step in these chosen lines are calculated to enable a comparison between them. The results are described in Tables 8.1, 8.2, 8.3, and 8.4. For each alternative, Figure 8.2 is constructed to illustrate the costs of each operating step.

8.4 Discussion of costs

As shown in the tables 6.2.1, 6.2.2, 6.2.3 and 6.2.4, it is clear that the lines with more processes display more costs because they involve more processes that require additional capital. Therefore briquetting of the stalks shows the highest costs as it involves the highest number of processes and modern technology. Its specific energy costs (LE/kWh) were only 5 % higher than the burning line including the costs of the purchasable fuel. It is also 35% higher in its specific energy costs than chopping line and double the costs of the storing line.

Economically briquetting is the most costly line, but considering the agronomic and ecological benefits that can be gained it is preferred to the chopping alternatives because it allows for complete destruction of the harmful worms. This will reduce the costs of pest control measures and increase the yield as well. It is much preferred to burning, as it allows the reduction of smoke pollution, one of the main causes of the formation of black clouds over Cairo in the autumn. The difference between the costs of the kerosene and the briquettes produced is also small and could be made even smaller by adopting more cost-effective machines and processes in the production of these briquettes.

Compared with stalk burning, the specific energy cost of briquetting is the highest. Both of these methods are suitable for eliminating the harmful cotton worms. Briquetting costs are high because of using the machine in these processes. These machines are usually imported and thus increase the costs. If these machines were collected or manufactured in Egypt, that would certainly reduce the costs of briquetting and make this the more useful and cheaper process. Labour in Egypt is cheap. Figure 8.2 and Figure 8.3 illustrates the costs of various production lines for the utilization of cotton stalks in Egypt.

Generally, for all lines, the most labour-intensive processes are the collection of the stalks from the field, transportation, and storage. Other processes require lower labour because they depend more on machines. As for the capital demand, chopping and briquetting have the highest capital demand.

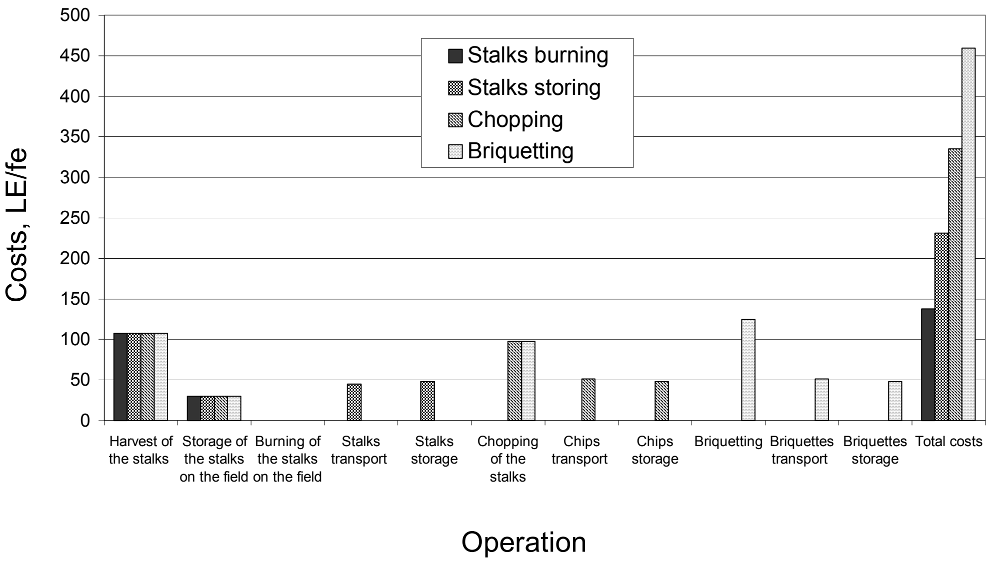


Fig. 8.2 : Costs of each process step of the production lines analysed

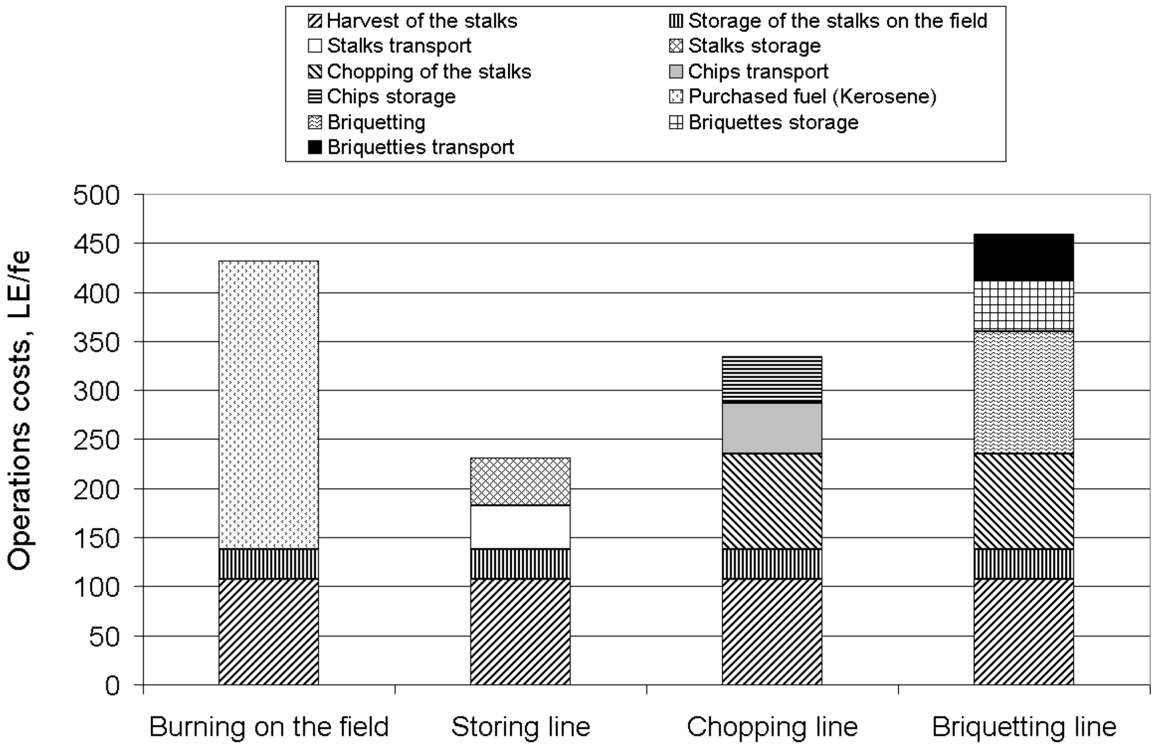


Fig. 8.3 : The costs of various production lines for the utilization of cotton stalks in Egypt

Table 8.1: Burning line (1)

Gross margin			
Process steps	Unit	Amount	%
Collection of the stalks	LE/fe	108.00	82%
Storage of the stalks on the field	LE/fe	30.00	18%
Burning of the stalks on the field	LE/fe	0.00	0%
Total variable costs	LE/fe	138.00	100%
Production value	LE/fe	0.00	
Gross margin	LE/fe	-138.00	
Labour productivity	LE/h	-1.50	
Land productivity	LE/fe	-138.00	
Capital productivity	LE/LE	-	
Total costs per feddan			
Process steps	Unit	Amount	%
Collection of the stalks	LE/fe	108.00	82%
Storage of the stalks on the field	LE/fe	30.00	18%
Burning of the stalks on the field	LE/fe	0.00	0%
Total costs	LE/fe	138.00	100%
Energy content of stalks	kWh/fe	7500	
Energy costs of fossil fuel	LE/kWh	0-04	
Substitute costs of fossil fuel	LE/fe	293.87	
Total costs (including the purchasable fuel)	LE/fe	431.87	
Specific energy costs	LE/kWh	0.058	
Specific energy costs	€/kWh	0.008	
Total costs per ton (DM)			
Process steps	Unit	Amount	%
Collection of the stalks	LE/t	72.00	78%
Storage of the stalks on the field	LE/t	20.00	22%
Burning of the stalks on the field	LE/t	0.00	0%
Total costs	LE/t	92.00	100%
Energy content of the stalks	kWh/t	5000	
Energy costs of fossil fuel	LE/kWh	0.04	
Substitute costs of fossil fuel	LE/t	195.91	
Total costs (including the purchasable fuel)	LE/t	287.91	
Specific energy costs	LE/kWh	0.058	
Specific energy costs	€/kWh	0.008	

Table 8.2: Stalks storing line (2)

Gross margin			
Process steps	Unit	Amount	%
Collection of the stalks	LE/fe	108.00	47%
Storage of the stalks on the field	LE/fe	30.00	13%
Stalk transport	LE/fe	45.00	19%
Stalk storage	LE/fe	48.00	21%
Total variable costs	LE/fe	231.00	100%
Stalk storage	t/fe	1.50	
Energy content of the stalks	kWh/t	5000	
Specific energy price	LE/kWh	0.039	
Production value	LE/fe	293.87	
Gross margin	LE/fe	62.87	
Labour productivity	LE/h	0.41	
Land productivity	LE/fe	62.87	
Capital productivity	LE/LE	-	
Total costs per feddan			
Process steps	Unit	Amount	%
Collection of the stalks	LE/fe	108.00	47%
Storage of the stalks on the field	LE/fe	30.00	13%
Stalk transport	LE/fe	45.00	19%
Stalk storage	LE/fe	48.00	21%
Total costs	LE/fe	231	100%
Energy content of the stalks	kWh/fe	7500	
Specific energy costs	LE/kWh	0.031	
Specific energy costs	€/kWh	0.004	
Total costs per ton (DM)			
Process steps	Unit	Amount	%
Collection of the stalks	LE/t	72.00	47%
Storage of the stalks on the field	LE/t	20.00	13%
Stalk transport	LE/t	30.00	19%
Stalk storage	LE/t	32.00	21%
Total costs	LE/t	154.00	100%
Energy content of the stalks	kWh/t	5000	
Specific energy costs	LE/kWh	0.031	
Specific energy costs	€/kWh	0.004	

Table 8.3: Chopping line (3)

Gross margin			
Process steps	Unit	Amount	%
Collection of the stalks	LE/fe	108.00	35%
Storage of the stalks on the field	LE/fe	30.00	10%
Chopping of the stalks	LE/fe	74.00	24%
Chip transport	LE/fe	51.50	17%
Chip storage	LE/fe	48.00	15%
Total variable costs	LE/fe	331.50	100%
Chips yield	t/fe	1.50	
Energy content of the chips	kWh/t	5000	
Specific energy price	LE/kWh	0.039	
Production value	LE/fe	293.87	
Gross margin	LE/fe	-17.63	
Labour productivity	LE/h	-0.11	
Land productivity	LE/fe	-17.63	
Capital productivity	LE/LE	-0.25	
Total costs per feddan			
Process steps	Unit	Amount	%
Collection of the stalks	LE/fe	108.00	32%
Storage of the stalks on the field	LE/fe	30.00	9%
Chopping of the stalks	LE/fe	97.50	29%
Chip transport	LE/fe	51.50	15%
Chip storage	LE/fe	48.00	14%
Total costs	LE/fe	335	100%
Energy content of the chips	kWh/fe	7500	
Specific energy costs	LE/kWh	0.045	
Specific energy costs	€/kWh	0.006	
Total costs per ton (DM)			
Process steps	Unit	Amount	%
Collection of the stalks	LE/t	72.00	32%
Storage of the stalks on the field	LE/t	20.00	9%
Chopping of the stalks	LE/t	65.00	29%
Chip transport	LE/t	34.33	15%
Chip storage	LE/t	32.00	14%
Total costs	LE/t	233.30	100%
Energy content of the chips	kWh/t	5000	
Specific energy costs	LE/kWh	0.045	
Specific energy costs	€/kWh	0.006	

Table 8.4: Briquetting line (4)

Gross margin			
Process steps	Unit	Amount	%
Collection of the stalks	LE/fe	108.00	30%
Storage of the stalks on the field	LE/fe	30.00	8%
Chopping of the stalks	LE/fe	74.00	20%
Briquetting	LE/fe	51.47	14%
Briquette transport	LE/fe	51.50	14%
Briquette storage	LE/fe	48.00	13%
Total variable costs	LE/fe	362.97	100%
Briquettes yield	t/fe	1.50	
Energy content of the Briquettes	kWh/t	5000	
Specific energy price	LE/kWh	0.039	
Production value	LE/fe	293.87	
Gross margin	LE/fe	-69.10	
Labour productivity	LE/h	-0.36	
Land productivity	LE/fe	-69.10	
Capital productivity	LE/LE	-0.48	
Total costs per feddan			
Process steps	Unit	Amount	%
Collection of the stalks	LE/fe	108.00	24%
Storage of the stalks on the field	LE/fe	30.00	7%
Chopping of the stalks	LE/fe	97.50	21%
Briquetting	LE/fe	124.38	27%
Briquette transport	LE/fe	51.50	11%
Briquette storage	LE/fe	48.00	10%
Total costs	LE/fe	459.38	100%
Energy content of the Briquettes	kWh/fe	7500	
Specific energy costs	LE/kWh	0.061	
Specific energy costs	€/kWh	0.009	
Total costs per ton (DM)			
Process steps	Unit	Amount	%
Collection of the stalks	LE/t	72.00	23%
Storage of the stalks on the field	LE/t	20.00	6%
Chopping of the stalks	LE/t	66.67	22%
Briquetting	LE/t	82.92	27%
Briquette transport	LE/t	34.33	11%
Briquette storage	LE/t	32.00	10%
Total costs	LE/t	307.92	100%
Energy content of the Briquettes	kWh/t	5000	
Specific energy costs	LE/kWh	0.062	
Specific energy costs	€/kWh	0.009	

9 Conclusions

The experimental materials used in this work, poplar, hemp, straw and cotton stalks, are suitable for briquetting. These materials belong to biomass so that their press characteristics are similar. The density-pressure function and stability-pressure function are also similar.

There is a correlation between the pressure and the briquette density. There is also a correlation between the pressure and the radial compressive strength of the briquette. Increasing the pressure will increase the briquette density digressively and its radial compressive strength progressively. Stable briquettes (radial compressive strength $\geq$ 0.25 N/mm^2 and dry matter density $\geq$ 0.8 g/cm^2) can be produced with pressure $\geq$70 MPa depending on the material, particle size, moisture content and press diameter. The theoretical model developed by Clauß (2002) for computing the density as a function of pressure agrees well with the values measured in this work.

The dry matter density and the radial compressive strength generally increase with the increase in moisture content of the material. Increasing the moisture content to more than 10% will decrease the density values. The optimal moisture content for briquetting ranges between 8-15%. Cotton stalks in Egypt reach this range of moisture content after one-week of field storage in October (harvest month). Cotton stalks lose more than 80% of their initial moisture content in this period. This implies that these residues can be briquetted directly on the field one week after the harvest operation by a suitable type of briquetting machine without incurring any additional costs for drying. Generally, briquettes pressed at 10% moisture content were more stable compared with others pressed at 15%.

There is a limited effect of particle size on the briquette density for the particles sizes studied. However, small particles (x_{50} < 3 mm) produce briquettes of a higher density than coarser particles (x_{50} > 3 mm). The small particle sizes are able to fill the voids in the briquettes and this leads to an increase in briquette density compared with similar briquettes made of coarse particles.

The dry matter density and the radial compressive strength of the cylindrical briquettes have a close correlation. The density is considered as dry matter because the moisture does not have any influence on this connection. Increasing the pressure increases the briquette density and as a consequence the briquette durability also increases. Increasing the pressure up to 70 to 100 MPa for cotton and straw briquettes will not affect the density. The processed materials then reach the plastic stage and resist pressing. Above 100 MPa, increasing the pressure will increase the briquette density again.

The temperature has a major influence on the elimination of the Pink Bollworm. In order to kill these worms and their eggs or larvae, a temperature of 70 °C is required for at least 2 minutes. Fifteen minutes are required to kill the worms when the temperature is reduced to 60 °C. As Scholz and Fürll (1978) proved, pellets from fibrous materials can reach these temperatures in a cog-wheel pellet press (ΔT = 40 - 60 K). According to the measurements, briquettes from slow-running piston press machines do not reach this temperature ($\Delta T \approx 10$ K). In this case, the briquettes should be heated by heating and/or extending the press channel.

If briquettes of diameter 42.5 mm are warmed up after pressing, temperatures of 70 °C to 105 °C and heating times from 20 minutes to about 2 hours are required in order to reach 60 °C in the centre of the briquette. This is necessary to kill any worms and their eggs or larvae that may be found in the centre of the briquette. Temperatures above 105 °C should be avoided because the volatile components escape and a loss of dry matter will occur.

The experimental materials including cotton stalks are well suited for combustion. The ecologically and firing-relevant material content, the ash content and the heating value lie within the ranges of usual solid biofuels (volatile components: 66-75%; sulphur: 0.1-0.25; nitrogen: 0.6-0.9%; chlorine; 60-4400 mg/kg; ash 1.7-4.8%; lower heating value: 17.5 -19.4 MJ/kg). The high value of the chlorine (4400 mg/kg) and ash content (4.8%) of the cotton stalks lies within the range of non-woody biofuels.

Combustion experiments show that the combustion of briquettes is more regular than the combustion of loose materials. This is because of the high density of the briquettes. Therefore the thermal output of a combustion boiler with briquettes increases and the carbon monoxide (CO) value decreases by 30% compared with the value for the loose materials of poplar, hemp, and straw. The sulphur dioxide emissions ($SO4$) are also within the values limited by the German pollution control regulation TA-Luft.

The economic evaluation indicates that briquetting of cotton stalks is costly, but economically competitive compared with the use of kerosene as an energy source in households. Briquetting of cotton stalks costs 0.061 LE per kWh and thus only 5% more than the environmentally unfriendly process of burning cotton stalks on the field including the purchasable fuel. The use of unprocessed cotton stalks as a domestic fuel has an economic advantage, but it is ecologically undesired. The higher costs of briquetting cotton stalks (5%) will be more than returned to the farmer in the form of a clean environment. In addition, the extermination of the cotton pink bollworm through briquetting will increase the crop production by about 20%. This was the amount of losses because of this worm.

It can be stated that stable briquettes without binding material can be produced from cotton stalks and the other experimental materials. This depends on the material, sufficient pressure, and a suitable moisture content. This means the application of briquette technology can solve the phytosanitary, environmental and storage problems of cotton stalks. The dilemma of contradictory laws for the disposal of cotton stalks in Egypt would be overcome. The farmer's household could cover its need for fossil fuels for cooking and baking by using a renewable energy source.

Further investigations should be directed towards developing a suitable adapted technology for briquetting cotton stalks in Egypt. Attention should also be paid to verifying the testing methods, as well as to the influence of the press on the mortality of cotton worms, their eggs and larvae.

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Summary

From the ancient civilization of Egypt up to the present, Egyptian farmers have been cultivating cotton crops in the Nile Valley and in the Nile Delta. After the harvest operation, the cotton crop residues comprising cotton stalks are collected and transported for storage on the fields and the roofs of houses. In former times the farmer's family used these residues throughout the year as a domestic energy resource for the traditional mud oven for cooking and baking.

These residues are an overwintering site for insects such as the pink bollworm. This worm attacks the cotton and nearby crops causing serious economic losses due to quantitative and qualitative crop damage affecting about 20% of the crop per year. This infestation by the harmful insects must be stopped. Because of this, the Ministry of Agriculture in Egypt obligated the farmers to burn the cotton residues on the fields immediately after the harvest operations. This resulted in huge emissions of harmful gases in rural areas, which also affected the nearby urban centres including Cairo. As a counter measure, the Ministry of the Environment issued a law forbidding the farmers to burn the residues. This confusion in laws has led to illegal burning and storage of these residues.

A new technology for handling cotton stalks in Egypt is required as a solution for this problem. Briquettes appear to be an advantageous solution for handling cotton stalk residues. Through this process an easily storable, pest-controlled and environmentally friendly biofuel can be produced. It serves as a complementary domestic biofuel and reduces the dependency of the farmer's family on fossil fuels. These investigations were carried out to clarify the fundamentals for such a technology.

Because their properties are similar to those of cotton stalks, poplar branches, hemp shives and rye straw were used as substitute materials. These materials were pressed in a mechanical laboratory press machine. Three cylindrical stamps with diameters of 30, 42.5, and 60 mm were used to press the materials. Five different moisture contents of about 0%, 5%, 10%, 15%, and 20% were chosen to press these materials. The materials used were also pressed in a commercial press machine to study the features in this type of machines.

The briquette density was measured, its stability was examined, and its durability was also tested. The materials used were also burned and analysed chemically in order to evaluate their use as environmentally friendly fuel.

The results show that there is a correlation between the pressure and the briquette density. There is also a correlation between the pressure and the radial compressive strength of the briquette.

Particle size has a limited effect on the briquette density. Small particles (x_{50} < 3 mm) produce briquettes of a higher density than coarser particles.

The optimal moisture content for briquetting the used materials is about 10%. Cotton stalks in Egypt reach this range of moisture content after one-week field storage in October (harvest month). This means that these residues can briquetted directly on the field one week after the harvest by a suitable type of briquetting machine without incurring any additional costs for drying.

The temperature has a major influence on the elimination of the Pink Bollworm. 70 °C for at least 2 minutes is required in order to kill these worms and their eggs or larvae. Decreasing the temperature will increase the time needed for this process.

The experimental materials including cotton stalks are well suited for combustion. The ecologically and firing-relevant material content, the ash content and the heating values lie within the ranges of usual solid biofuels. The combustion of briquettes is more regular than the combustion of loose materials. This is because of the high density of the briquettes.

Briquetting of cotton stalks is 5% more costly, than the use of kerosene as an energy sources in households. These higher costs of briquetting cotton stalks (5%) will be more than returned to the farmer the form of a clean environment. In addition, the extermination of the cotton pink bollworm through briquetting will increase the crop production by about 20%. This is equivalent to the losses because of this worm.

It can be stated that stable briquettes without binding materials can be produced from cotton stalks in Egypt depending on the material, sufficient pressure, and suitable moisture content. This application of briquette technology can solve the phytosanitary, environmental and storage problems of cotton stalks. The confusion in cotton stalk disposal laws in Egypt would also be overcome. Then farmers' households could cover their needs for fossil fuels for cooking and baking by using a renewable and environmentally friendly source of energy.

Appendix

Appendix 1

Example of a measuring record

Experimental results of briquetting - Measuring protocol									
Press: Lab press with dim. 42,5 mm, length 400 mm									
Experimental material: Hanf, middle									
Exp. No.	Moisture content	Force	Briquette mass o	Briquette length o	Briquette density	Bulk density	Briquette length 1	Radial stability	Compr. ratio
	%	kp	g	mm	g/cm³	g/cm³	mm	N/mm³	%
1a	0	2000							
1b	0								
1c	0								
2a	0	4000							
2b	0								
2c	0								
3a	0	6000							
3b	0								
3c	0								
4a	0	8000							
4b	0								
4c	0								
5a	0	10000							
5b	0								
5c	0								
6a	5	2000							
6b	5								
6c	5								
7a	5	4000							
7b	5								
7c	5								
8a	5	6000							
8b	5								
8c	5								
9a	5	8000							
9b	5								
9c	5								
10a	5	10000							
10b	5								
10c	5								
11a	10	2000							
11b	10								
11c	10								
12a	10	4000							
12b	10								
12c	10								
13a	10	6000							
13b	10								
13c	10								
14a	10	8000							
14b	10								
14c	10								
15a	10	10000							
15b	10								
15c	10								

Experimental results of briquetting - Measuring protocol									
Press: Lab press with dim. 42,5 mm, length 400 mm									
Experimental material: Hanf, middle									
Exp. No.	Moisture content	Foace	Briquette mass o	Briquette length o	Briquette density	Bulk density	Briquette length 1	Radial stability	Compr. ratio
	%	kp	g	mm	g/cm³	g/cm³	mm	N/mm³	%
1a	15	2000							
1b	15								
1c	15								
2a	15	4000							
2b	15								
2c	15								
3a	15	6000							
3b	15								
3c	15								
4a	15	8000							
4b	15								
4c	15								
5a	15	10000							
5b	15								
5c	15								
6a	20	2000							
6b	20								
6c	20								
7a	20	4000							
7b	20								
7c	20								
8a	20	6000							
8b	20								
8c	20								
9a	20	8000							
9b	20								
9c	20								
10a	20	10000							
10b	20								
10c	20								

Appendix 2

Abstract of the questionnaire used for

The Economic Evaluation of the Energetic Use of Cotton Stalks in Egypt

A. Cotton stalks harvest

1. Methods used for harvesting cotton stalks (manual and mechanic)
2. Labour requirements, organisation and costs
3. Machine requirements and costs
4. Total costs for harvesting cotton stalks

B. Field storage of cotton stalks

1. Methods used for storing the cotton stalks on the field (time, place, size, duration)
2. Labour requirements, organisation and costs
3. Machine requirements and costs
4. Total costs for storing the cotton stalks on the field

C. Burning the stalks on the field

1. Methods used for burning the stalks on the field
2. Costs of alternative fossil fuel purchase
3. Labour requirements, organisation and costs

D. Transport of cotton stalks from the fields to processing site

1. Methods used for transporting cotton stalks (manual and mechanic)
2. Labour requirements, organisation and costs
3. Machine requirements and costs
4. Total costs for transporting cotton stalks from the fields to the processing site

E. Storage of cotton stalks

1. Methods used for storing cotton stalks (time, place, size, duration)
2. Labour requirements, organisation and costs
3. Machine, equipment and building requirements and costs
4. Total costs for storing cotton stalks

F. Energetic use of unprocessed cotton stalks

1. Methods for using unprocessed cotton stalks for energy supply (efficiencies)
2. Machine, equipment and building requirements and costs
3. Total costs for using unprocessed cotton stalks for energy supply

G. Chopping of cotton stalks on the fields

1. Methods used for chopping cotton stalks on the fields (manual and mechanic)
2. Labour requirements, organisation and costs
3. Machine and energy requirements and costs
4. Total costs for chopping cotton stalks on the fields

H. Transport of chips from the field to processing site

1. Methods used for transporting chips from the fields to the processing site (manual and mechanic)
2. Labour requirements, organisation and costs
3. Machine requirements and costs
4. Total costs for transporting chips from the fields to the processing site

I. Storage of chopped cotton stalks

1. Methods used for storing the chopped cotton stalks (chips) (time, place, size, duration)
2. Labour requirements, organisation and costs
3. Machine, equipment and building requirements and costs
4. Total costs for storing the chopped cotton stalks/chips

J. Energetic use of chopped cotton stalks

1. Methods for using chopped cotton stalks (chips) for energy supply (efficiencies)
2. Machine, equipment and building requirements and costs
3. Total costs for using chopped cotton stalks (chips) for energy supply

K. Chopping of the cotton stalks at the processing site

1. Methods used for chopping cotton stalks at the processing site (manual and mechanic)
2. Labour requirements, organisation and costs
3. Machine and energy requirements and costs
4. Total costs for chopping cotton stalks at the processing site

L. Briquetting at the processing site

1. Methods used for briquetting
2. Labour requirements, organisation and costs
3. Machine, equipment and building requirements and costs
4. Energy requirements and costs
5. Total costs for briquetting

M. Storage of briquettes

1. Methods used for storing the briquettes (time, place, size, duration)
2. Labour requirements, organisation and costs
3. Machine, equipment and building requirements and costs
4. Total costs for storing the briquettes

N. Energetic use of briquettes

1. Methods for using briquettes from cotton stalks for energy supply (efficiencies)
2. Machine, equipment and building requirements and costs
3. Total costs for using briquettes from cotton stalks for energy supply

EIDESSTATTLICHE ERKLÄRUNG

Hiermit erkläre ich an Eides Statt, dass die hiermit vorgelegte Dissertation von mir selbst und ohne die unzulässige Hilfe Dritter verfasst wurde, auch in Teilen keine Kopie anderer Arbeiten darstellt und die benutzten Hilfsmittel sowie die Literatur vollständig angegeben sind.

Ort, Datum Unterschrift