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# THE ENERGETIC USE OF CORN STALKS BRIQUETTES AND ITS PROPERTIES

**Mohammed, M.A.; Aboamera, M.A.H. and Khouder, Amira H.M.**
Department of Agricultural and Bio-Systems Engineering, Faculty of Agriculture, Menoufia University, Shibin El-Kom, Egypt.

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**ABSTRACT:** The experimental procedure comprised four stages outlined below: Assessing certain physical properties of corn stalks - Chopped corn stalks utilizing a hammer mill at a cutting speed of 1600 rpm and three distinct moisture contents (8%, 9%, 10%). - Material was processed in a screw press machine at a pressure of 100 MPa and a temperature of 170-175ºC, with three moisture contents for corn stalks (8%, 9%, 10%). - Assessing various quality attributes of pressed briquettes, including durability, hardness, compression ratio, bulk density, calorific value, and resiliency.

The results obtained from this study can be summarized as the following: (Physical properties for corn stalks - Measuring some quality properties of corn stalks briquettes produced by screw press).

The results obtained during the experiment showed that the best moisture content to start the corn stalks pressing process under a temperature of 175°C is 8%, as found that the resulting briquettes are more cohesive and when burned, they have a lower emission rate of $CO_2$ (1.1%), CO (0.0146%) and $SO_2$ (0.000%), and thus this treatment is the best environmentally friendly treatment, and it also gave the highest calorific value (16.80 MJ/kg).

**Key words:** Calorific value - corn stalks - moisture content - durability - bulk density.

## INTRODUCTION

Disposal of farm residuals is one of the main problems facing Egyptian farmers, estimating about 59 million tons/year (Ministry of Environment -2020). Agricultural waste plants and animal by-products that are within the agricultural production system represent a big problem for farmers and negatively affect the surrounding environment where they are disposed of in primitive ways by burning or storage, leading to increased pollution. So should maximize the use of turning it into organic fertilizer or feed or clean energy or manufactured thus contributing to cleaning agriculture, protecting the environment from pollution, and improving the economic situation and the environment. Cotton stalk and rice straw are considered as the one of the main environmental problems in Egypt.

Agricultural waste resulting from various farming activities including crops remains suitable for recycling and the production of energy or animal feed and fertilizers, Pesticide residues and agricultural fertilizers which are regarded as hazardous waste, and Animal manure and sludge of sewage pits and sanitary wastewater tanks. El-Bateh (2020), mentioned that Egypt produces more than 35 million tons of agricultural waste annually, including 23 thousand tons of plant waste, where the percentage of straw reached 39.4% of the total agricultural waste, while the percentage of firewood reached 3.6%, straw 14.1%, and twigs 10.9% at the level of the Republic, and what is recycled does not exceed 12% of the quantity, while millions of other tons are disposed of improperly by burning or throwing it into canals and drains, etc.

Biomass for energy generation has attracted much attention because it is an abundant resource and $CO_2$-neutral. According to the World Energy Council, biomass contributes 14% out of the 18% of global energy supply from renewables and contributes 10% of total global energy consumption. It is the predominant source of energy in developing countries e.g. over 80% in sub-Saharan Africa, which is mainly used for cooking. Biomass is heterogeneous in terms of

* Corresponding author: graduatedagri@gmail.com 

size, shape, and composition and has low bulk density (e.g. about 4 times slower than the bulk density of diesel), leading to difficulties in handling, storage, and transport (World Energy Council, 2016).

Biomass is a renewable alternative source that is found all over the world. Biomass resources cover crops, plant residues, forest resources, and special energy plants. Biomass is obtained as residues in the whole process of agricultural production. Many residues have been obtained from the arable field crops and horticultural crops during the production of crops and fruits in agriculture. Energy policies and planning ensuring food security in the world should be supported in local, national, and global scale biomass utilization for energy (Avcıoglu, *et al.* 2019).

The design of the cutting tool or machine significantly impacts the effectiveness of cutting agricultural residues. The geometry of the cutting blades, the configuration of the knives, the cutting speed, and the force applied all determine how well the machine can cut through various types of residues. For instance, in a flywheel-type cutter head, the positioning and sharpness of the knives are crucial for maintaining cutting precision and reducing energy consumption (Tahir *et al.,* 2019). Similarly, hammer mills rely on the rotational speed of hammers and the arrangement of screens to control particle size and achieve uniform cutting (Kaliyan and Morey, 2009). Blade sharpness and wear are also important considerations. Dull blades increase cutting resistance, resulting in higher energy consumption, inefficient cutting, and greater strain on the machinery (Zhang *et al.,* 2021).

The moisture content of agricultural residues is another critical factor influencing cutting efficiency. Residues with high moisture content, such as freshly harvested green stalks, tend to be more pliable, which can reduce the cutting efficiency of some machines. High moisture levels can also lead to clogging in certain types of cutting equipment, such as hammer mills or rotary mowers, as the wet material sticks to the cutting surfaces and impairs airflow (Shinners *et al.,* 2009). On the other hand, very dry residues, such as sun-dried wheat straw, can become brittle and break unevenly, leading to inconsistent particle sizes and potentially higher wear on cutting equipment (Wilkinson and Elevitch, 2015). Therefore, optimizing the moisture content for cutting is essential; most studies suggest that moderately dry residues offer the best balance between ease of cutting and minimal equipment wear (Mani *et al.,* 2004).

The core process of briquetting involves compressing the reduced corn stalk material into briquettes using piston press, screw press, or roller press briquetting machines. Piston press briquettes are commonly used for compressing corn stalks into cylindrical briquettes, applying mechanical pressure and sometimes heat to bind the particles. Screw press briquettes, on the other hand, use a rotating screw to compress and extrude the material through a die. The friction and pressure in screw presses often produce enough heat to activate the natural lignin in the stalks, which acts as a binder, eliminating the need for additional binders (Grover and Mishra, 1996).

Briquetting corn stalks offers a sustainable solution for managing agricultural residues while providing a valuable source of renewable energy. Corn stalks, which are typically left in the field after the harvest of maize, represent a large proportion of the biomass that can be converted into high-density, energy-rich briquettes. These briquettes can serve as a substitute for firewood, charcoal, and even coal in domestic heating and cooking applications, as well as in industrial processes requiring thermal energy. By transforming corn stalks into briquettes, farmers and rural communities can manage agricultural waste and create a useful product that helps address energy poverty and reduces reliance on fossil fuels (Kaliyan and Morey, 2009).

Several factors, such as moisture content, particle size, and briquette pressure, affect the quality of corn stalk briquettes. High-quality briquettes should have a high density, which enhances their combustion efficiency and reduces the volume required for storage and transport. Density also affects the durability of the briquettes, as denser briquettes are less likely to break or crumble during handling (Stolarski *et al.,* 2013).

One of the primary benefits of producing briquettes from corn stalks is the ability to transform an abundant agricultural residue into a valuable fuel source. Corn stalks are one of the most widely available residues in maize-producing regions, yet they are often underutilized or disposed of through open-field burning, which contributes to air pollution and greenhouse gas emissions. Briquetting offers a sustainable solution by converting this waste into a renewable energy source that can substitute for firewood, charcoal, or fossil fuels (Lal, 2005).

In addition to reducing environmental impacts, corn stalk briquettes provide significant economic benefits to farmers and rural communities. By processing and selling briquettes, farmers can generate additional income, and small-scale entrepreneurs can develop local briquetting businesses. The production of briquettes also supports rural energy security by providing a low-cost, locally available alternative to expensive or scarce conventional fuels like kerosene or LPG (Yadav *et al.,* 2019).

Corn stalk briquettes also have the potential for use in bioenergy production. In industrial applications, these briquettes can be co-fired with coal in power plants, reducing the carbon footprint of electricity generation. The use of agricultural residues like corn stalks in bioenergy systems is aligned with broader efforts to transition to renewable energy sources and promote circular agriculture (Zhang *et al.,* 2020).

## MATERIALS AND METHODS

The experiments were carried out in the Department of Agric. Eng. Faculty of Agric. Menoufia Univ., Laboratory of Soil Science Department., Faculty of Agric. Menoufia Univ., resistance of concrete laboratory, Civil Engineering Department, Faculty of Engineering, Menoufia Univ. and biomass laboratory of the New and Renewable energy authority, Nasr City, Cairo.

Determining the parameters leads to achieving the aim of this study.

### Corn Stalks

Whole corn stalks were collected at harvest time from private farms in Menoufia governorate. Corn stalks used at three moisture contents (8%, 9%, 10%). The corn stalk material was naturally dried. The initial moisture content of samples was about 13% (Wet base) as the mean, then the samples were dried to achieve the required level of moisture content (8.3-10.6%). The stem length ranged from 158 to 210 cm, the stem diameter ranged from 18 to 23.7 mm, the weight of one stalk ranged from 45 to 185 gm, and numbers of branches ranged from 11 to 28.

### Types of equipment

The main equipment used in this work were hammer mill and screw press. The specific components of each machine can be summarized as follows:

### 1. Hammer mill:

The cutting machine Fig (1), which is used in this work consists of the following parts:

#### a. Cutting head:

The cutting head of a diameter of 55 cm has 16 knives which are fixed on it by four bolts. It rotated at a speed of 1600 rpm Fig (2).

#### b. Feeding drum:

The feeding drum dimensions of 40 cm in length, and 22 cm in diameter and was constructed in the machine. It is considered an assistant element in the cutting process, which was used to push the plant stems to the cutter head for cutting.

#### c. Knives:

The cutting knives of spring steel were sharpened at an angle of 45º. The cutting knives were 20 cm in length, 6 cm in width and the thickness was 0.8 cm.

**Fig. (1): Photographic picture of the hammer mill machine**

**Fig. (2): The cutting head of the hammer mill machine**

## 2. Screw press machine

The screw press machine Shimada (Type SPMM-850 KS). The production capacity of the machine was 400 kg/h. The machine is powered by a 30 KW electric motor. It has 2 electrical ceramic heater bands, each requiring 3 KW for operation, and has an integrated "T" Stirrer with a 1.5 KW Motor. The press requires a standard 220/380 Volt, 50 Hz, and 3-phase electrical power supply. The machine has also a control panel. The chopped materials were put in a container above the machine. The materials feeding was rotated with different velocities with a belt. The operating velocity of the belt was 0.38 m/s. The screw press is illustrated schematically in Fig (3).

The main parts of the machine are the screw and die; the rotating screw takes the material from the feet port and compacts it against the die which assists the buildup of a pressure gradient along the screw. During this process, a frictional effect occurs at the die wall. In addition, the combined effect due to the internal friction in the material and the high rotational speed of the screw causes an increase in temperature in the closed system which helps in heating the material. Then it is forced through the die, where the briquette with the required shape is formed.

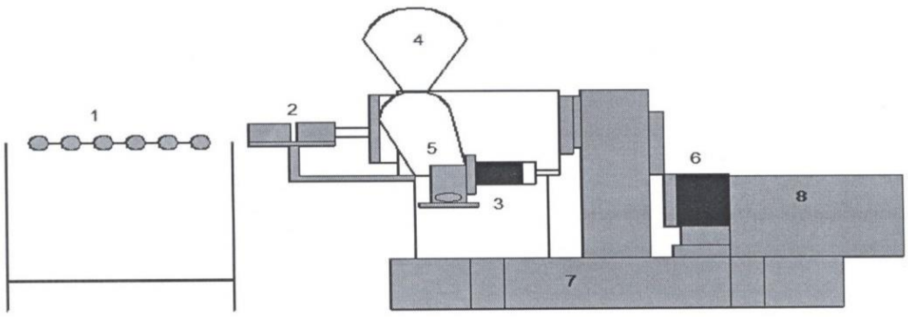


**Fig. (3): The Screw Press Machine**
**1- Colling Zoon 2- Heaters 3- Motor (1.5 HP) 4- Hopper 5- Die**
**6- Motor (40 HP) 7- Base 8- Control Panel**

## Measuring instruments

### 1. Digital balance

The digital balance used in this work was used for determining the weight samples of chopping corn stalks.

### 2. Stopwatch

It was used to estimate the time requirement for each test during the cutting process. Its accuracy is 1 / 1000 seconds.

### 3. Drying oven

The electrical drying oven was used to dry the samples of residues to calculate the moisture content.

## Briquette durability instrument

The durability (Du) of the briquettes was determined according to ASAE Standard S269.4, (2003). A 500 g sample of briquettes tumbled at 50 rpm for 10 min, in a dust-tight enclosure. A No. 5 US Sieve with an aperture size of 4.0 mm was used to retain crumbled briquettes after tumbling. Durability is expressed by the percentage ratio of the mass of briquettes retained on the sieve after tumbling ($m_{pa}$) to the mass of briquettes tumbling ($m_{pb}$) according to the following equation (3-1) (Fasina, 2008).

$$DU = \frac{mpa}{mpb} \times 100 \dots\dots (3-1)$$

## Compression stress test

The compressive stress of each briquette was measured using an ELE International compression testing machine. The flat surface of the briquette sample was placed on the machine's horizontal metal plate and compressed between two disks using hydraulic pressing at a specific loading level. The distance between this metal plate and a second plate parallel to it was slowly reduced. An increased load was applied at a constant rate until the test sample failed by cracking or breaking. The load at the fracture point and the maximum load were converted to compression stress using the following equation (Gibiiz and Kucukbayrak, 1996).

$$\text{Compression stress} = \frac{\text{Load at fracture}}{\text{Cross-sectional area of plane of fracture}} \quad ..(3\text{-}2)$$

## Measuring calorific value

The calorific value was measured by using an electrical oven (GALLENKAMP Auto bomb). The moisture content of the corn stalk briquette was measured before measuring the calorific value by using an electric furnace and the balance of technical according to ATM 1756-01 standard. The sample was inserted into the bomb, and it was closed and charged with oxygen. The bomb was fired up by pressing the ignition switch to burn the sample in an excess of oxygen.

## Measuring gas emissions

The emission gases were measured using an analyzer (Rize 700 EIUK). Estimated emissions were carbon monoxide (CO), carbon dioxide ($CO_2$), oxides of nitrogen (NO), and sulfur dioxide ($SO_2$) for corn stalks (loose and briquettes) samples were at the moisture content (4.87 and 5.1%) for corn stalks. The samples were burned in the stove and the data of emissions from the chimney height of 180 cm. Ethyl Alcohol was used as an assistant at the start of the burning process and the reading was taken during the ignition samples.
Combustion efficiency (η) was calculated from the following equation:

$$\eta = CO_2\ \% / (CO\ \% + CO_2\ \%) \dots\dots\dots\dots (3\text{-}3)$$

## Methods

### 1. Physical properties of crop residuals

The dimensional description of each stalk in all residuals implied the measure of sample number, length, and diameter. The average diameter of each sample was determined using a digital slide caliper.

### 2. Moisture content (M.C)

Plant samples were oven-dried at 105ºC for 24 hours using an electrical oven. The samples were weighed before and after drying and the moisture content was determined by using the following equation: (AOAC,1990).

$$M.C = \frac{SB-SA}{SB} \times 100 \ \% \text{(Wet base)} \ldots \quad (3\text{-}4)$$

Where:

SB = Sample weight before drying (g).

SA = Sample weight after drying (g).

## 3. Quality of briquettes product

### 1. Bulk density (ρb)

Bulk density is an indicator of savings in storage, transportation space, and cost of blocks. The bulk density of the briquettes was calculated using Eq. (3-4) with the sample volume and the measured drying mass. The bulk density was measured using the paraffin wax method. The volume was calculated using the volume of the sample and wax. The drying mass was determined by the weight of the sample wax and the sample in the air.

$$\rho b = \frac{Drying\ mass}{volume} = \frac{\frac{Wsx}{WSA}}{Vsx - VA} \ldots\ldots (3-5)$$

Where:

$\rho b$ = Bulk density of stalk briquette of corn (kg.m$^{-3}$)

$W_{SX}$ = Weight of the sample briquette and Weight of wax (kg)

$W_{SA}$ = Weight of the sample briquette in the air (kg)

$V_{SX}$ = Volume of the sample briquette (m$^3$)

$V_X$ = Volume of the wax (m$^3$)

### 2. Compression ratio (CR)

The compression ratio indicates volume reduction during compression. It was obtained from the ratio of the bulk density of the compact block to the initial density of the material being compressed and can be calculated of follows (Jha, *et al.* 2008).

$$CR = \frac{\rho b}{\rho raw} \times 100 \quad \ldots\ldots\ldots (3-6)$$

CR = Compression ratio

$\rho_b$ = Bulk density of stalk briquette of corn (kg.m$^{-3}$)

$\rho_{raw}$ = Bulk density of loose corn stalk briquette (kg.m$^{-3}$)

### 3. Elasticity (R)

Elasticity was determined as the ratio between the increases in thickness to the initial thickness of the briquette according to the following equation (3-7) (Jha, *et al.* 2008).

$$R = \frac{T - Ti}{Ti} \times 100 \quad \ldots\ldots\ldots\ldots (3-7)$$

R = Elasticity (%)

T = Thickness of stabilized corn stalks briquette (mm)

$T_i$ = Initial thickness of corn stalk briquette (mm)

### 4. Hardness

Hardness reflects the degree of binding. It was measured as the maximum force recorded while a briquette was broken by a probe incorporated in a Texture Analyzer (Jha, *et al* 2008).

### 5. Water resistance.

The water resistance is determined by the percentage of water absorbed by a briquette when immersed in water. The briquettes were immersed in water and measured the time required for the onset of the dispersion in water. The resistance to water penetration is determined from the following equation (Orisaleye, *et al* 2019).

$$WR = 100 - \left(\frac{Mwet\ briquette - Minitial}{Minitial} \times 100\right) \ldots\ldots\ldots (3-8)$$

Where:

WR = Water resistance (%)

$M_{wet\ briquette}$ = Mass of wet briquette (kg)

$M_{initial}$ = Initial mass of briquette (kg)

## RESULTS AND DISCUSSION

### 1. Physical properties of corn stalks

The results obtained from measuring corn stalk samples showed that the maximum value of stem length was 210 cm, while the minimum value was 158 cm. The maximum value of stem diameter was 2.37 cm, while the minimum value was 1.8 cm. The stem weight varied between 45 grams and 185 grams. The quantity of leaves varied from 11 to 28 per stalk. The initial moisture content of stored samples was about 13% (Wet base) as the mean, and then the samples were dried to achieve the required moisture levels (8.6 and 10%). The average values of stalk length, diameter, weight, and number of leaves per stalk are listed in Table (1).

**Table (1): Average values of some physical properties of corn stalks at moisture (13%)**

| Characteristics | Range | Average |
|---|---|---|
| Length, cm | 158-210 | 184.5 |
| Diameter, cm | 1.8-2.37 | 2 |
| Weight of one stalk, (gm) | 45-185 | 115.86 |
| Number of leaves | 11-28 | 18 |

## 2. Problem of the briquettes machine explosion

Before pressing, the heaters must be heated to about 175ºC to produce suitable briquettes. The lignin that exists in corn stalks becomes fluid at elevated temperatures, functioning as a natural adhesive to bind the briquettes. A piece of briquette that remained from the previous process in the heater zone. It started to lose its moisture content. The chopped material was also heated up and lost a part of its moisture, Moreover, a considerable amount of water vapor rises and collects in the die. This pushes the briquette until it overcomes the adhesive force between the briquette and the die wall. The remaining briquette exits the press die like a cannon shot, causing an explosion-like sound according to (Abdel Aal *et al.*, 2023). The produced briquettes are shown in Fig (4).

**Fig. (4): Produced briquettes**

## 3. Moisture content for corn stalks briquettes.

The final moisture content due to the pressing of the chopped corn stalks to produce briquettes, decreased compared with the initial moisture content before the pressing process at 170ºC. The initial moisture content of corn stalks pressed at (8, 9, and 10%) decreased to (4.87, 5.23 and 6.12%), respectively, as shown in Fig (5).

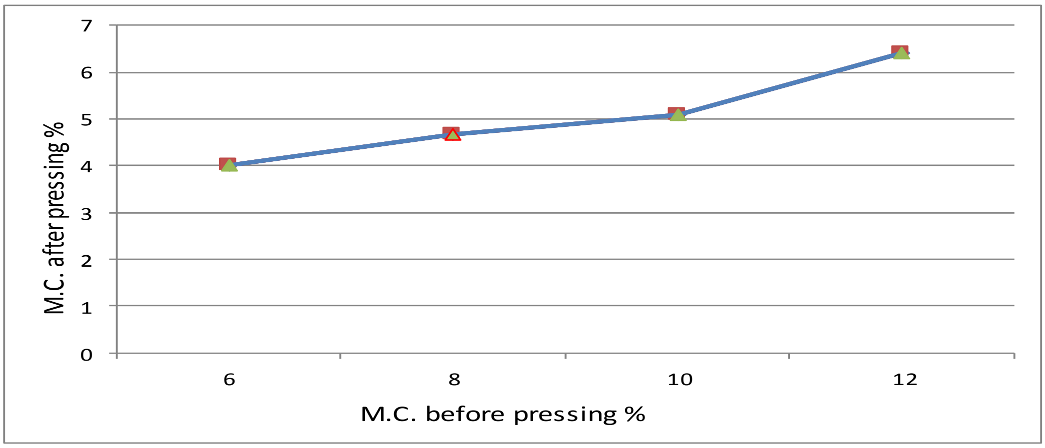


**Fig. (5): Effect pressing on at 175ºC the moisture content of corn stalks briquettes.**

## 4. Evaluate the quality of the produced corn stalks briquetting product

### 4.1. Effect of moisture content on compression stress

The relationship between briquette moisture content and compression stress is presented in Table (2). Compression stress was increased (6.92, 7.43, and 13.8 MPa) with decreasing briquettes moisture content (6.12, 5.23, and 4.87%, respectively). As shown in Fig (6) compression stress decreased by 46.2% when briquette's moisture content increased from 4.87 to 5.23%. However, it decreased to about 6.9% when the briquette moisture content increased from 5.23 to 6.12%. The following equation can express the relationship between briquette's moisture content and compression stress:

Compression stress (MPa) = -3.44 M.C. + 16.263
$R^2$ = 0.8053

Table (2) illustrated that there were significant differences between compression stress values at (P ≤ 0.01) from different briquettes' moisture contents (6.12, 5.23, and 4.87%). Results were in harmony with the finding by Gamea *et al.* (2012), the highest compression stress for cotton stalks and rice straw briquettes were 8.95, and 10.39 MPa, respectively.

**Table (2): Average values of quality parameters of corn stalk briquette at the moisture content (4.87, 5.23 and 6.12%)**

| Final M.C.% | Comp. S MPa | Durability, % | Hardness, kN | BD g/cm$^3$ | Compression ratio (%) | Elasticity, % | CV MJ/kg | Water resistance, min. |
|---|---|---|---|---|---|---|---|---|
| 4.87 | 20.23$^A$ | 91.74 | 47 | 0.95$^c$ | 19.79$^c$ | 9.4$^c$ | 16.80$^a$ | 68 |
| 5.23 | 16.7$^B$ | 86.36 | 40 | 1.00$^b$ | 21.28$^b$ | 11.07$^b$ | 15.23$^b$ | 46 |
| 6.12 | 13.8$^C$ | 82.19 | 34 | 1.10$^a$ | 23.92$^a$ | 13.38$^a$ | 12.60$^c$ | 19 |
| Sig. | 0.000** | 0.000** | 0.000** | 0.000** | 0.000** | 0.000** | 0.000** | 0.000** |

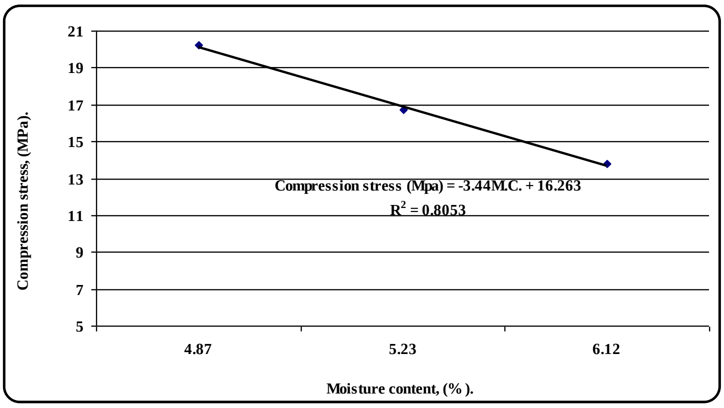


**Fig. (6): Effect moisture content (4.87, 5.23 and 6.12%) on corn stalks briquettes compression stress**

### 4.2. Effect of moisture content on durability%

It is clear from Figure (7) and Table (2) that there is an indirect relationship between the final moisture content and the durability of the briquettes. It was found that durability increased from 82.19% to a moisture content of 6.12% to 91.74% at a moisture content of 4.87%. This means that with the increasing moisture content, the cohesion between the particles decreases because the briquettes dissolve due to moisture absorption. The following equation can express the relationship between briquette moisture content and its durability:

Durability, %= -4.775M.C.+ 96.313
$R^2$ = 0.9947

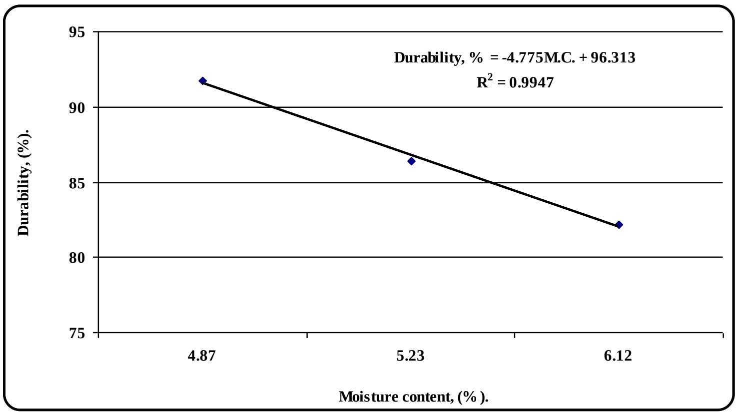


**Fig. (7): Effect moisture content (4.87, 5.23, and 6.12%) on corn stalks briquettes durability, %**

Table (2) illustrated that there were significant differences between durability values ($P \leq 0.01$) from different moisture contents (6.12, 5.23, and 4.87%).

According to ASABE Standard S269.4 (2003) and (Mohd-Faizal *et al.*, 2022), when shatter resistance was >90%, between 80% and 90%, and <80%, the briquette had good, medium, and poor durability, respectively. The result was the agreement with the finding by Abdel Aal *et al.*, (2023), they found that the durability value was 96.9% for pressed briquettes with a moisture content of 8%, while the durability value was 95.5% for pressed briquettes with a moisture content of 10%. The results indicated that the corn stalk briquette recorded the greatest durability of 91.74 % at a moisture content of 4.87% followed by 86.36% at a moisture content of 5.23%, finally, 82.19% at a moisture content of 6.12%.

### 4.3. Effect of moisture content on hardness (kN)

It is clear from Figure (8) and Table (2) that there is an indirect relationship between the final moisture content and the hardness of the briquettes. It was found that the hardness was 34 kN at a moisture content of 6.12% followed by 40 kN at a moisture content of 5.23%, then, 47 kN at a moisture content of 4.87%. This may be due to increasing bulk density by increasing the briquette's moisture content. The following equation can express the relationship between a briquette's moisture content and hardness:

Hardness (kN) = -6.5 M.C. + 53.333

$R^2 = 0.998$

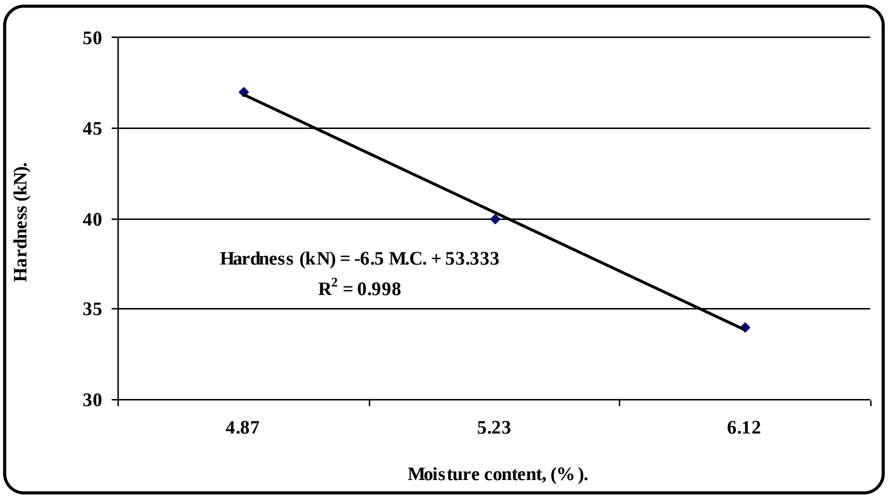


**Fig. (8): Effect moisture content (4.87, 5.23, and 6.12%) on corn stalks briquettes hardness, kN**

Table (2) illustrated that there were significant differences between hardness values at ($P \leq 0.01$) from different briquette moisture contents (6.12, 5.23, and 4.87%).

The results concur with those of Jamradloedluk and Wiriyaumpaiwong (2007), who found that briquettes produced from higher-density materials may be able to withstand more ultimate stress than those made from lower-density materials.

### 4.4. Effect of moisture content on bulk density (g/cm$^3$)

It is clear from Figure (9) and Table (2) that there is a direct relationship between the final moisture content and bulk density (g/cm$^3$) of the briquettes. It was found that the bulk density (g/cm$^3$) increased from 0.95 (g/cm$^3$) at a moisture content of 4.87% to 1.00 (g/cm$^3$) at a moisture content of 5.23%, then 1.1 (g/cm$^3$) at a moisture content of 6.12%. The following equation can express the relationship between briquette moisture content and bulk density (g/cm$^3$):

Bulk density, BD (g/cm$^3$) = 0.075M.C. + 0.8667 $R^2 = 0.9643$

Table (2) illustrated that there were significant differences between bulk density (g/cm$^3$) values at ($P \leq 0.01$) from different briquette moisture contents (6.12, 5.23 and 4.87%).

The results were in harmony with Abdel Aal *et at.*, (2023), who found that the pressed loose material with an 8% moisture content produced briquettes with a density of 1.21 g·cm$^{-3}$, while the average value for the pressed material with a 10% moisture content was 1.25 g·cm$^{-3}$. Raising the moisture content to 15% increased the density to 1.61 g·cm$^{-3}$.

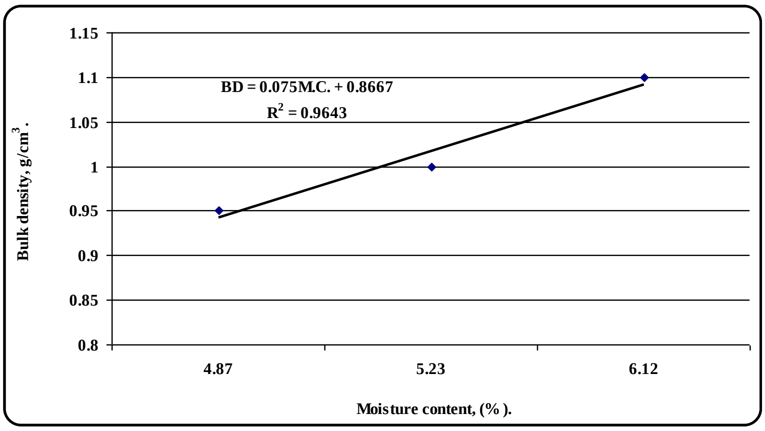


**Fig. (9): Effect moisture content (4.87, 5.23, and 6.12%) on corn stalks briquettes bulk density (g.cm$^{-3}$)**

### 4.5. Effect of moisture content on compression ratio

Figure (10) and Table (2) clearly illustrate a direct correlation between the final moisture content and the compression ratio of the briquettes. It was found that the compression ratio increased from 19.79 % at a moisture content of 4.87% to 21.28 % at a moisture content of 5.23%, then 23.92 % at a moisture content of 6.12%. The following equation can express the relationship between briquette moisture content and compression ratio:

Compression ratio CR = 2.065M.C. + 17.533

$R^2 = 0.9748$

Table (2) illustrated that there were significant differences between compression ratio values ($P \leq 0.01$) from different briquette moisture contents (6.12, 5.23, and 4.87%).

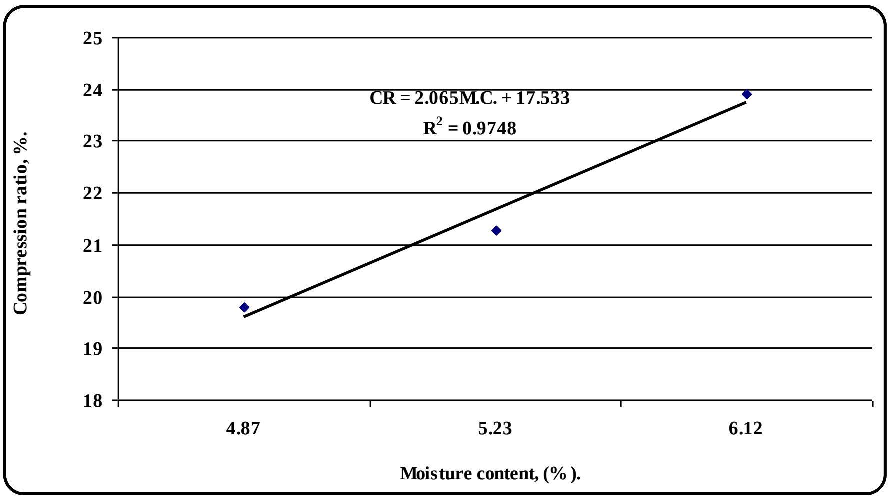


**Fig. (10): Effect moisture content (4.87, 5.23 and 6.12%) on corn stalks briquettes compression ratio, (%)**

Abdel Aal *et al.* (2023) found the same trend of our data; they found that raising the moisture content to 10% elevated the density of the loose material to 0.21 $g{\cdot}cm^{-3}$. As such, raising the moisture content to 15% raised the loose material density value to 0.27 $g{\cdot}cm^{-3}$.

## 4.6. Effect of moisture content on elasticity (%)

It is clear from Figure (11) and Table (2) that there is a direct relationship between the final moisture content and elasticity (%) of the briquettes. It was found that the elasticity (%) increased from 9.4 at a moisture content of 4.87% to 11.07 at a moisture content of 5.23%, then 13.38 at a moisture content of 6.12%. The following equation can express the relationship between briquettes moisture content and elasticity (%):

Elasticity (%) = 1.99M.C. + 7.3033

$R^2 = 0.9915$

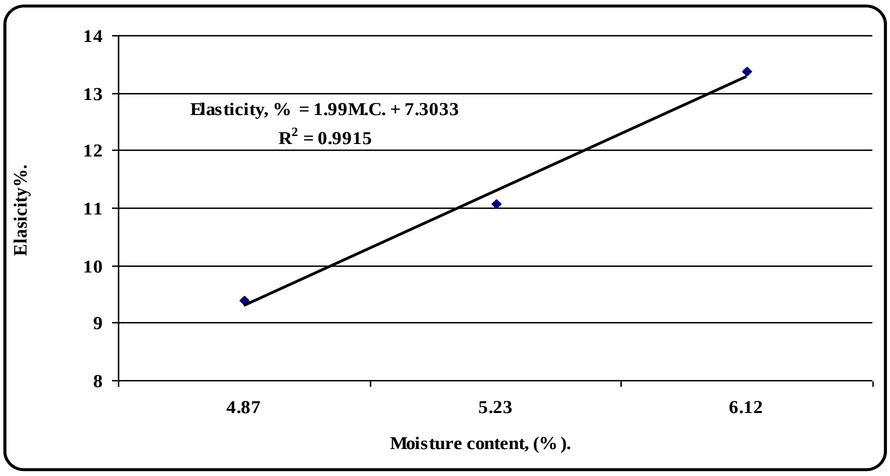


**Fig. (11): Effect moisture content (4.87, 5.23, and 6.12%) on corn stalks briquettes Elasticity, (%)**

Table (2) illustrated that there were significant differences between elasticity (%) values at ($P \leq 0.01$) from different briquette moisture contents (6.12, 5.23, and 4.87%).

The results disagreed with that found by Haidong *et al.*, (2021), who showed that the slope of the linear elastic stage of the stress-strain curve gradually decreases with the increase of moisture content.

## 4.7. Effect of moisture content on calorific value CV (MJ/kg)

It is clear from Figure (12) and Table (2) that there is an indirect relationship between the final moisture content and calorific value CV (MJ/kg) of the briquettes. It was found that the calorific value CV (MJ/kg) decreased from 16.80 (MJ/kg) at a moisture content of 4.87% to 15.23 (MJ/kg) at a moisture content of 5.23% and 12.60 (MJ/kg) at a moisture content of 6.12%. These results may be due to the increase of bulk density for moisture content of 4.87% compared with the highest moisture content of 6.12% with a low value of its bulk density. The following equation can express the relationship between briquette's moisture content and calorific value CV (MJ/kg):

Calorific Value CV (MJ/kg) = -489.72M.C.+ 4524.3

$R^2$ = 0.974

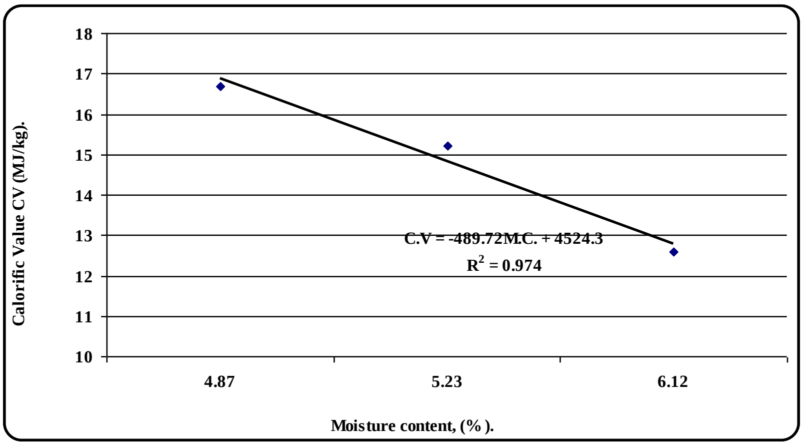


**Fig. (12): Effect moisture content (4.87, 5.23, and 6.12%) on corn stalks briquettes calorific value CV (MJ/kg)**

Table (2) illustrated that there were significant differences between calorific value CV (MJ/kg) values at (P ≤ 0.01) from different briquette moisture contents (6.12, 5.23, and 4.87%).

Saeed *et al.* (2021) showed the higher heating value of rice husk blend and briquette at various moisture contents. At a moisture content of 14%, the highest heating values were 14.23 MJ/kg before briquetting and 17.69 MJ/kg after briquetting. While at the moisture contents of 12% and 16% the heating value rose significantly from 13.87 MJ/kg to 14.04 MJ/kg and 13.08 MJ/kg to 13.11 MJ/kg, respectively.

## 4.8. Effect of moisture content on water resistance, (min)

It is clear from Figure (13) and Table (2) that there is an indirect relationship between the final moisture content and water resistance, (min) of the briquettes. It was found that the water resistance, (min) decreased from 68 (min) at a moisture content of 4.87% to 19 (min) at a moisture content of 6.12%. The following equation can express the relationship between the briquette's moisture content and water resistance, (min):

Water resistance, W.R. (min)= -24.5M.C. + 93.333

$R^2$ = 0.9965

Table (2) illustrates significant differences between water resistance, and (min) values at (P ≤ 0.01) from different briquette moisture contents (6.12, 5.23, and 4.87%).

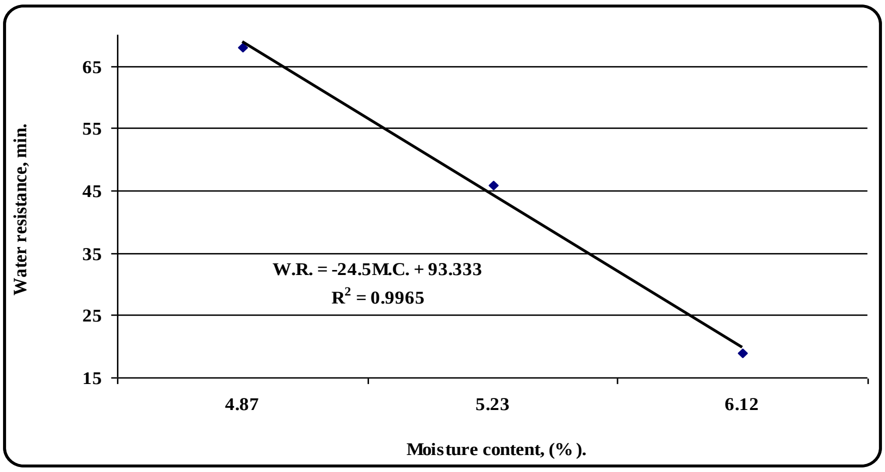


**Fig. (13): Effect moisture content (4.87, 5.23 and 6.12%) on corn stalks briquettes water resistance (min)**

## 5. Effect of moisture content on gases ratios

### 5.1. Effect of moisture content on $CO_2$ gas ratios

The initial moisture content and briquette moisture content affected both the gas ratio and $CO_2$%. Table (3) and Figure (14) demonstrate that $CO_2$% rose as the initial moisture content of the straw and the moisture content of the briquettes increased. For stalks with initial moisture contents of 10, 9, and 8%, it was measured at 2.6, 3.1, and 4.1%, respectively. However, for briquettes with a final moisture content of 6.12, 5.23, and 4.87%, respectively, it was measured at 1.7, 1.4, and 1.1%.

The decrease in $CO_2$ emissions upon burning of briquettes with low moisture content can be attributed to the increased content of completely combustible fibers and the decrease of pores between the fibers because of the increased bulk density.

The following equation can express the relationship between the stalk's initial moisture content and the stalk's $CO_2$%, and between the briquette's final moisture content and the briquette's $CO_2$%:

Stalks $CO_2$%= 118.55 Initial M.C. - 3.1429
$R^2 = 0.9975$

Briquettes $CO_2$%= 0.45 Final M.C.% + 2.867
$R^2 = 0.907$

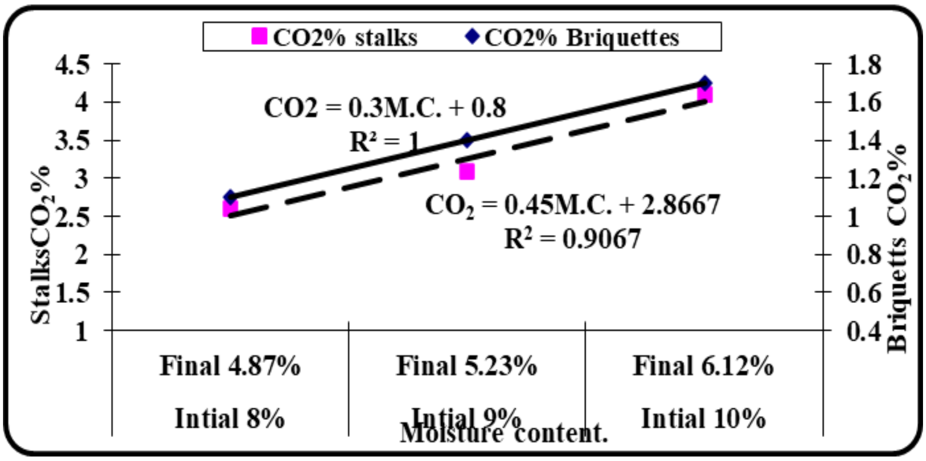


**Fig. (14): Effect of initial and final moisture content on $CO_2$% of corn stalk and briquettes**

**Table (3): Average values of gases of corn stalk and briquettes at initial and final moisture content.**

| Initial M.C.% of stalks | Final M.C.% of briquettes | Stalks | | | | | Briquettes | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $CO_2$% | CO% | $SO_2$% | NO% | µ% | $CO_2$% | CO% | $SO_2$% | NO% | µ% |
| 8 | 4.87 | 2.6[b] | 0.287 | 0.0071 | 0.0065 | 90.8 | 1.1[c] | 0.0145 | 0 | 0.0002 | 97.6 |
| 9 | 5.23 | 3.1[b] | 0.432 | 0.0019 | 0.0079 | 90.21 | 1.4[b] | 0.0243 | 0 | 0.0006 | 97.36 |
| 10 | 6.12 | 4.1[a] | 0.531 | 0.0011 | 0.0014 | 89.73 | 1.7[a] | 0.0259 | 0.0001 | 0.0005 | 96.22 |
| Sig. | | 0.000** | 0.000** | 0.000** | 0.000** | 0.000** | 0.000** | 0.000** | 0.000** | 0.000** | 0.000** |

Table (3) illustrated that there were significant differences between the ratio of $CO_2$% values at ($P \leq 0.01$) from different stalk's initial moisture contents (8, 9, and 10%) and briquettes final moisture contents (6.12, 5.23 and 4.87%).

## 5.2. Effect of moisture content on CO gas ratios

The gas ratio was influenced by the moisture content of the briquettes and the initial moisture content, as indicated by the CO2%. CO% increased as the initial moisture content of the stalk increased, as demonstrated in Table (3) and Fig (15). Conversely, it increased as the moisture content of the briquettes increased. 0.287, 0.432, and 0.531% were recorded for stalks at an initial moisture content of 10, 9, and 8%, respectively. In contrast, the final moisture content of briquettes was 6.12, 5.23, and 4.87%, respectively, with values of 0.0259, 0.0249, and 0.0146%.

The following equation can express the relationship between the stalk's initial moisture content and the stalk CO%, and between the briquette's final moisture content and the briquette's CO%:

Stalks CO% = 0.122 Initial M.C.% + 0.1727

$R^2 = 0.9883$

Briquettes CO% = -0.004 Fin.M.C.%2 + 0.022 Fin. M.C.% - 0.0035 $R^2 = 1$

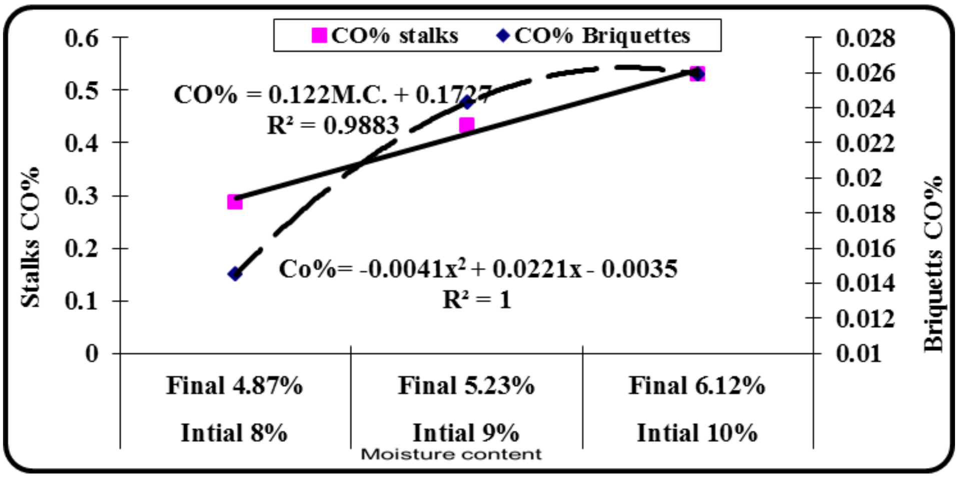


**Fig. (15): Effect of initial and final moisture content on CO% of corn stalk and briquettes**

Table (3) illustrates that significant difference between the ratio of CO% values at ($P \leq 0.01$) from different stalk's initial moisture contents (8, 9, and 10%) and briquette's final moisture contents (6.12, 5.23, and 4.87%).

The emission of unburned carbon-based pollutants such as carbon monoxide results from incomplete combustion of briquettes, following Obernberger *et al.* (2006).

## 5.3. Effect of moisture content on $SO_2$ gas ratios

Table (3) illustrates significant differences between the ratio of $SO_2$% values at ($P \leq 0.01$) from different stalk's initial moisture contents (8, 9 and 10%) and briquette's final moisture contents (6.12, 5.23 and 4.87%).

The initial moisture content and briquette moisture content affected both the gas ratio and $SO_2$%. As shown in Table (3) and Fig (16) $SO_2$% decreased with increasing the initial moisture content in stalks moisture content but it increased with increasing briquettes moisture content. Where it was recorded at 0.0011, 0.0012, and 0.0068% for stalks at initial moisture content 10, 9, and 8% respectively. Whereas it was recorded as 0.0001, 0.000, and 0.000% for briquettes at a final moisture content of 6.12, 5.23, and 4.87% respectively.

The following equation can express the relationship between the stalk's initial moisture content and stalk $SO_2$%, and between the briquette's final moisture content and briquette $SO_2$%:

Stalks $SO_2$% = -0.0022 Init. M.C.%2 - 0.0118 Init. M.C.% + 0.0167 $R^2 = 1$

Briquettes $SO_2$%= 5E-05 Fin. M.C.% 2 - 0.0002 Fin. M.C.% + 0.0001 $R^2 = 1$

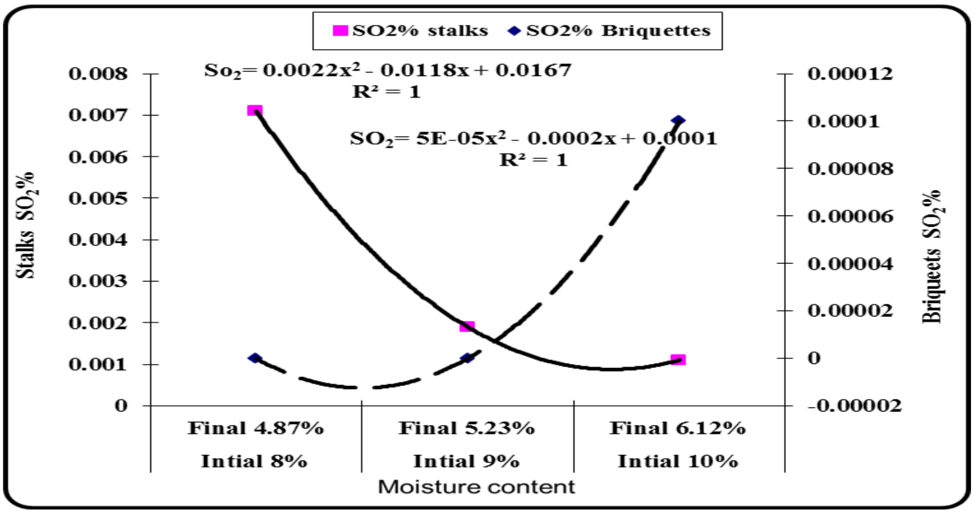


**Fig. (16): Effect of initial and final moisture content on $SO_2$% of corn stalk and briquettes**

## 5.4. Effect of moisture content on NO gas ratios

Table (3) illustrates the significant difference between the ratio of NO% values at ($P \leq 0.01$) from different stalk initial moisture contents (8, 9, and 10%) and briquette's final moisture contents (6.12, 5.23, and 4.87%).

The initial moisture content and briquette moisture content affected the gas ratio as well as NO%. As shown in Table (3) and Fig (17) NO% decreased with increasing the initial moisture content in stalks but it increased with increasing briquettes moisture content. It was recorded 0.0014, 0.0079, and 0.0065% for stalks at initial moisture content 10, 9, and 8% respectively. However, it was recorded at 0.0005, 0.0006, and 0.0002% for briquettes at a final moisture content of 6.12, 5.23, and 4.87% respectively.

The following equation can express the relationship between the stalk's initial moisture content and the stalks NO%, and between the briquette's final moisture content and the briquette's NO%:

Stalks NO% = -0.0029 Initial M.C.%+ 0.0087

$R^2 = 0.7632$

Briquettes NO% = 5E-05 Final M.C.% - 7E-05

$R^2 = 0.75$

Nussbaumer (2003) stated that the nitrogen fuel component is transformed into $N_2$ and $NO_2$ throughout the combustion process, with extremely few levels of $NO_2$ present in the combustion gases produced by modern biomass solid fuels.

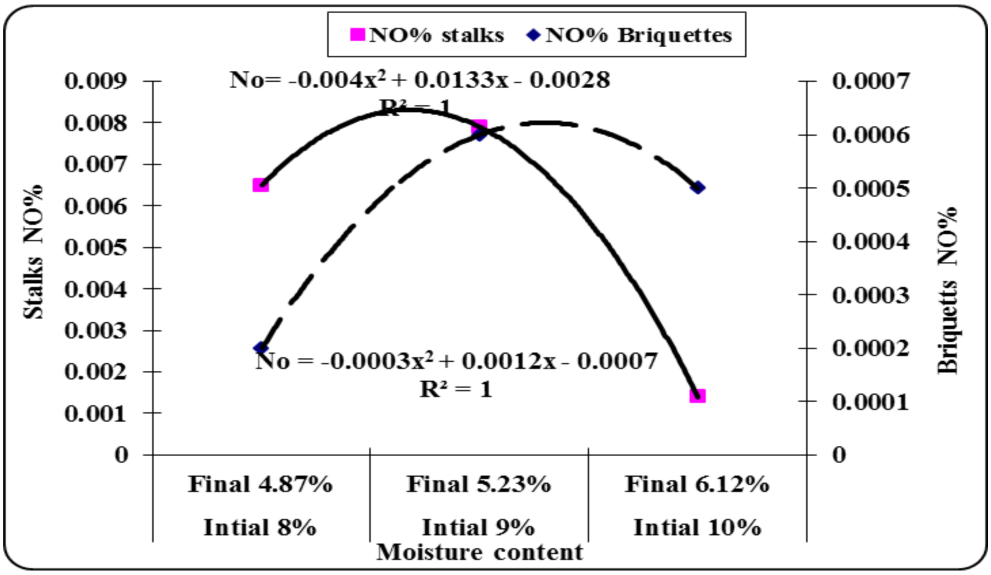


**Fig. (17): Effect of initial and final moisture content on NO% of corn stalk and briquettes**

## 5.5. Effect of moisture content on µ gas ratios

Table (3) illustrates a significant difference between the ratio of µ % values at ($P \leq 0.01$) from different stalk's initial moisture contents (8, 9, and 10%) and briquette's final moisture contents (6.12, 5.23, and 4.87%).

The initial moisture content and briquette moisture content affected the gas ratio as well as µ %. As shown in Table (3) and Fig (18) µ% were decreased with increasing the initial moisture content in stalks moisture content but it increased with increasing briquettes moisture content. Where it was recorded at 0.0038, 0.0058, and 0.0076% for stalks at initial moisture content 10, 9, and 8% respectively. Whereas it was recorded at 0.0014, 0.0007, and 0.0002% for briquettes at a final moisture content of 6.12, 5.23, and 4.87%, respectively.

The following equation can express the relationship between the stalk's initial moisture content and stalk µ%, and between the briquette's final moisture content and briquettes µ%:

Stalks µ% = -0.535x Initial M.C.% + 91.317

$R^2 = 0.9965$

Briquettes µ% = -0.45 Fin. M.C.%2 + 1.11 Final M.C.% + 96.94      $R^2 = 1$

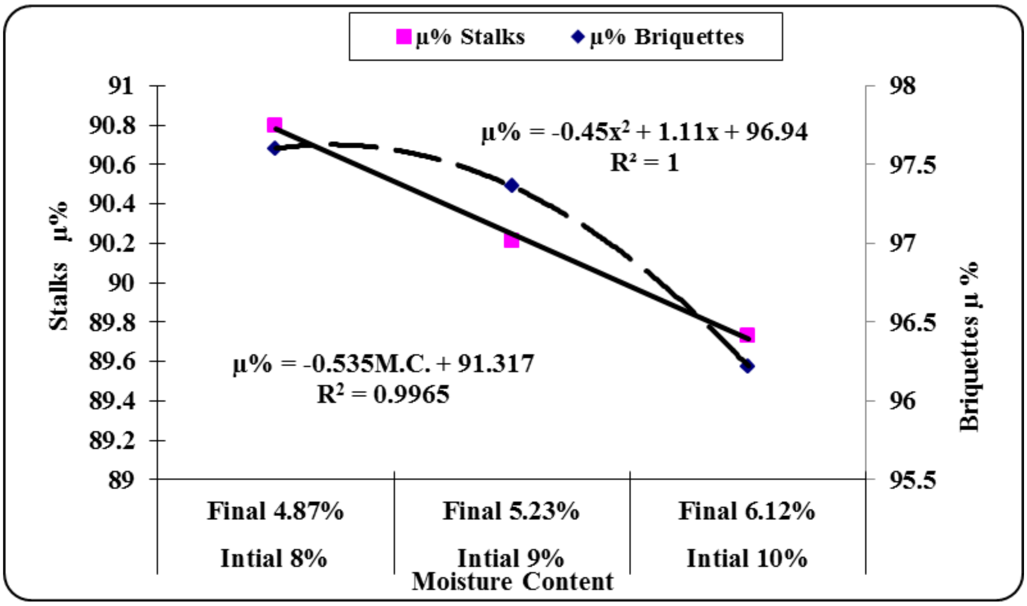


**Fig. (18): Effect of initial and final moisture content on µ % of corn stalk and briquettes**

## CONCLUSION

The experimental results showed that the optimal moisture content for initiating the corn stalk pressing process at a temperature of 175°C is 8%. This condition produced briquettes that exhibited superior cohesion and lower emission rates of $CO_2$ (1.1%), CO (0.0146%), and $SO_2$ (0.000%). Consequently, this treatment is deemed the most environmentally sustainable option, yielding the highest calorific value of 16.80 MJ/kg.

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# الاستخدام الفعال لقوالب سيقان الذرة وخصائصها

**محمود علي محمد، محمد علي أبو عميرة، أميرة حمدي خضير**
قسم الهندسة الزراعية والنظم الحيوية – كلية الزراعة – جامعة المنوفية

**الملخص العربي**

قياس بعض الخصائص الفيزيائية لحطب الذرة - تقطيع حطب الذرة باستخدام مطحنة المطرقة بسرعة قطع ١٦٠٠ دورة في الدقيقة وبمحتويات رطوبة مختلفة (٨%، ٩%، ١٠%) - ضغط المواد المقطعة في مكبس لولبي عند ضغط ١٠٠ ميجا باسكال ودرجة حرارة ١٧٠-١٧٥ درجة مئوية وبمحتويات رطوبة مختلفة لحطب الذرة (٨%، ٩%، ١٠%) - قياس بعض خواص الجودة للقوالب المضغوطة مثل المتانة والصلابة ونسبة الضغط، والكثافة الظاهرية، والقيمة الحرارية، والمرونة. وتم دراسة كلا من الخواص الفيزيائية لحطب الذرة وقياس بعض خواص الجودة لقوالب حطب الذرة المنتجة بواسطة المكبس اللولبي. وجد من النتائج المتحصل عليها أثناء التجربة أن أفضل نسبة رطوبة لبدء عملية كبس حطب الذرة تحت درجة حرارة ١٧٥ درجة مئوية هي ٨% حيث وجد أن القوالب الناتجة أكثر تماسكاً وعند الحرق تكون أقل في نسبة انبعاث غازات ثاني أكسيد الكربون (١,١%) وأول أكسيد الكربون (٠,٠١٤٦%) وثاني أكسيد الكبريت (٠,٠٠٠%) وبذلك تكون هذه المعاملة أفضل نسبة صديقة للبيئة كما أنها أعطت أعلي قيمة حرارية (١٦,٨٠ ميجا جول/كجم).

**الكلمات المفتاحية:** القيمة الحرارية - سيقان الذرة - محتوى الرطوبة - المتانة - الكثافة الظاهرية.