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Effect of binder variations on the performance of one-phase induction motors in bio-pellet production process

Ediwan[1,2], Arnawan Hasibuan[3], Abubakar Dabet[4], Muhammad Daud[3], Fajar Syahbakti Lukman[5], Gandi Supriadi[6]
[1]Department of Renewable Energy Engineering, Faculty of Engineering, Malikussaleh University, Lhokseumawe, Indonesia
[2]PT. PLN Persero UP3 Jambi, Jambi, Indonesia
[3]Department of Electrical Engineering, Faculty of Engineering, Malikussaleh University, Lhokseumawe, Indonesia
[4]Department of Vocational Education of Mechanical Engineering, Malikussaleh University, Lhokseumawe, Indonesia
[5]Administrator of the Indonesian Engineers Association (PII) in the City of Lhokseumawe, Lhokseumawe, Indonesia
[6]Department of Electric Power Business Economics, Faculty of Engineering, PLN Institute of Technology, Jakarta, Indonesia

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ABSTRACT

Indonesia has many oil palm plantation areas. One of the negative impacts is the large amount of empty fruit bunch (EFB) waste. Utilizing EFB as a bio-pellet as a renewable energy source is one of the solutions to reduce waste while supporting the green energy transition. EFB bio-pellets have the potential to replace fossil fuels, but face challenges in setting good quality standards. The production process of EFB bio-pellets uses a variety of binder contents. This study aims to analyze the influence of different levels of binder content on the quality of bio-pellet products. Statistical analysis of linear regression was performed to measure energy consumption and motor performance in the production process of EFB bio-pellets. This study provides recommendations to help maximize the quality and efficiency of the bio-pellet production process from palm oil EFB waste.

Corresponding Author:

Arnawan Hasibuan
Department of Electrical Engineering, Faculty of Engineering, Malikussaleh University
Lhokseumawe, North Aceh, Indonesia
Email: arnawan@unimal.ac.id

1. INTRODUCTION

The agricultural sector plays a significant role in the Indonesian economy, as reflected in its significant contribution to gross domestic product (GDP) of approximately 13.28% in 2021, ranking second only to the processing industry, which contributed 19.25% [1]. The area of land used for oil palm plantations continues to increase. In 2021, the plantation area was estimated to reach 14.62 million hectares, producing 45.12 million tons of crude palm oil (CPO). The plantation area consisted of 55% private plantations (8.04 million hectares), 41.24% smallholder plantations (6.03 million hectares), and 3.76% state plantations (0.55 million hectares). One region showing significant growth in palm oil production is Aceh Province, which has developed rapidly in the palm oil sector. According to data from the Aceh agriculture and plantation service in 2021, the area of oil palm plantations in Aceh reached 470,827 hectares-247,101 hectares managed by smallholders and 223,725.01 hectares by large-scale plantations. Palm oil production reached 795,035 tons in 2021 (456,426 tons from smallholders and 338,035 tons from large plantations), with an average productivity of 2,745 kg/ha per year in the form of CPO [2].

This results in a large amount of agricultural waste from palm oil processing. Agricultural waste has high biomass potential due to its widespread availability, but it remains underutilized for energy applications. One source of this waste is empty fruit bunches (EFB), which are abundant in Indonesia's annual CPO production of 2,745 kg/ha [3], [4]. EFB is a major source of solid waste in palm oil mills, with 23-30% of each ton of fresh fruit bunches (FFB) being processed into EFB waste [5], [6]. Given the large volume of EFB, this study utilizes EFB to produce bio-pellets for co-firing applications in power plants, using an electric induction motor as the driving mechanism. Co-firing is the process of adding biomass as a partial replacement or blending with coal. According to the national energy policy (RUEN), the Indonesian government plans to achieve a 23% share of renewable energy by 2025 [7], [8]. In the future, biomass will be increasingly vital in addressing energy and environmental challenges. Biomass is known to have zero CO_2 emissions because it does not contribute to the accumulation of CO_2 in the atmosphere and contains less sulfur than coal. Despite its large availability, agricultural biomass waste remains underutilized [9].

Oil palm empty fruit bunch (OPEFB) is a by-product of FFB after oil extraction, especially from the sterilization stage. OPEFB contains nutrients such as potassium (K), chlorine (Cl), sulfur (S), nitrogen (N), sodium (Na), phosphorus (P), magnesium (Mg), and calcium (Ca) [6], [10]. However, high content of alkali metals, Cl, and S in OPEFB can cause slag formation, combustion layer agglomeration, corrosion, and a decrease in the melting temperature of ash during combustion [11], [12]. Depending on the growing conditions, OPEFB can contain up to 1.65% nitrogen and 1.06% sulfur, which are harmful to the environment due to increased NOx and SOx emissions [13]. Other elements such as Si, Ca, Mg, and P are also present and tend to form slag at temperatures below 700 °C [11], [14].

Since low ash content is desirable for co-combustion, OPEFB must undergo pre-treatment to improve its quality. Pretreatment through water washing can remove dissolved elements such as K, Na, S, and Cl, thereby reducing the risk of fouling, slag formation, and corrosion [15], [16]. Other researchers improved the effectiveness of washing by modifying time and temperature parameters. Lam *et al*. [17] found a 36% ash reduction after 120 minutes of washing, following second-order kinetics. Tan *et al*. [18] achieved a 73-89% potassium reduction by varying the washing time (30-120 minutes), the solid-liquid ratio (1:10-1:20), and the temperature between 28-60 °C. Chin *et al*. [19] reported a 45-73% reduction in Ca, Mg, and P after washing.

The use of biomass as a fuel for co-combustion is a promising alternative for renewable thermal energy production [20]. However, compared to fossil fuels, biomass has a lower calorific value, low density, and high moisture content, making it less efficient in handling and storage. To increase density, standardize shape and size, and reduce drying and storage costs, OPEFB can be pelletized using a binder. This process also increases the energy value per unit volume, making biomass pellets a viable solid fuel alternative to coal [21].

Induction motors are the most widely used motors in industry, along with direct current (DC) motors. While three-phase induction motors are common in large-scale industries, single-phase induction motors play an important role in a variety of applications, particularly in small machines [22]. Single-phase motors offer technical and economic advantages and are estimated to comprise approximately 70% of industrial motors, used in devices such as pumps, compressors, conveyors, power systems, and grinders [23], [24]. This motor operates with alternating current (AC) to produce magnetic induction from the stator to the rotor. Although more dominant in small-scale industries or MSMEs, the role of single-phase motors is very significant [25].

2. RESEARCH METHOD

2.1. Place and time of research

This research was conducted at the Biomass and Bioenergy Laboratory of Malikussaleh University. Sample testing was carried out at the Chemical Engineering Laboratory of the Lhokseumawe State Polytechnic and the Mechanical Engineering Laboratory of Malikussaleh University. The testing was performed during the period from January to June 2024.

2.2. Tools and materials

The materials used in this study are: EFB, water, and tapioca flour. Meanwhile, the tools used in this study are: scales, analytical, oven, desiccator, furnace, porcelain cup, beaker, bucket, stopwatch, mesh (sieve), sieve shaker, and a set of pellet machines designed to adopt the flat die roller-plate type. A visual illustration of this machine is shown in Figure 1. Pellet making machine specifications: i) dimension length: 1520 mm, width: 1060 mm, height: 935 mm, ii) drive motor: 1.5 kW/3000 rpm, iii) design capacity: 50 kg/h.

2.3. Research variables

The fixed variables in this study are: i) raw material: empty palm oil bunches (TKKS), ii) ratio of TKKS to water: 1:5, iii) soaking time: 60 minutes, and iv) the immersion process is carried out by the bubbling technique (blowing air with the help of a compressor into the immersion water). Testing the characteristics of bio-pellet products made from empty oil palm bunches is carried out with several independent variables (controls), namely preparation variations and process variations. In this study, nine types of samples will be varied: i) preparation of raw materials (TKKS size: 20, 40, and 60 mesh, adhesive concentration: 10, 15, and 20%wt), ii) pellet forming process (disc use in the pellet machine: rotate the disc and the fixed disc). The bound variables in this study are: i) characteristics of the physical, mechanical, and thermal properties of bio-pellet products, ii) mass and energy balance analysis.

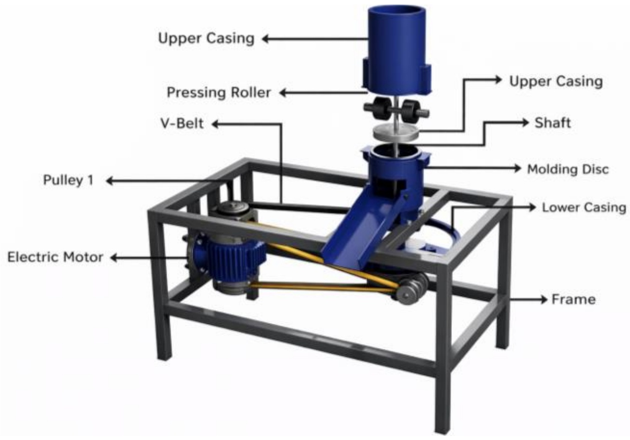

Figure 1. Set of bio-pellet printing tools

2.4. Experimental treatment design

The bio-pellet production process begins by cutting the EFB into long fibers, which are then dried in the sun and cut into pieces about 3-5 cm in size, then immersed in water in a ratio of 1:5 using the bubbled immersion technique, where air is circulated through the immersion water using a compressor for 60 minutes. After soaking, the fibers are dried in the oven at 60 °C for 30 minutes, then ground using a crusher with mesh sizes varying from 20, 40, and 60. The prepared fibers are mixed with binders at varying concentrations. The mixture is stirred manually for 10 minutes until homogeneous, then put into a pellet-making machine to form pellets. The resulting pellets are collected and dried in an oven at 105 °C for 6 hours. This study analyses the energy consumption and performance of single-phase induction motors during the pellet forming process, focusing on how different concentrations of binders affect motor operation and process efficiency.

3. RESULTS AND DISCUSSION

3.1. Energy consumption

The results of the measurement of the load of a single-phase induction motor during the pellet formation process from TKKS with varying levels of adhesive are presented in Table 1. The test was conducted by measuring the current and frequency during the pellet-forming process, based on the assumption of a theoretical voltage of 220 V and a power factor of 0.88. The data show that the increase in adhesive content (ranging from 5% to 25%) is directly proportional to the increase in power consumption. For example, at a 5% adhesive level, power consumption ranges from 0.47 to 0.48 kWh.

Table 1. Load measurement results of single-phase induction motors

Repetition	Fastener (gr)	Voltage (V)	Current (A)	Power factor (PF)	Frequency (Hz)	Energy (kWh)
1	5%	220	2.42	0.88	49.04	0.47
2	5%	220	2.50	0.88	50.02	0.48
3	5%	220	3.54	0.88	50.15	0.69
1	10%	220	2.48	0.88	49.09	0.48
2	10%	220	2.52	0.88	50.10	0.49
3	10%	220	3.62	0.88	50.15	0.70
1	15%	220	3.24	0.88	50.11	0.63
2	15%	220	3.34	0.88	51.67	0.65
3	15%	220	4.12	0.88	52.82	0.80
1	20%	220	4.25	0.88	50.15	0.82
2	20%	220	4.33	0.88	51.78	0.84
3	20%	220	5.10	0.88	52.93	0.99
1	25%	220	4.26	0.88	50.15	0.82
2	25%	220	4.37	0.88	51.78	0.85
3	25%	220	5.75	0.88	52.95	1.11

However, at 25%, power consumption increases significantly to 1.11 kWh. This trend suggests that the higher the adhesive content, the more energy is required, likely due to increased material viscosity and resistance during the pelletization process. The denser and stickier the mixture, the harder the motor must work, resulting in much higher energy consumption. From a technical point of view, materials with higher viscosity and density require greater torque to process. As a result, the machine's workload increases along with the adhesive level, which directly affects its energy consumption.

There is a linear pattern between the fastener content and the engine power consumption. Although there was a small variation in each experiment overall, the higher the binder content, the greater the energy consumption required. By calculating the change in the level of binder and power consumption, at 5% of the binder content, the energy consumption was recorded at 0.1 kWh. The low binding content keeps the viscosity of the raw material at a level that is not too dense, allowing the machine to pelletize with minimal difficulty. At 10% of the binder, the average power consumption increases slightly to 0.56 kWh, with a difference of only 0.01 kWh compared to the 5% rate of the binder, as shown in Table 2.

Table 2. Average energy consumption of a single-phase induction motor

Binder portion (%)	Average energy consumption (kWh)	Energy difference (kWh)
5	0.55	0.00
10	0.56	0.01
15	0.69	0.13
20	0.88	0.19
25	0.93	0.04
Average energy increase (kWh)		0.10

A significant increase occurred when the binder content was increased to 15%, where the average power consumption reached 0.69 kWh, showing a power difference of 0.13 kWh compared to the previous 10% level. This greater increase indicates that the machine is starting to require more energy to handle raw materials with higher viscosity. The higher binding content makes the material thicker, so the machine has to work harder to produce pellets of the desired quality. At the 20% binder level, power consumption increases further to 0.88 kWh, with a power difference of 0.19 kWh from the 15% level. At 25% of the binder content, the increase in power consumption is smaller, with a difference of only 0.04 kWh and an average power consumption of 0.93 kWh. Further analysis showed that the average increase in power consumption for every 5% increase in the binder content was 0.10 kWh. This trend highlights that the levels of binder content of 15% and 20% correspond to the highest increase in energy consumption.

3.2. Performance of single-phase induction motors

The binding content has a reverse effect on the speed of the bio-pellet machine. As the fastener content and energy consumption increase, the engine speed decreases. The data in Table 3 shows a decrease in speed as the fastener content increases. At low binder content, raw materials tend to be easier to process because the consistency is non-sticky and does not burden the performance of the motor. This allows the machine to operate at optimal speed. However, as the binding content increases, the viscosity of the raw material also increases, adding an extra load to the machine. At 10% binder content, a significant decrease in speed was observed, with the motor speed dropping to 2713 rpm.

An increase in the fastening content of up to 15% led to a decrease in engine rotation speed (rpm) to 2,645, while at 20% fastening content, the speed dropped further to 2,550 rpm, and at 25%, rpm to 2,469. The speed of the engine, which is affected by the content of the binder, also has an impact on energy consumption. Machines that work harder to process thicker materials require more energy. This shows that the content of the binder not only affects speed but also impacts operational cost efficiency. The average speed difference due to an increase in binder content is approximately 80.25 rpm for every 5% increase in binder content, or 16.05 rpm for every 1% increase in binder content. These figure shows a general pattern that any increase in binder content adds resistance to engine performance. In addition, the relationship between the binder content and the speed of the machine suggests that materials with too high binder content can reduce operational efficiency, as seen from the decrease in rpm during operation.

3.3. Relationship between energy consumption and performance of single-phase induction motors

Using simple linear regression analysis, we can predict motor performance and power consumption by varying the binder content. In the context of this study, the independent variable is the binder content used, while the dependent variables include induction motor performance, power consumption, and production costs. This method can model the relationship between binder content and the dependent variable to understand how variations in binder content affect the overall system efficiency.

Through regression analysis, as shown in Table 4, we can determine the extent to which the binding content contributes to changes in motor performance. This allows us to identify the optimal binding content that results in the best motor performance with the most efficient power usage. Simple linear regression not only provides information about the relationships between variables, but also helps predict the value of dependent variables based on the content of a particular binder. This predictive model allows simulation with a variety of scenarios without the need to perform repeated physical tests. This saves time and resources in the process of research and development of bio-pellets.

On the Figure 2, it can be observed that energy consumption increases as the fastener concentration increases, while the performance of the motor decreases almost linearly in a linear manner. The cut-off point on the graph shows the concentration of the binder where the energy consumption and motor performance are balanced. Based on the curve, the cut-off point lies between the binding concentrations of 15% and 20%. This is a key marker for understanding the optimal efficiency limits of a bio-pellet production system. The cut-off point represents a significant change in energy consumption and motor speed. Before reaching this point, energy consumption remains relatively low even though the concentration of binders increases. However, after this point, energy consumption increases sharply, while the speed of the motor decreases drastically.

Table 3. Variations in fastening and performance of single-phase induction motors

Binding variation (%)	Speed (rpm)	Speed difference (rpm)
5	2,790	-
10	2,713	77
15	2,645	68
20	2,550	95
25	2,469	81
Average speed drop (rpm)		80.25

Table 4. Simple linear regression formula with binding variations

	Speed regression (rpm)			Energy consumption regression (kWh)		
X	Y	X2	XY	Y	X2	XY
5	2,790	25	13,950	0.55	25	2.73
10	2,713	100	27,130	0.56	100	5.56
15	2,645	225	39,675	0.69	225	10.37
20	2,550	400	51,000	0.88	400	17.66
25	2,469	625	61,725	0.93	625	23.19
75	13,167	1,375	193,480	3.60	1,375	59.50
a		2874.9			0.39	
b		-16.1			0.02	
n		5			5	

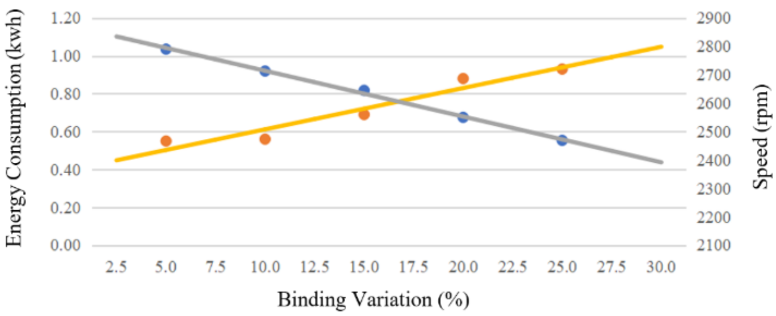

Figure 2. Regression results

Under the binding concentration of 15%, the system shows efficient performance. Low energy consumption and high motor speed indicate that the motor does not experience heavy mechanical loads, making it suitable for producing bio-pellets with optimal energy efficiency. However, low concentrations of binders can result in low-quality bio-pellets, such as lower density or resistance. On the other hand, a fastener concentration above 20% indicates that the motor is starting to operate beyond its efficiency limits. Energy consumption increased sharply, while motor speed decreased significantly. This indicates that the motor faces higher mechanical resistance due to increased fastener concentration. At this concentration, although the resulting bio-pellets may be of better quality, energy costs increase significantly, and the risk of motor damage increases. With the same bio-pellet weight (500 grams), linear regression analysis showed that the single-phase induction motor would stop spinning at a binding concentration of 178.57%, with a motor speed of 0 rpm, which far exceeded the available experimental data. With the maximum nominal load limit of the motor set at 5.66 A or an energy capacity of 1.09 kWh, the analysis shows that the motor will overheat and potentially burn at a binding concentration of 32%. This suggests that, in general, the binding concentration of 25% is close to the maximum operational capacity limit of the motor.

4. CONCLUSION

The results showed that every 5% increase in the binder content led to an average increase in energy consumption of 0.1 kWh, while the performance of single-phase induction motors decreased by an average of 80.25 rpm. The higher the fastener content, the more difficult the material will be to process, causing the motor speed to decrease and requiring more energy and operational costs. The optimal point based on the linear regression between energy consumption and motor speed performance is at a binding content of 15% to 20%. With a maximum nominal current of the motor of 5.66 A (or 1.09 kWh), there is a risk of the motor catching fire at a binding content of 32%. Since 25% is already close to that critical threshold, the recommended binding level for bio-pellet production is between 15% and 20%, which corresponds to the optimum of linear regression. Note: this study used tapioca flour dissolved in water as a binder. Further research can explore other types of binders to compare the quality of bio-pellets. In addition, mixing TKKS with other renewable biomass materials, such as coconut shells, can improve the overall quality of pellets.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Ediwan	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	✓
Arnawan Hasibuan	✓	✓				✓		✓	✓	✓	✓	✓		✓
Abubakar Dabet	✓		✓	✓			✓			✓	✓		✓	✓
Muhammad Daud		✓			✓		✓		✓					
Adi Setiawan	✓	✓		✓	✓	✓			✓	✓		✓	✓	
Fajar Syahbakti Lukman	✓			✓		✓	✓	✓	✓	✓	✓		✓	
Gandi Supriadi	✓		✓	✓	✓			✓	✓	✓		✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

DATA AVAILABILITY

Data not shared.

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BIOGRAPHIES OF AUTHORS

Ediwan is a Master's of Renewable Energy Engineering student at the Faculty of Engineering, Malikussaleh University, Aceh, Indonesia. He is also the manager of PT. PLN Persero UP3 Jambi, Indonesia. He can be contacted at email: ediwan@pln.co.id.

Arnawan Hasibuan he was born in Sei Liput, Keujruen Muda District, Aceh Tamiang, Indonesia, in 1972. At Malikussaleh University (UNIMAL), he is a lecturer in the field of electric power systems and the use of renewable energy. Currently, he works as an associate lecturer at the Faculty of Engineering, Malikussaleh University, Aceh, Indonesia. He works as a senior lecturer and researcher in the Electrical Engineering Undergraduate Program, the Renewable Energy Engineering Master's Program, and the Informatics Engineering Master's Program. In addition to teaching, he is also active as editor-in-chief of the Journal of Renewable Energy, Electrical Engineering, and Computers (JREECE) and the Journal of Dikara Community Solutions (JSMD). He can be contacted at email: arnawan@unimal.ac.id.

Abubakar Dabet is an associate professor at the Faculty of Engineering, Malikussaleh University, Aceh, Indonesia. He works as a senior lecturer and researcher in the Mechanical Engineering Undergraduate Program, the Mechanical Engineering Vocational Education Undergraduate Program, and the Renewable Energy Engineering Master's Program. He currently serves as the Head of the Department of Mechanical Engineering Vocational Education at the Faculty of Teacher Training and Education, Malikussaleh University. He can be contacted at email: abubakar@unimal.ac.id.

Muhammad Daud is an associate professor at the Faculty of Engineering at Malikussaleh University, Aceh, Indonesia. He works as a senior lecturer and researcher in the. Undergraduate Program of Electrical Engineering, Master Program of Renewable Energy Engineering, and Master Program of Information Technology. Interest in research in the field of power systems, renewable energy, and telecommunications. Apart from teaching, he is also active as Co-Chief Editor at the Journal of Renewable Energy, Electrical, and Computer Engineering (JREECE). Currently, as dean at the Faculty of Engineering, Malikussaleh University. He can be contacted at email: mdaud@unimal.ac.id.

Fajar Syahbakti Lukman has graduated Master's in Renewable Energy Engineering from the Faculty of Engineering, Malikussaleh University, Aceh, Indonesia in 2021. He's also an electrical engineer at PT. PLN Persero UP3 Lhokseumawe. Graduated as an engineer (Ir.) from the University of North Sumatra (USU) in 2022. Has a certificate (ASEAN Eng) registration of professional engineers issued by the ASEAN Federation of Engineering Organizations (AFEO). Administrator of the Indonesian Engineers Association (PII) in the city of Lhokseumawe. He can be contacted at email: fajar.sl@pln.co.id.

Gandi Supriadi is a Master’s student in Electrical Power Business Economics at the Faculty of Engineering, PLN Institute of Technology, Jakarta, Indonesia. He is also the Team Leader of the Distribution Operation System at PT. PLN (Persero) UP3 Jambi, Indonesia. He can be contacted at email: gandi.supriadi@pln.co.id.