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Mechanical, Chemical and Physical Characteristics of Palm Kernel Shell and Polystyrene Mixture Pellets

Syafiq Syahidan Mohamad[1], Mohd Hafif Basha[1,*], Nasrul Amri Mohd Amin[1], Ras Izzati Ismail[1], Md Tasyrif Abdul Rahman[1], Mohd Fadzli Hamid[2]

[1] Faculty of Mechanical Engineering & Technology, Universiti Malaysia Perlis, 02600, Perlis, Malaysia
[2] School of Innovation, Science and Technology, TAJ International College, 30100 Ipoh, Perak, Malaysia

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ABSTRACT

The pelletization of biomass has the potential to replace fossil fuels as a source of energy. Pellet characteristics such as high durability and low moisture content are essential for making a good pellet. There are currently no studies on the physical, chemical, and mechanical properties of pellets made from a mixture of Palm Kernel Shell (PKS) and Polystyrene Plastic (PS). The focus of this research is to analyze the effect of different PS mass percentage on the physical, chemical, and mechanical properties of PKS-PS pellets. The PKS-PS mixture percentage is varied from 100%-0%, 70%-30%, and 50%-50% with varying corn starch binder percentages of 0%, 2%, and 4%. From the findings, increasing the PS mass percentage in the mixture decreases the density and moisture content. Furthermore, increasing the PS mass percentage increases the volatile matter while decreasing the ash content. Compressive strength and impact resistance increase significantly with higher PS mass percentage. Adding corn starch as a binder agent increases the impact resistance and compressive strength of the pellet, regardless of the PKS-PS mixture percentage. To conclude, producing pellet blends of PKS and PS utilizing corn starch as a binder agent has excellent results for both mechanical properties testing, resulting in high-quality pellets that are less prone to breaking during combustion.

1. Introduction

Biomass is one of the renewable energy sources that may be generated from the organic waste of plants and animals. Various materials can be found as biomass resources that can produce bioenergy such as wood, straw, seed waste, sawdust, paper waste, manure, household, waste, and more. Biomass resources from the agriculture industry, especially waste, benefit the economy and the environment because they are frequently cheap and consistent. Thus, using waste from the agriculture industry may significantly reduce the issue of dumping and open burning [1].

Furthermore, since biomass resources are readily available, it is feasible to produce pellets from biomass and utilize them as a co-fired fuel in conventional power plants [2]. Biomass pellets have a

* *Corresponding author.*
E-mail address: hafifbasha@unimap.edu.my

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lot of potential as a renewable energy carrier that can replace the usage of fossil fuels. Because of its high moisture content, low energy density, and variable particle size and structure, raw biomass is difficult to utilize as a solid fuel [3]. Hence, biomass density is increased by compressing it by applying pressure to break down its cell structure into pellets using a mechanical process [4]. Pelletization is also an essential technique in biomass. Compared to raw biomass, the pelletizing process may reduce density and moisture, resulting in a more consistent solid fuel with better heating efficiency and shape uniformity, ash reduction, and clean burning.

To begin with, palm oil is one of the fastest-growing high demands in the world and makes an important contribution to the economy, especially in Malaysia [5]. For many years, Malaysia has been recognized as one of the world's most productive palm oil producers. Agencies like the Federal Land Development Authority (FELDA), Federal Land Consolidation and Rehabilitation Authority (FELCRA), and Malaysian Palm Oil Board (MPOB) have engaged in the palm oil industry. However, oil palm is produced on plantations after a few decades of rotational cultivating, followed by expulsion and replanting. When being planted numerously, the issue of the abundance of biomass waste arises. There are many types of oil palm biomass waste such as oil palm trunks (OPT), oil palm fronds (OPF), palm kernel shells (PKS), empty fruit bunches (EFB), pressed palm fibres (PPF), oil palm leaf (OPL), and mesocarp fibre (MF) [6].

This work focuses on utilizing palm kernel shells as an energy source. As mentioned above, the palm oil industry in Malaysia produces a considerable amount of biomass waste, which is difficult to dispose of [7]. The shell fractions left after the nut has been stripped after grinding in the palm oil mill are known as palm kernel shells (PKS). Kernel shells are a fibrous material that can be conveniently treated in bulk from the production line to the final application. Dust-like fractions and thin fibre are mixed with large and tiny shell fractions[7]. Also, palm kernel shells are mostly employed as a boiler fuel to replace fossil fuel in a palm mill. This is due to its high carbon content, and high calorific value while having low ash content [8]. Palm kernel shells have been sold as an alternative fuel in recent years all over the world.

Polystyrene (PS) is a popular and commonly used plastic that is both inexpensive and durable. It is clear but can be coloured by adding colourants. It is heat resistant, lower in weight, and has good strength and durability, making it suitable for a wide range of applications. Most polystyrene waste is currently disposed of in landfills rather than recycled, owing to the difficulty of sorting and cleaning the material [9]. To put it another way, this sort of plastic cannot be recycled using the normal process of recycling and needs a more expensive and time-consuming method of recycling [10]. There was previous research that utilised PS as a feedstock or co-feedstock to biomass waste for energy conversion. Jeong *et al.,* [11] performed two-stage air gasification to produce hydrogen-rich gas. The authors concluded that clean, tar-free hydrogen gas can be produced with the right parameters and equipment. Basha *et al.,* [12] co-gasified PKS with PS with air as its gasifying agent. It was concluded that mixing PKS and PS is promising, due to the produced gas having high energy value.

The feasibility of using PS as feedstock or co-feedstock for the thermochemical conversion process has been documented in previous research. However, to improve the logistics of these feedstock, the densification process of these feedstock is imperative. To date, research on the pelletization of a mixture of biomass and plastics, let alone PS, is scarce. Thus, the main goal of this research is to determine the feasibility of producing densified pellets made from blends of palm kernel shells and polystyrene plastics. The focus of this study is to analyze the effect of the PKS-PS mass fraction and the presence of a binder agent on the physical, chemical, and mechanical properties of PKS-PS pellets. The physical properties include the density, impact resistance and moisture content of the pellets. The chemical properties include the volatile matter, ash content and fixed carbon of the pellets. The mechanical properties of the pellet include the compressive strength of the pellets.

2. Methodology

2.1 Material Preparation

Palm kernel shell (PKS) waste was selected as the primary source of biomass material used to produce pellets in this research. The palm kernel shell was taken from the FELDA Palm Oil Industries Sdn.Bhd, Kemahang, Kelantan. Polystyrene (PS) is used as the co-feedstock for this study. PS granule was procured from Dow Plastics. The binding agent used in this study is food-grade corn starch, procured from local supermarkets. The feedstocks were ground to obtain the particle size of 0.5 mm – 1 mm.

2.2 Pelletization

1 g of the samples with a different mass fraction of palm kernel shell and polystyrene mixture which is 100% (meaning: 100% PKS), 70-30 (meaning: 70% PKS 30%PS), 50-50 is prepared. Then, the sample is mixed with the desired percentage of corn starch as a binding agent. The pellet is produced using a single hydraulic press with a pressure of 3 tonnes. 30 – 35 pellets were produced for each sample, and each analysis was repeated three times.

2.3 Pellet Properties Testing

2.3.1 Density

The density of matter measures how much matter is present in a particular volume. The density of matter is an essential physical attribute used to identify and categorize materials. Density refers to the compactness of the material being crushed into pellets in pellet production. The density of the raw material is also significant in pellet manufacturing since denser raw materials may be crushed more effectively into pellets with greater density and energy content.

Density was formulated by the mass proportional to the volume of the material substance. It indicates that mass is above volume when calculating the density value. Also, a weighing scale must be used to determine the raw material's mass. Vanier Caliper equipment will be used to measure the pellet's height and length throughout production to determine the pellet's volume. In calculating the total density, the recorded mass and volume were entered in Eq. (1).

$$\rho = mv \tag{1}$$

where:
ρ = density (g/cm^3)
m = mass (g)
v = volume (cm^3)

2.3.2 Moisture content

Moisture content was one of the most critical elements influencing pellet characteristics [13]. Sufficient moisture may aid in developing internal adhesives from lignocellulosic materials. The author also noted that the raw material's water content, along with heat generated by pellet machines or steam, would aid in physical and mechanical changes such as biomass softening, protein denaturation, starch gelatinization, and sugar crystallization. Furthermore, the moisture content is reported as a percentage of the initial sample mass. It significantly impacts other pellet properties such as heating value, combustion efficiency, durability, and bulk density.

Furthermore, moisture's function as a lubricant and binding agent, as well as the interaction between moisture and lignin during compression, resulted in a more condensed structure and an increase in binding forces between individual particles, which is consistent with earlier research [14]. Varying additives need different quantities of moisture content in the raw material to bind the substance efficiently[15].

The pellets' moisture content was measured using an AND MX-50 moisture analyzer. The moisture content of the pellets was determined by putting around 1 gram of sample into the moisture analyzer. Moisture content was set at low accuracy and 105 °C as temperature. Then, the results will be shown through the screen of the moisture analyzer.

2.3.3 Volatile matter

Volatile Matters (VM) are compounds in fuels such as methane, hydrogen, and unburned gas. Because of the volatile materials, most of the calorific value would be released as vapour combustion. The volatile matter is an essential factor in the production of pellets because it can affect the energy content, combustion energy, and storage stability of the pellets [16].

ASTM E872 standard is used to measure the VM. To measure the VM, the Initial sample pellet is weighted before being inserted in a muffle furnace. The temperature of 950 ± 20 °C is maintained for 7 minutes. The sample pellet was allowed to cool to room temperature once the combustion process was complete. The sample's final weight was then measured. The VM is calculated using Eq. (2).

$$Volatile\ matter = \frac{Initial\ mass - Final\ mass \times 100}{Initial\ mass} - moisture\ content\ \% \tag{2}$$

2.3.4 Ash Content

Ash content describes the percentage of inorganic mineral materials in a fuel or meal. The amount of ash created during combustion and inorganic material contained in the raw material used to form pellets may be considered "ash content." The heating value, handling qualities, and environmental effect of a fuel may all be affected by its ash concentration. Thus, it is necessary to take these into account. Pellet stoves and boilers are similarly susceptible to ash's adverse effects, such as blocking the burn pot or chimney and necessitating periodic cleaning. Thus, having a low concentration of ash residue after combustion is suggestive of an efficient and clean-burning process [17].

The ash content measurement is performed in accordance to ASTM E1755 standard. The ash content percentage was determined by measuring the mass of the residue left after heating the sample in the air at a controlled temperature of 575°C for 5 hours in the Muffle Furnace. The pellet samples were then allowed to cool at room temperature before final measurement samples were taken. The formula used to determine the ash content in dry mass is shown in Eq. (3).

$$Ash\ Content = \frac{Final\ mass\ \times 100}{Initial\ mass} \tag{3}$$

2.3.5 Fixed carbon

Fixed carbon is the amount of carbon in a material that is not quickly released as carbon dioxide when heated. Fixed carbon is a crucial concern in pellet manufacture since it is connected to the energy of the pellets. As a result, pellets having a more excellent fixed carbon content will have higher energy content and be more suited for usage as a fuel. Not to mention the fixed carbon content of pellets, which impacts the energy content and performance in applications where the pellets will be utilized as fuel. Fixed carbon calculations in made following the procedures written in ASTM E870-82. Fixed carbon is calculated by subtracting the mass of volatile matter (VM), moisture content, and ash content from the original mass of the sample, as shown in Eq. (4).

$$Fixed\ Carbon = 100 - moisture\ content\ (\%) - \ Volatile\ matter(\%) - Ash\ Content\ (\%) \tag{4}$$

2.3.5 Compressive strength

A pellet's compressive strength measures its resistance to crushing under compressive stresses. It is a crucial property of pellets since it influences their capacity to survive handling and transit without breaking. A pellet's compressive strength is evaluated by applying a compressive load and measuring the most significant force at which it fractures or deforms. Moreover, the axial meaning of compressive strength testing in relation to pellets refers to the measurement of the maximum amount of compressive stress a pellet can withstand before it breaks or deforms. The pellet is typically placed between two plates or cylinders and compressed along its axial direction. The force required to compress the pellet is gradually increased until the pellet breaks or deforms. The compressive strength of the pellet is then calculated as the maximum compressive stress that the pellet can withstand before failure.

The pellet's axial strengths were tested using a testing compression machine, with the pellet sandwiched between the plates. The specimen was subjected to 1 mm/min of compression until cracking or breaking occurred. Compression strength was defined as the amount of force that could cause the material to deform to its maximum. The compressive strength is determined using the methodology specified in the Shimadzu Autograph AGS-X 250 kN Universal Testing Machine.

2.3.6 Impact resistance

Impact resistance is a critical quality for pellet-making materials since it influences how effectively the pellets can endure physical impacts without breaking or deteriorating. This is particularly critical in situations where the pellets will be handled or transported over long distances or exposed to harsh handling or other mechanical forces.

The impact resistance was tested when the pellets were dropped from a height of roughly 1.5 m. After releasing the pellets, the sample weight is calculated by picking the heaviest pellet. Thus, the impact resistance was then determined by dividing the final weight by the original weight and multiplying the result by 100 as is shown in Eq. (5).

$$Ash\ Content = \frac{Final\ mass\ after\ drop\ \times\ 100}{Initial\ mass} \tag{5}$$

3. Results

3.1 Density of Pellets

Figure 1 shows the density with various PS mass percentages of the pellets with various percentages of corn starch as a binder agent. The density decreases when more PS is mixed in the pellet. This was due to PS being a thick and heavy plastic substance, while PKS is a lightweight and porous biomass material [18]. When these materials are combined, the lightweight PKS fibres may form voids or pockets within the mixture, lowering the overall density of the pellets. PS is also a thermoplastic, which softens when heated and hardens when cooled. Also, PS may lose part of its density during the pelletization process owing to its thermoplastic nature.

Furthermore, adding corn starch from 0% to 4% improves the density of each percentage of 100% PKS (2.86% to 3.14%), 70-30% (2.57% to 2.82%), and 50-50% (2.51% to 2.54%). The starch molecules absorb water, expand, and gel, which aids in holding the PKS particle together, resulting in a more compact structure. Greater compactness lowers the space between particles, resulting in increased density. However, it can be seen that when a higher PS mass percentage in the pellets, the increment of density when starch is near negligible.

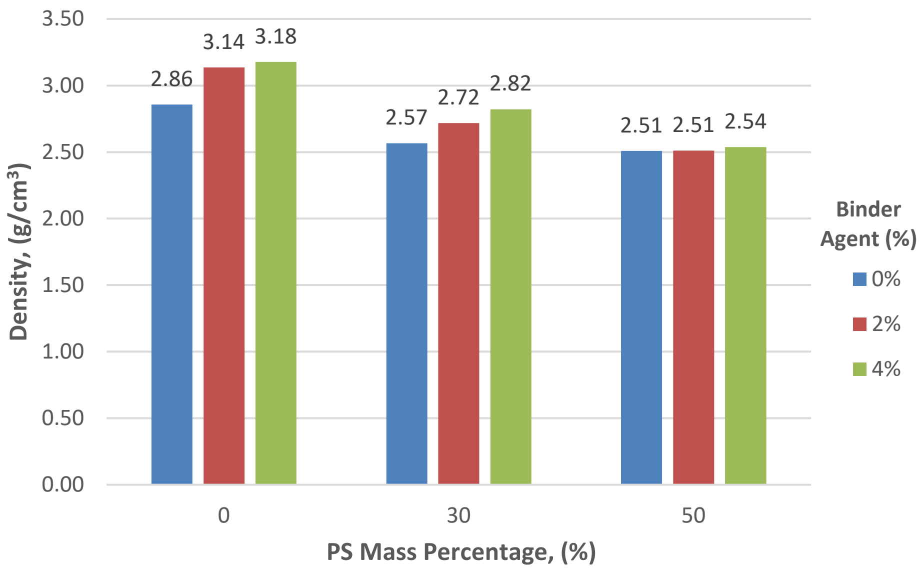

Fig. 1. The effect of polystyrene mass percentage and presence of binder agent on the density of the pellet

3.2 Moisture Content

The effect of different PS mass percentages of the PKS-PS pellets on the moisture content of the pellets is shown in Figure 2. The data illustrates that moisture content decreased with increasing percentages of PS and corn starch. It can be said that when more PS is mixed with PKS, the moisture content decreases. This is because polystyrene is a hydrophobic substance that does not absorb water readily [19]. As a result, the total moisture content of the pellet combination will be reduced. Furthermore, using polystyrene might limit the porosity of the pellet, resulting in less surface area for water to attach. The binding ability of PKS and PS may also decrease moisture content since PS may not bind as efficiently as other materials, resulting in less moisture retention in the pellets.

When corn starch was added from 0% to 4%, the results also decreased for each different mass percentage of polystyrene. As a result, adding corn starch as a binder agent to a combination of PKS and PS causes the moisture content of the pellets to drop. Senila *et al.,* [20] state that a moisture content of 6-12% delivers more excellent performance, resulting in a 30% PS addition that is acceptable in pellet production.

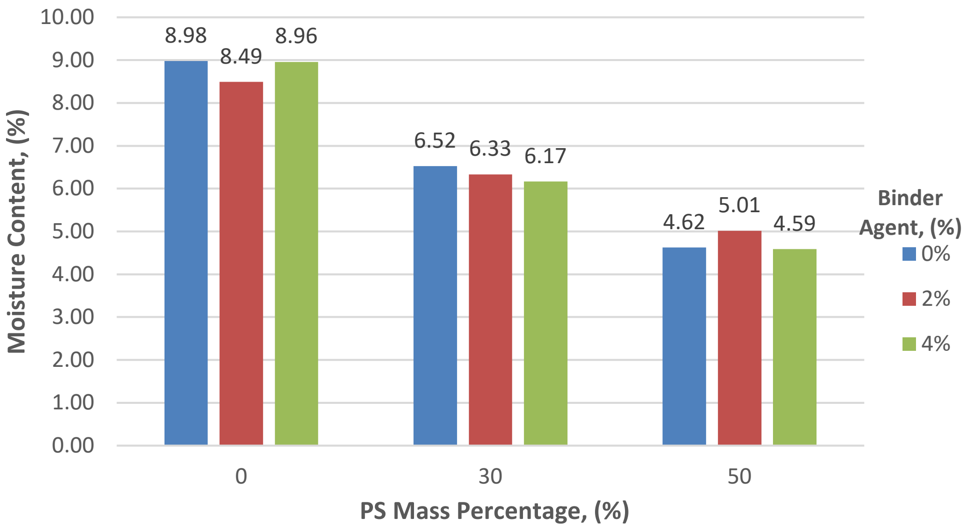

Fig. 2. The effect of different polystyrene mass percentages and the presence of binder agent on the moisture content of the pellet

3.3 Volatile Matter

Figure 3 shows the effect of different polystyrene mass percentages and the presence of binder agent on the volatile matter percentage of the pellet. As we can see, a higher PS mass percentage in the PKS-PS pellet will result in higher volatile matter. This is because polystyrene is a hydrocarbon-based plastic which has higher volatile matters compared to biomass. Increasing the mass percentage of PS in the pellet will result in the increase of the pellets volatile matter.

When corn starch was added, the volatile matter doesn't change much. The small amount of corn starch added is not significant enough to change the volatile matters of the pellets. Therefore, when added to the PKS mixture, it does not affect the volatile matter content of the pellets.

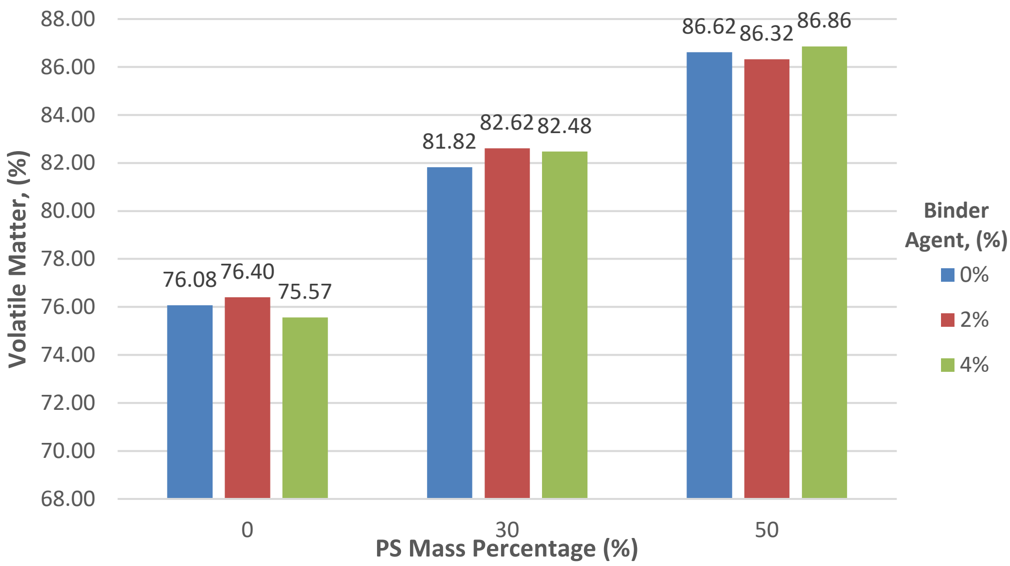

Fig. 3. The effect of different polystyrene mass percentages and presence of binder agent on the volatile matter percentage of the pellet

3.4 Ash Content

The effect of different PS mass percentages of the PKS-PS pellets on the ash content of the pellets is shown in Figure 4. The findings showed that the ash content varied from 6.49% to 11.91%. With increasing PS percentage in the pellet, the ash content decreases. This was because polystyrene is a synthetic polymer that does not include ash-forming elements, thus when PS percentage is increased in the mixture, the ash content of the pellet will decrease.

With the addition of corn starch, the ash content shows a small reduction for all PS mass percentages of the PKS-PS pellet. This is due to the absence of ash-forming components such as minerals and metals in corn starch. Lower ash content has its advantages. According to Rashedi *et al.,* [21], pellets with a lower ash content are less likely to lose their shape during storage. A previous study by Gilvari *et al.,* [22] also states that pellets with a lower ash content are less prone to storage deterioration and have a higher resistance to moisture absorption.

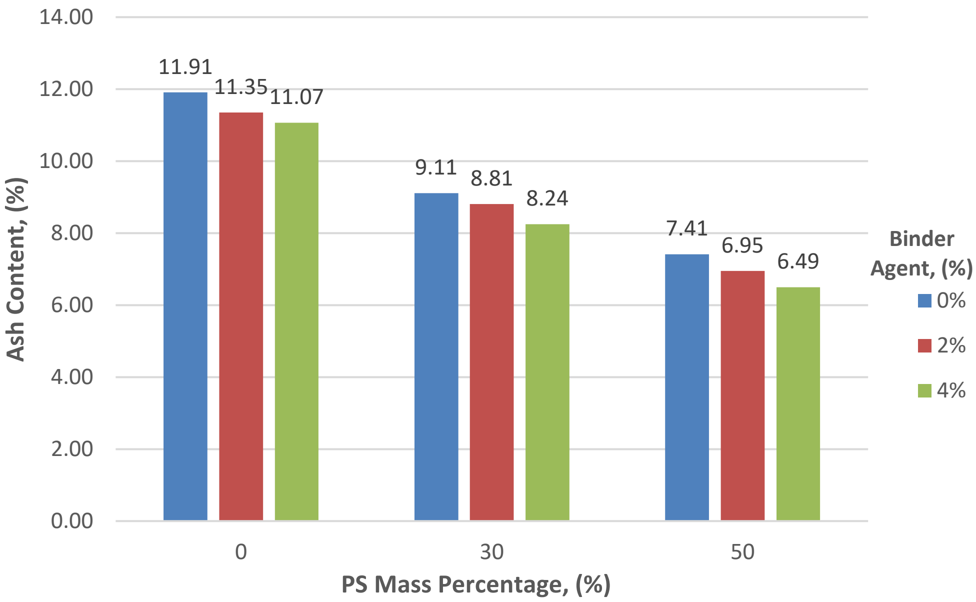

Fig. 4. The effect of different polystyrene mass percentages and presence of binder agent on the ash content of the pellet

3.5 Fixed Carbon

Figure 5 shows the fixed carbon with various percentages of PS and corn starch of the pellets. As we can see, the fixed carbon decreases when more PS is mixed with PKS. This is because polystyrene is a synthetic polymer that contains a very small amount of fixed carbon. Additionally, when corn starch was added from 0% to 4%, the fixed carbon increased for each percentage of 100% PKS (3.04% to 4.40%), 70-30% (2.54% to 3.11%), and 50-50% (1.34% to 2.06%).

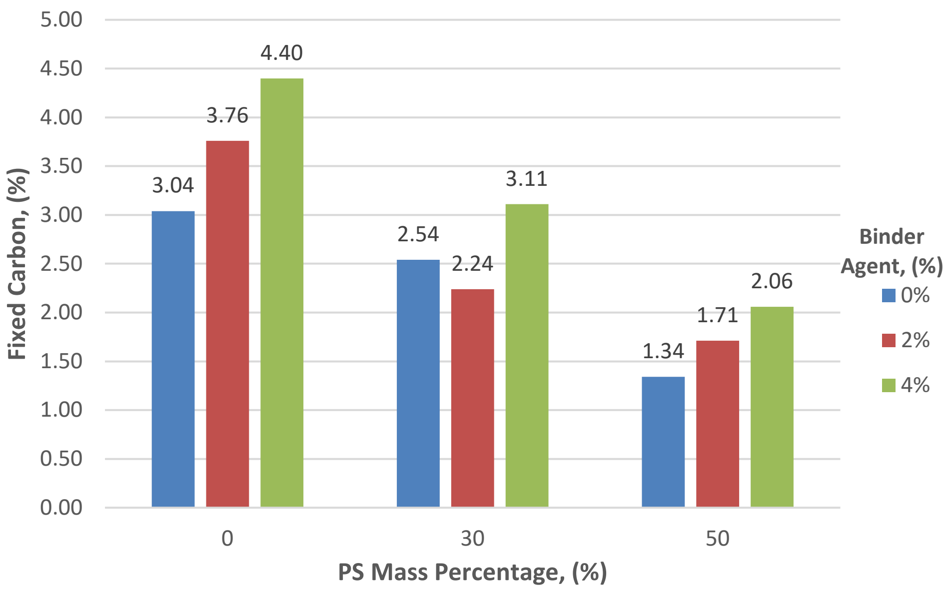

Fig. 5. The effect of different polystyrene mass percentages and presence of binder agent on the fixed carbon of the pellet

3.6 Compressive Strength

The compressive strength of varying percentages of PS and corn starch increases, as shown in Figure 6, with the maximum compressive strength being 21.60% at 30% PS mass percentage and 4% corn starch and the lowest compressive strength being 11.22% at 0% PS mass percentage with no addition of corn starch. As a result, adding PS to PKS may enhance the compressive strength of the pellets. This is because polystyrene is a solid and rigid material that may improve the overall strength of the pellet combination.

Furthermore, when corn starch was added from 0% to 4%, the compressive strength increased for every percentage of PS in the PKS-PS pellets. These results agree with the findings of Ismail *et al.,* [23] where the compressive strength increases when 4% of starch binder agent is added to the pellet mixture. Corn starch is a natural polymer that aid in bonding PKS and polystyrene particles.

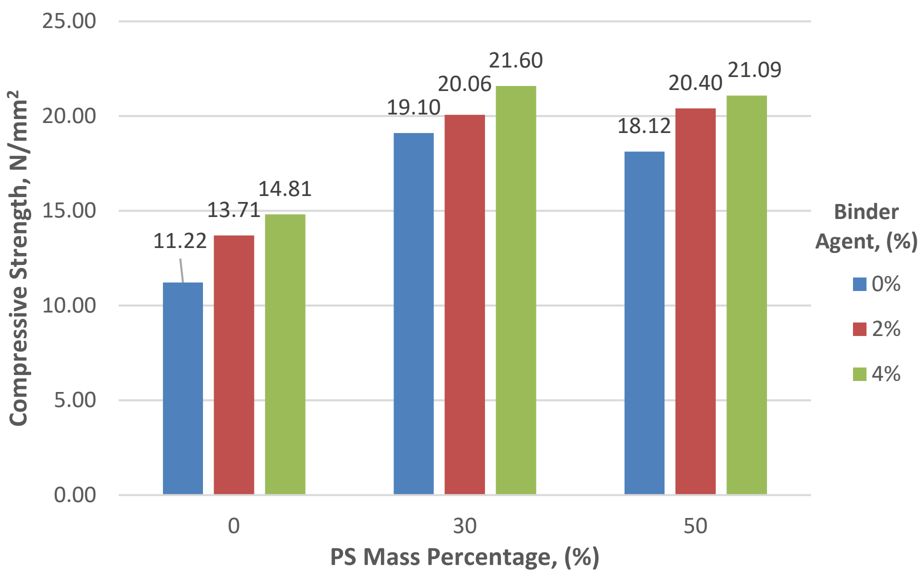

Fig. 6. The effect of different polystyrene mass percentages and presence of binder agent on the compressive strength of the pellet

3.7 Impact Resistance

Figure 7 shows the effect of different polystyrene mass percentages and presence of binder agent on the impact resistance of the pellet. The result shows that the maximum impact resistance comes from 50% PS mass percentage, which is 91.58%, and the lowest comes from 0% PS percentage, which is 87.03%. The way polystyrene absorbs energy causes an increase in impact resistance when PS is added. Polystyrene has a unique structure that enables it to operate as a shock absorber, which means that when an impact force is delivered to the pellet, the polystyrene will disperse the energy equally over the pellet rather than concentrating all of the stress in one location. This may assist in keeping the pellet from breaking or deforming when it hits the ground. Polystyrene also has a high modulus of elasticity [24], which means it may be stretched and bent without breaking. As a result, the pellet may absorb the impact energy. Combining these polystyrene qualities may aid in increasing impact resistance.

Further, the impact resistance increased with each percentage of PKS and PS added from 0-4% corn starch. When corn starch is added to the mixture and heated, it forms a gel-like structure that aids in the hardness and flexibility of the pellets. This may assist in absorbing impact energy and keep the pellet from shattering. It can also assist the pellet in keeping its shape and size throughout handling and transport, which may help avoid deformation during these procedures.

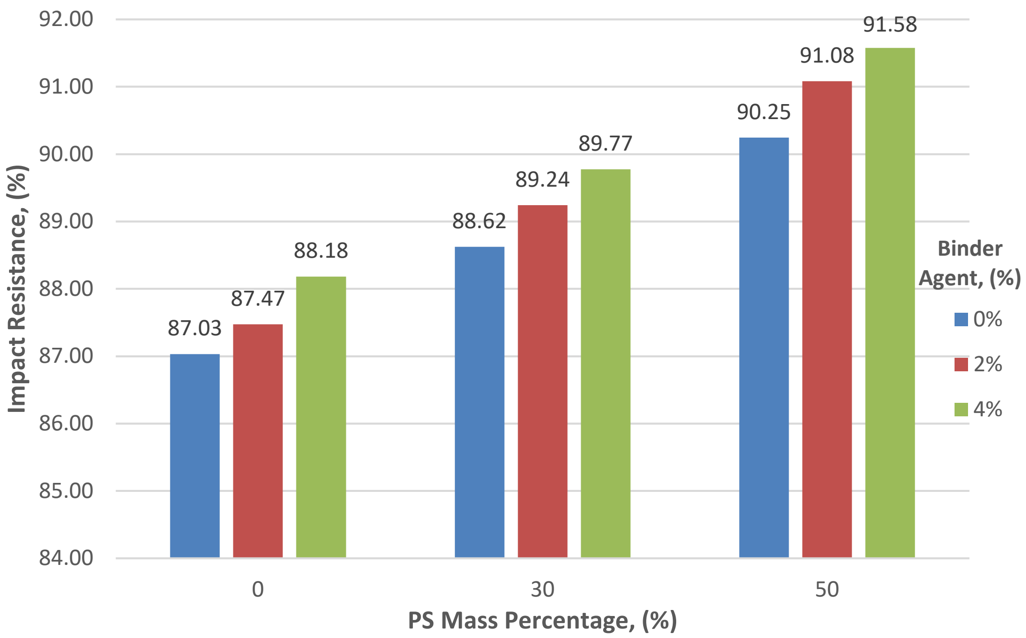

Fig. 7. The effect of different polystyrene mass percentages and presence of binder agent on the impact resistance of the pellet

4. Conclusions

From the findings, increasing PS mass percentage decreases the density and moisture content. Furthermore, adding a higher PS mass percentage increases the volatile matter while decreasing the ash content. The growth in the volatile matter may increase the energy content of pellets, making them more efficient to burn. In contrast, the lower ash content is desirable as they produce less ash during combustion. The increment of volatile matter causes the fixed carbon to decrease with increasing PS mass percentage in the pellet mixture. Furthermore, when a higher mass percentage of PS is blended in the PKS-PS pellet, compressive strength and impact resistance increase significantly, which benefits pellet production by making them more resistant to breakage during handling and transportation.

For the study on the effect of the presence of corn starch as a binding agent at three different percentages, that is, 0%, 2%, and 4% on the physical, chemical, and mechanical properties of pellets made from PKS-PS, the finding illustrates that adding 4% of corn starch resulted in higher mechanical properties for impact resistance (from 88.18% to 91.58%) and compressive strength (from 14.82% to 21.09%). In summary, the results show that combining PKS and PS in the production of pellets produces a diverse range of outcomes and is a suitable combination since they both have strong mechanical properties.

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