ADVANCES IN AGRICULTURAL AND FOOD RESEARCH JOURNAL

Original Research Article

Physiochemical Assessment of Powdered and Pelletized Sweet Potato (*Ipomoea batatas)* Plant Parts for Potential Animal Feed Applications

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Abstract: This study delves into the potential of utilizing various components of the sweet potato plant (*Ipomoea batatas*) for animal feed production, focusing on leaves, stems, tubers, and peels processed into powdered and pelletized forms. Proximate analysis is employed to ascertain their characteristic properties. The investigation aims to determine the viability of marketing sweet potato plant parts as a technical-grade powder for animal feed formulation. Powder properties are thoroughly examined, including cohesion, caking, and powder flow speed dependency. Simultaneously, the research uses a compaction process to explore the feasibility of generating animal feed pellets from underutilized sweet potato leaves and stems. Pellets are formulated at a 1:1 ratio of leaves to stems, with the moisture content varying from 40% to 60%. Evaluations encompass friability, bulk density, true density, porosity, and tensile strength. Results highlight that sweet potato plant parts, mainly leaves and stems, contain substantial nutritional substances, rendering them suitable for animal feed production. Flowability analysis categorizes the powders as stable and free-flowing. Moreover, the study pinpoints the optimal moisture content for pellet production at 60%, showcasing the formulation's lowest friability (0.30%), lowest bulk density (629.5 kg/m^3), highest porosity (56.51%), and highest work of compression (303.79 kg.s). This formulation also yields superior tensile strength than other moisture-content formulations for sweet potato leaves and stem pellets. The comprehensive findings underscore the potential of sweet potato plant components in animal feed production, presenting a sustainable alternative with nutritional benefits.

Keywords: animal feed; by-products; proximate; sweet potato; waste utilization

Received: 19th July 2024

Accepted: 17th October 2024

Available Online: 10th December 2024

Published: 31st December 2024

Citation: Zakaria, N. Z., Nor, M. Z. M., Zabidi, N. 'A., *et al.* Physiochemical assessment of powdered and pelletized sweet potato (*Ipomoea batatas*) plant parts for potential animal feed applications. *Adv Agri Food Res J* 2024; 5(2): a0000550. https://doi.org/10.36877/aafrj.a0000550

1. Introduction

Sweet potatoes flourish globally in humid tropical and subtropical regions, with a short growing period of 90 to 120 days, making them pivotal crops in developing nations (Low *et al*., 2020). Sweet potatoes are among the top seven crops globally, contributing to over 135 million metric tons of edible food products annually (Sapakhova *et al*., 2023). Their popularity stems from high yield, versatility, resilience, and adaptability to various ecological conditions (Sanoussi *et al*., 2016). In Malaysia, sweet potatoes hold significant agricultural importance, ranking second among tuber crops after cassava in production since the 17th century (Hanim *et al*., 2014). Notably, purple sweet potatoes such as the Anggun variety, distinguished by their purple-coloured flesh rich in anthocyanin pigment, offer enhanced nutritional value. Anthocyanins exhibit antioxidant and anti-inflammatory properties crucial in disease prevention, including neurological and cardiovascular disorders, cancer, and diabetes (Ochoa *et al*., 2020; Yusoff *et al*., 2018).

While previous research has mainly focused on using the tuber part (Sawicka *et al*., 2020; Behera *et al*., 2022), sweet potato plants' leaves, stems, and skins have been largely overlooked. Despite their considerable nutritional value, these underutilised plant components are often discarded as "waste" without proper management, potentially leading to environmental repercussions. Therefore, optimizing the utilization of these plant parts is crucial for enhancing sustainability while mitigating environmental impact. In the pursuit of implementing circular economy principles within the industrial sector, waste valorization has emerged as a promising approach to address waste management challenges while upholding environmental sustainability (Garcia-Garcia *et al*., 2019).

One alternative is to explore the potential of utilizing the inedible parts of sweet potatoes to produce low-cost, nutrient-rich feed alternatives. Today, animal feed production faces numerous challenges, such as poor nutrition, limited fertile land, climate change, and competition for food, fuel, and feed resources (Pulina *et al*., 2017; Valdez-Arjona *et al*., 2019; Tayengwa *et al*., 2018). These issues arise from inadequate management of degraded grazing lands and insufficient green forage production, leading to feed shortages for a large population of animals. Overgrazing is a common problem in Malaysia, leading to rapid pasture degradation and excessive soil nutrient depletion (Shah *et al*., 2019). This situation highlights the need to explore cost-effective, nutritious feed alternatives to replace grazing forages and improve herbivore productivity (Pino *et al*., 2019). Sweet potato stems and leaves emerge as promising substitutes to alleviate feed scarcity for herbivores, offering economic benefits while supporting environmental sustainability. Recent studies have highlighted the nutritional richness of sweet potato leaves, which are abundant in ß-carotene, vitamin B, protein, calcium, zinc, and iron (Chirwa-Moonga *et al*., 2020). Specific cultivars of purple-fleshed sweet potatoes demonstrate a high tolerance to diseases, pests, and moisture, making them favourable vegetable options (Cartabiano-Leite *et al*., 2020).

This can be achieved by exploring the benefits offered by these parts and aligning them with the basic requirements for animal feed production. Furthermore, the production will need to undergo product processing. From a processing standpoint, pelletization presents a viable method for sweet potato utilization in animal feed production. Compaction processes, including compression, extrusion, and globulation, enhance pellets' physical properties and nutritional value, rendering them more digestible and palatable for animals (Zainuddin *et al*., 2014). However, limited research exists on the physicochemical properties and pelletization processes tailored explicitly to sweet potato stems and leaves for herbivore feed applications. Understanding compaction properties such as true density, bulk density, porosity, and tensile strength is essential to optimize the densification process further and design energy-efficient compaction equipment (Styks *et al*., 2020). Therefore, this study aims to evaluate the physicochemical properties of sweet potato plant components. Besides this study also explores the feasibility of generating animal feed pellets from underutilized sweet potato leaves. It stems through a compaction process, enhancing their suitability for animal feed applications.

2. Materials and Methods

Purple sweet potato plants (*Ipomoea batatas*) species from variety Anggun 1 were collected from a sweet potato plantation in Semenyih, Selangor, Malaysia, as shown in Figure 1. Given its high nutritional content and market demand, Anggun 1 was selected for this study due to its abundant production and anticipated growth potential compared to other local sweet potato varieties. The sweet potato samples, including leaves, stems and tubers, were stored in a chiller at 12°C for further analysis.

Figure 1. Sweet potato plantation in Semenyih, Selangor, Malaysia.

2.1 Preparation of Powders from Leaves, Stems, Tuber and Peels of Sweet Potato Plant

The leaves, tubers, and stems were separated and cut down to 2 to 3 cm in similar uniform sizes. Subsequently, they were placed into the aluminium foil, as shown in Figure 2. All samples were dried in the oven (OF-G22W, Jejo Tech, Korea) at 50°C for 72 hours to preserve the nutritional content of the materials. The samples were ground and sieved at 250 µm using a mill grinder (Retsch, SM200 Rostfrei, Germany). Feeds without large (>1 mm) particles are most rapidly digested after being chewed (Svihus *et al.*, 2024). The dried samples were kept in a chiller for further analysis.

Figure 2. Anggun one sweet potato leaves stems, peels, and tuber samples in the form of (a) fresh, (b) dried and (c) ground and sieved.

2.2 Pellets Production from Stem and Leaves Powders of Sweet Potato Plant through Compaction Process

For the compaction process, all the powder samples of leaves and stems were mixed at a ratio of 1:1. The sample was then moisturized with water with different moisture levels (40%, 45%, 50%, 55% and 60%). The moisture can affect the physicochemical and stability of the pellets (Lisowski *et al.*, 2020). The chosen range of moisture content (40%–60%) was determined because the equipment used, a manual noodle maker, functioned effectively only with the sample exceeding 40% moisture content. The moisture content of the sample was measured based on a wet basis. The samples with the desired moisture content area were prepared by adding distilled water, as in Equation 1.

$$Q = \frac{Wi\ (Mf - Mi)}{100 - Mf} \quad [1]$$

where Q is the mass of distilled water added (kg), Wi is the initial mass of the sample (g), Mi is the initial moisture content mass of the sample in % (dry basis), Mf is the final moisture content of the sample in % (dry basis.).

After the compaction process, the pellets were obtained with different moisture content. The length of each of the pellets was 1.4 to 3 cm. According to the Bureau of Rice Research and Development (2012), standard sizes for pelleting biomass indicate that first-class pellets must be smaller than 8.0 mm in diameter and less than 3.2 cm in length. The pellets, known as sweet potato leaves and stems (SPLS), with different moisture content, are shown in Figure 3.

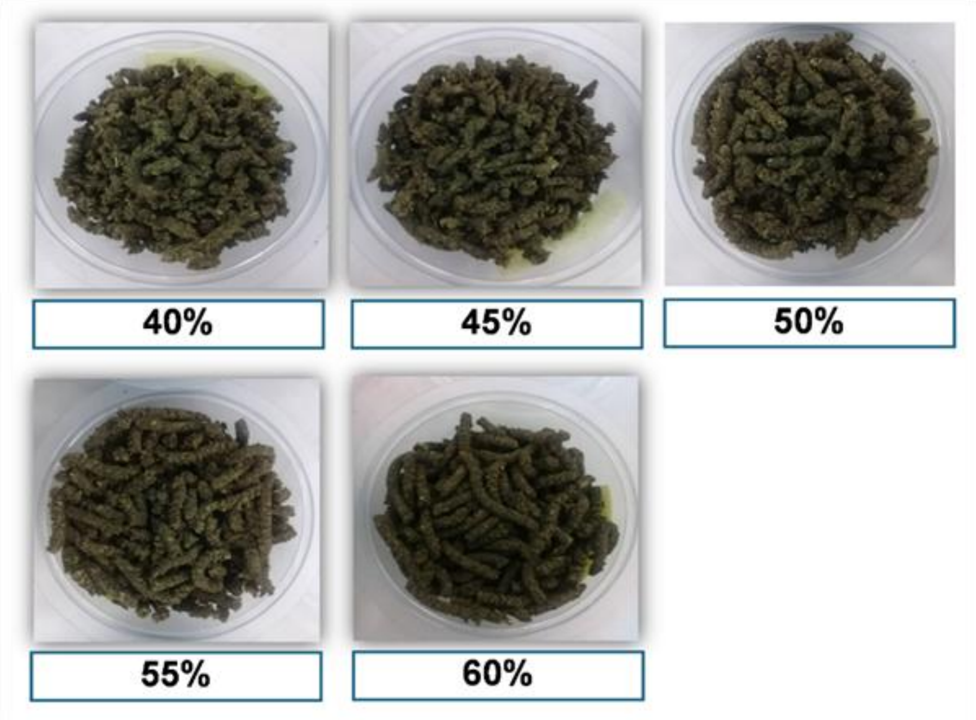

Figure 3. A mixture of stems and leaves of the Anggun 1 sweet potato plant in pellets form with different moisture content.

2.3 Sweet Potato Plant Powders Analyses

2.3.1 Cellulose, hemicellulose, and lignin content

The hemicellulose, cellulose and lignin content were measured using a Thermogravimetric Analyzer (TGA) (TGA/SDTA851e, Metler Toledo, USA). Approximately 10 mg of the sample dried in an oven was placed in a crucible made of alumina ceramic. The samples were heated within a temperature range of 30°C to 600°C at a heating rate of 10°C per minute while being purged with 10 mL per minute of nitrogen gas. Subsequently, the temperature was raised to 900°C using the same rate while flushed with 10 mL/min of air (Volpe *et al.*, 2020).

2.3.2 Proximate analysis

The powder sample underwent a proximate analysis to determine its composition, including parameters such as total ash, moisture content, total fat, protein, carbohydrate, energy, and crude fibre content, using the AOAC protocols (Horwitz, 1964).

2.3.3 Flowability analysis

Analysing the flow parameters of various parts of sweet potato powder was conducted using a probe powder flow analyser connected to a texture analyser (TA-XT plus, Stable Micro Systems, Surrey, UK) (Singh *et al.,* 2022). The tests included the caking test, cohesion test and powder flow speed dependency test (PFSD test). The volume of all samples was standardised to 70 mL for each experiment. The caking test, cohesion test, and PFSD test were conducted and triplicated, apart from the caking test. At the beginning of the testing process, a conditioning cycle was conducted to eliminate any variance caused by user loading. This was done by rotating the blade downwards and upwards through the powder column at a tip speed of 50 mm.s^{1}.

2.4 Sweet Potato Leaves and Stems (SPLS) Pellets Analyses

2.4.1 Friability

A total of 20 SPLS pellets were randomly selected and weighed using an electronic balance (ER-120A, A&D, Japan). Subsequently, the pellet was subjected to rotation at a speed of 25 rpm using electronic friability (DF-3, Distek, USA). The pellets were then allowed to roll and fall 20 times through drum rotation while ensuring that any loose dust formed from the pellets was removed during the test. Next, the pellets were cleaned of dust particles, and their weight was measured. The weight reduction percentage was computed using Equation 2, as described by Onalo *et al.* (2021).

$$\text{Friability (\%)} = \frac{W1-W2}{W1}\ x\ 100 \qquad [2]$$

W1 is the initial weight (g), and W2 is the final weight (g).

2.4.2 True density

True density refers to the weight of powder material per unit volume without considering any empty spaces inside it (Zainuddin *et al.,* 2014). The helium gas pycnometer (AccuPyc II 1340, Micromimetics, U.S.A.) measured the true density of single components and binary mixes. The measurement was determined by calculating the pressure differential between the known reference volume and the whole cell sample (Zainuddin *et al.,* 2014). The experiment was conducted by quantifying 1.0 g for each sample. The results of the true densities of the pellets were recorded in triplicate.

2.4.3 Bulk density

The bulk density was determined by filling a 25 mL measuring cylinder with a sample dropped from a specific height, followed by two taps to ensure consistent packing and reduce the impact of the cylinder walls. Subsequently, the contents were measured by employing the digital balance. The bulk density was determined by dividing the mass of the sample by the volume of the measuring cylinder, as described in Equation 3 (Sonjaya *et al.*, 2023).

$$\rho \mathrm{b} = \frac{mb}{Vb} \quad [3]$$

where ρb: Bulk density (kg/m^3), mb: Total mass of pellets (kg) and Vb: Volume of the cylinder (m^3)

2.4.4 Porosity

The porosity was determined using the true density and bulk density, as reported by Sreeja *et al*. (2023). Porosity refers to measuring the empty spaces or void fraction within a substance as described in Equation 4. The void volume fraction relative to the total volume ranges from 0 to 1.

$$Porosity = 1 - \left(\frac{\rho \mathrm{b}}{\rho t}\right) x\ 100\% \quad [4]$$

where ρb: Bulk density (kg/m^3) and ρt: True density (kg/m^3).

2.4.5 Tensile strength

The tensile strength of pellets was assessed using a texture analyzer (TA-XT plus, Stable Micro Systems, Surrey, UK) to determine the maximum force the samples could withstand before breaking. The two chosen pellets are approximately 1.4 cm long and have a diameter of around 0.3 m. The length and diameter were selected according to the specific probe utilised: a 35 mm Cylinder Probe employing a 5 kg load. Next, the two pellets were placed in the centre under the probe, and the compression test began. The results were recorded for analysis of data.

2.5 Statistical Analysis

Analysis of variance was applied to determine statistically significant differences between the means of triplicate raw data of samples by using one-way ANOVA. Significance was accepted at p<0.05 using IBM SPSS Statistic Software Version 25.

3. Results and Discussions

3.1 Physicochemical Properties of Sweet Potato Plant Powders

3.1.1 TGA analysis

Thermogravimetry (TG) is a thermal analysis, along with the corresponding derivative of the DTG peaks, that provides insight into the various phases of thermal decomposition and stability of materials under various conditions (Zainuddin *et al.,* 2014). Figure 4 displays the TG and DTG curves for several sections of Anggun one sweet potato powders, covering a temperature range from 0 to 700°C. According to Figure 4(a), thermal degradation of lignocellulose can be categorized into three primary stages. The first phase occurs at a temperature below 200°C, attributed to the drying process, during which water and moisture from the biomass evaporate. The second phase, the active zone, occurs at 200 to 350°C. In this stage, hemicellulose decomposes, followed by cellulose and lignin (Martinez *et al.,* 2021). Hemicellulose in plant fiber generally consists of mannose, arabinose, galactose, xylose, and glucose and is responsible for the stiffness and strength of fibers or individual cells (Zamora-Mendoza *et al*., 2023). The decomposition of hemicellulose and cellulose in sweet potato leaves occurs in low temperatures as low as 200°C, followed by sweet potato stems at the highest temperature of 304°C. The presence of hemicellulose contents in sweet potato plant parts was shown to have the potential in pelletization since it helps for the absorption of the formulation of pellet production in the controlled condition in terms of the amount of water, process, handling, storage and transportation (Cui *et al.,* 2021).

Figure 4 (b) displays three distinct peaks that are observable within the temperature range under investigation. The initial peaks mainly result from the hydrolysis of the glycosidic connections and the breakdown of side-chain configurations, notably the 4-O-methyl glucuronic acid unit. The second peak is subsequently linked to the degradation of different depolymerized units, such as Xylan units (Yeo *et al.,* 2019). The third stage occurs at temperatures over 400°C, during which the breakdown of lignin occurs endothermic reaction (Singh *et al.,* 2020). The lignin demonstrated gradual degradation, showing a good level of heat resilience. Unlike cellulose, it is widely regarded as the most challenging component to break down. The resistance to hydrolysis in this material is attributed to its three-dimensional polymer structures that contain ether linkages, hydroxyl, and methoxy groups (Amiandamhen *et al.,* 2020). Char formation occurs at temperatures of 600°C and above at the last step.

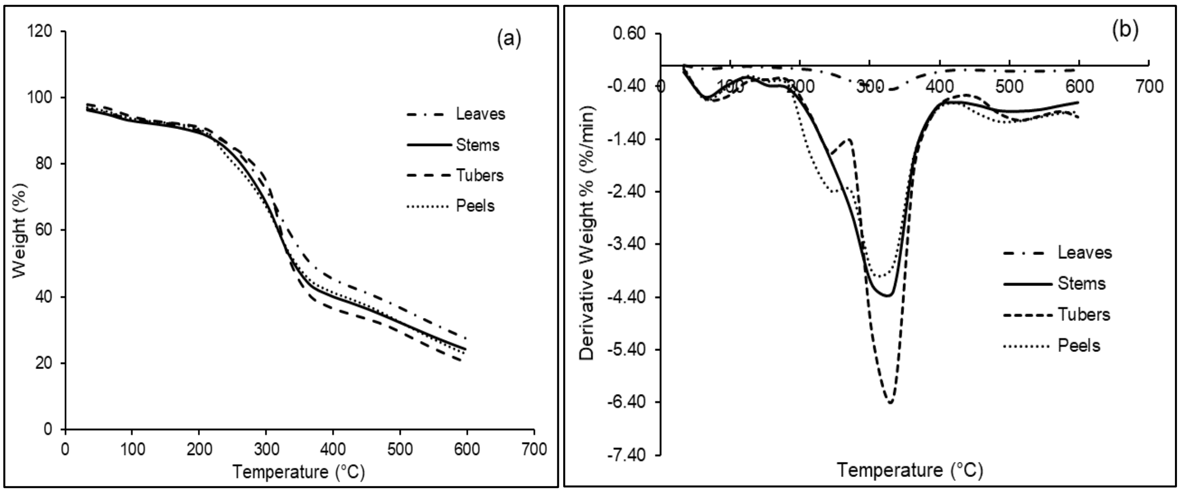

Figure 4. (a)TGA and **(b)** DTG curves for sweet potato leaves, stems, tubers and peels in powder form.

3.1.2 Proximate analysis

Table 1 displays the findings of the proximate analysis of the Anggun 1 sweet potato, which includes the leaves, stems, tubers, and peels based on a dry basis. The proximate compositions differed significantly among the leaves, stem, tuber, and peels. The analysis revealed that leaves had the largest concentration of crude protein. In contrast, stems had the highest fat levels, a significan

t quantity of ash and crude fibre, and other nutrients in both portions of the sweet potato plant.

Table 1. Proximate composition of powders of the leaves, stems, tubers and Anggun 1 sweet potato peels.

Constituents	Proximate Analysis (%)			
	Sweet Potato Powder			
	Leaves	Stems	Tubers	Peels
Dry Matter	92.62 ± 0.20^{b}	91.96 ± 0.19^{c}	93.14 ± 0.13^{a}	91.75 ± 0.19^{c}
Moisture Content	7.18 ± 0.57^{b}	7.70 ± 0.41^{b}	7.12 ± 0.24^{b}	8.83 ± 0.18^{a}
Crude Protein	29.76 ± 0.05^{a}	5.08 ± 1.91^{c}	7.40 ± 0.03^{b}	6.52 ± 0.03^{bc}
Fat	4.41 ± 0.20^{a}	4.58 ± 0.57^{a}	0.69 ± 0.11^{c}	1.40 ± 0.32^{b}
Crude Fiber	14.53 ± 0.59^{b}	10.92 ± 1.46^{c}	8.33 ± 0.17^{d}	16.34 ± 0.58^{a}
Ash	9.93 ± 0.01^{c}	11.80 ± 0.02^{a}	4.02 ± 0.02^{d}	11.67 ± 0.04^{b}
Carbohydrate	34.18 ± 1.39^{d}	59.92 ± 1.20^{b}	72.43 ± 0.50^{a}	55.24 ± 1.07^{c}

*Means (± SD) with the same letter are not significantly different at $p > 0.05$ for each row

3.1.2.1 Dry matter content

Table 1 displays the empirical data about the DM (dry matter) contents of several Anggun 1 sweet potato sections. The moisture levels of leaves, stems, tubers, and peels varied between 91.75% and 93.14%. The tubers had the highest DM content, which aligns with the findings of X. Wang *et al.* (2020). Their investigation demonstrated that unpeeled tubers have the highest DM contents, ranging from 21.80 to 36.53%. Nevertheless, the analysis yielded a statistically negligible result (p>0.05) for the dry matter (DM) content of both the stem and peels. This suggests that the composition of the stem and peels had minimal impact on DM contents. The source and variety significantly impacted the dry matter composition of sweet potatoes. According to Sanoussi *et al.* (2016), three varieties of orange-fleshed sweet potato obtained from the Benin Republic were found to have a low amount of dry matter because of the presence of carotenoid substances. In their study, Nair *et al.* (2017) discovered that orange-fleshed sweet potato genotypes cultivated during the *rabi* season exhibited more excellent dry matter contents in their storage roots than those grown in the *Kharif* season. Nobel *et al*. (2016) stated that increased dry matter levels can potentially enhance the derivative products' yields and textures. The detected DM levels corresponded to the presence of organic and inorganic materials, which are significant features for Anggun 1 sweet potato since they can potentially impact the nutritional intake of herbivores. Hence, the tuber exhibits the highest dry matter content in this study, making it well-suited for utilisation as an affordable and nourishing raw material. This is particularly relevant since dry matter content is associated with favourable cooking characteristics and prolonged shelf life (Martinez *et al.,* 2020).

3.1.2.2 Moisture content

According to the data in Table 1, no significant difference (p<0.05) was seen among tubers, leaves, and stems. The moisture content (MC) in tubers, leaves and stems was 7.12%, 7.18%, and 7.70%, respectively. Peels had the highest moisture content (MC) at 8.83%. The peels were anticipated to have a higher moisture content because of their decreased dry matter content. The difference in the obtained value for the DM contents indicated variations in water content among different parts of the Anggun 1 sweet potato plant. Due to their elevated moisture levels, sweet potatoes are prone to quick degradation during the harvesting process, facilitating the growth of microbes (Elijah *et al.*, 2020). In addition, the MC content for all components was less than 10%, indicating a reduced risk of spoiling-caused microbes (Shaari *et al.*, 2021). A study by Dako *et al.* (2016) found that orange sweet potato had a moisture content of 77%, which was considered high. According to Senthilkumar *et al*. (2020), the moisture content of sweet potato roots was approximately 62%. The variation in moisture content of the powders in this study may attributed to differences in sample preparation, such as in sample thickness throughout the drying process. It is important to note that all drying parameters, including temperature and duration, were kept constant for all samples. According to Seidu *et al.* (2012), sweet potatoes with the least amount of moisture had the highest levels of protein fibre and lower levels of ash.

3.1.2.3 Crude protein content

The crude protein (CP) concentrations of leaves, stems, tubers, and peels ranged from 5.08% to 29.76%, as indicated in Table 1. The CP content of the leaves, tubers and peels of the Anggun one sweet potato significantly varies at a significance level of $p<0.05$. The leaves had the highest CP content at 29.76%, followed by tubers at 7.40% and peels at (6.52%). The stems had the lowest CP content at 5.08%. Albrektsen *et al.* (2022) found that the content of CP varies among different types of feed. Generally, a greater level of CP is typically linked to better quality. The elevated concentration of CP content in the leaves observed in this research aligns with other investigations, including those conducted by Sun *et al*. (2014). According to their report, the sweet potato leaves had a CP content ranging from 16 to 31 g per 100 g of dried weight. This substantial protein content positions sweet potato leaves as a valuable resource for various dietary applications, including meals and animal feed. The significance of having a suitable and accessible energy supply in a well-rounded diet for cattle was emphasised, highlighting the requirement for a high energy-to-protein ratio to maximise protein utilisation (Henchion *et al*., 2017). The protein requirements of different species will vary depending on the animals' age and growth stage. Typically, young animals in the process of growing have higher protein needs compared to older animals. According to Even *et al*. (2021), a larger body requires more energy to sustain itself and accommodate a higher percentage of fat accumulation. The study by Yin *et al*. (2020) emphasized the importance of proteins in their impact on the immune system, both as antigenic factors and as agents that can hinder nutrition. The study also highlighted the impact of proteins on animal nutrition. The leaves of the Anggun 1 sweet potato plant have the potential to substitute feed resources due to their high crude protein content, as evidenced by the obtained results. Additionally, sweet potato plants, particularly their leaves, are readily accessible locally and cost-effective. In addition, Anggun 1 sweet potato leaves were deemed as waste and subsequently thrown during the processing phase. Transforming this underutilised component into by-products will benefit the sweet potato producer while mitigating environmental concerns.

3.1.2.4 Crude fat content

The CF contents of Anggun 1 sweet potatoes ranged from 0.69 to 4.58% and exhibited the following order: stems > leaves > peels > tubers (Table 1). Furthermore, no statistically significant distinction ($p<0.05$) was seen between stem and leaves. The content of CF was found to differ among several sweet potato varieties. In their 2014 study, Sun *et al*. found that cultivar Xinong No. 1 had the highest CF concentrations compared to other cultivars. Ishida *et al.* (2000) found that the mean crude fat content of leaves (3.69 g/100 g DW; 0.46 g/100 g FW) was higher than sweet potato tubers (0.33 g/100 g FW) and sweet potato stems (0.53 g/100 g FW). According to Alam et al. (2016), the sweet potatoes they studied CF content varied between 0.17% to 0.63%. On the other hand, Zulkifli *et al*. (2021) suggested that different parts of sweet potato storage roots, such as the epidermis, cortex, and cambium ring with central parenchyma, contained different amounts of total fat. It is essential to recognise that fat plays a crucial role in animal feeds, serving as a source of omega three and omega six fatty acids, aiding in digestion and absorption, and acting as a medium for transporting vitamins A, D, E and K. This is advantageous for animal feeds. Furthermore, fat is crucial in providing insulation for body organs, regulating body temperature, and supporting cell activity. Like other plants, Anggun one sweet potato plants can adjust their fat content to meet the appropriate fat level in their feeding sources.

3.1.2.5 Crude fiber content

The fiber content of Anggun 1 sweet potatoes exhibited significant variance. The fibre content ranged from 8.33% to 16.34% (Table 1). The peels contained a high fibre content of 16.34%. The leaves had a fibre content of 14.53%, the stems had a fibre level of 10.92%, and the tubers had a fibre content of 8.33%. In their study, Sun *et al*. (2014) demonstrated that the fibre content of different sweet potato cultivars ranged from 9.15 to 14.26 g per 100 g of dry weight, falling within an acceptable range. According to Sun *et al*. (2014), changes in crude fibre concentration can be attributed to factors such as genotype, maturity, and nutritional makeup. There is an increasing demand for higher levels of fibre in animal feed. According to Choct (2015), correctly allocating fibre fractions in the diet of monogastric animals, such as pigs, enhances the efficiency of compounded feed. Regarding ruminants, it is worth noting that fibre plays a crucial role in the metabolic processes occurring in the rumen (L. Wang *et al.*, 2020a). Fiber is a determining factor for the hydrolysis of all nutritional ingredients in the feed, playing a crucial role in the breakdown of all the nutritious components in the diet through hydrolysis. Elevated quantities of dietary fibre would decelerate the pace of digestion and restrict the intake of dry matter (Llonch *et al.*, 2021). Nevertheless, a specific quantity of fibre is necessary to increase rumen activity. This study demonstrates that Anggun 1 sweet potato tubers have the optimal fibre proportions for feeding animals, as their low crude fibre concentration predicts good palatability.

3.1.2.6 Ash content

The empirical data on the ash content is displayed in Table 1. There was a substantial variation in the ash level of different regions of Anggun 1 sweet potato. The stems exhibited the highest ash concentrations, measuring 11.80 ± 0.02%. The peels followed closely with 11.67 ± 0.04%, while the leaves had a somewhat lower ash content of 9.93 ± 0.01%. On the other hand, tubers exhibited the lowest ash concentrations, measuring at 4.02 ± 0.02%. In contrast to the earlier study conducted by Abubakar *et al.* (2010), it was discovered that the ash level of sweet potato leaves is higher than that of other meal samples, including mashed, porridge, boiling, and fried sweet potatoes. The ash concentration ranged from 1.13 to 8.83 g, which aligns with the findings of this study. The stem and peel parts of Anggun 1 sweet potato exhibited a high ash content, which was positively associated with mineral salts in the cultivars (Ayeleso *et al*., 2024). Logically, the outside portions should possess more ash concentration than the interior portions. According to Shaari *et al*. (2021), the high ash level in sweet potatoes is attributed to heavy inorganic nutrients, including potassium, phosphorus, magnesium, and calcium.

3.1.2.7 Carbohydrate content

Conventionally, as nutrients, carbohydrates occupy the dominant composition in nutritional feedstock sources. The total content of carbohydrates can directly affect the feeding effects of herbivores. Anggun one sweet potato, with its high carbohydrate contents, can be used as a supplement with other conventional forages. As shown in Table 1, tabulated data for carbohydrate content in tubers accounts for 72.43%. Meanwhile, the stem occupied the second place at 59.92%, followed by peels (55.24%), and the lowest carbohydrate was leaves (34.18%). Notably, tubers have higher carbohydrate contents than other parts, suggesting they are an excellent energy source (Sanoussi *et al.*, 2016). In practice, limitations on physiological performance and survival of herbivores can be addressed by consuming plant-based with high carbohydrate content (Talal *et al.*, 2020). Besides, foods with appropriate carbohydrate levels tend to undergo slower breakdowns, gradually releasing glucose into the bloodstream. This ultimately results in a low glycaemic index (Astawana *et al.*, 2011). Thus, it was clear that high carbohydrate content in tuber is very good for food production, especially flour. However, carbohydrate content in stems and leaves was also appreciable; hence, they can be an energy supplement in animal feed.

3.2 Flowability Analysis of Potential Technical-grade Powders of Sweet Potato Plant

Based on the findings in Table 1, Anggun 1 sweet potato plant parts have been proven to have high potential to be applied as animal feed and can be commercialized either as animal feed in a palate shape as they are or marketed as technical grade powder to be mixed with other ingredients in the animal feed formulation. Investigating flowability properties is crucial in exploring the potential of marketing the sweet potato plant parts powder as a technical-grade animal feed powder (Hanim *et al*., 2014). The Anggun one sweet potato part might influence the powders' behaviour during processing, handling, and storage.

Table 2. The flow characteristic features of various components of sweet potato plant powders.

Parameter	Leaves	Stems	Tubers	Peels
Cohesion index	2.9 ± 0.07^{b}	1.63 ± 0.03^{d}	3.01 ± 0.05^{a}	2.1 ± 0.07^{c}
Flow stability	0.92 ± 0.01^{ab}	0.95 ± 0.01^{a}	1.01 ± 0.06^{ab}	0.86 ± 0.10^{b}
Cohesion coefficient 50 mm/s	488.09 ± 23.56^{b}	495.34 ± 4.96^{b}	717.08 ± 69.52^{a}	204.36 ± 6.71^{a}
Cake strength (g.mm)	8275.04	2272.25	21336.52	9336.97
Mean cake strength (g)	344.82	307.25	853.85	577.27

*Means (± SD) with the different letters are significantly different at p>0.05 for each row.

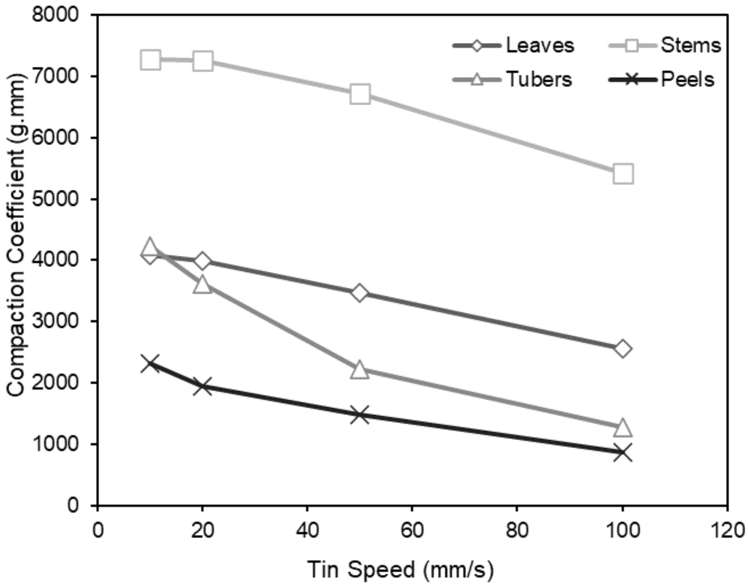

Figure 5. Comparison of tin speed and compaction coefficient across several sweet potato plant powder components.

Table 2 presents the tabulated data regarding the flow properties of powders obtained from various sections of the sweet potato plant. The cohesiveness index for leaves stems, tubers and peel powders varied greatly, ranging from 1.63 to 3.01 based on the findings. The cohesiveness index of tuber powders was the highest at 3.01, followed by leaves, peels, and stems in that order. Nevertheless, all samples were classified as powders that flow effortlessly, exhibiting a cohesion index lower than 11. This could be attributed to the reduced particle size of the powders sieved at 250 µm during the sample preparation phase. As the particle size of the powder decreases, its cohesiveness increases, making it more difficult for it to flow. The decrease in flowability for smaller particle sizes is attributed to the powders' higher surface area per unit mass. Increased surface area or surface contacts result in more excellent resistance to fluid movement. Furthermore, it is worth noting that all the samples were deemed stable powders due to their flow stability values being near 1.

A flow stability index close to 1 suggests that the powders will exhibit minimal tendency to change. According to Figure 5, stem powder's compaction coefficient is highest, followed by leaves, tuber, and peel powder in that order. The results demonstrated that the compaction coefficient of all materials reduced when the tin speed was high. As the velocity of the flow increases, the powders gradually disintegrate into smaller particles, ultimately becoming more mobile. Caking is the process by which food powders transform into a sticky substance that is undesirable and can lead to a decline in the quality and effectiveness of the powders. The strength of a cake can be influenced by various aspects, including interactions between particles, moisture content, and packing efficiency (Rosland *et al*., 2020). Among the different types of powder, the tuber powder exhibited the highest cake strength, measuring 21336.52 g.mm, with a mean cake strength of 853.85 g. This is compared to the powder derived from leaves, stem and skin powder, as shown in Table 2.

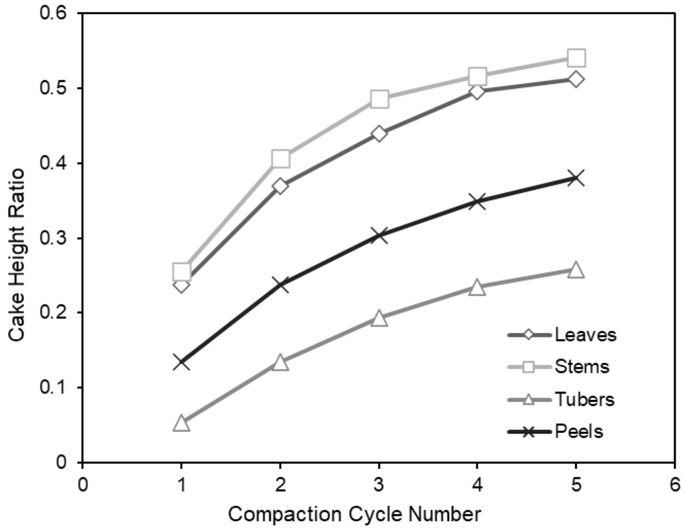

Figure 6. Comparison of the caking height ratio with the number of compaction cycles for various sweet potato plant powder components.

Figure 6 demonstrates that the number of compaction cycles significantly impacts the cake height ratio. The finding suggests that all Anggun one sweet potato components have a significant potential for caking, which can be attributed to a high cake aspect ratio. On the other hand, a high cake ratio indicates that the powders have high mean cake strength and a greater tendency to cake. This finding is important, especially for food production, where the results might be applied to the technical grading of powders to be standardized as food formulation or ingredients for living consumption or used formulation to produce animal feed pellets (Tan *et al*., 2017).

3.3 Physical Properties Analyses of Sweet Potato Leaves and Stems (SPLS) Pellets

As tabulated in Table 1, stems and leaves were shown to have high protein and fat content; hence, these parts were further used in this study to investigate animal feed pellet production. Since both parts were considered waste in the sweet potato processing lines, the utilization of both parts for pellet production will offer some economic advantages. This study utilised the compaction process for pellet production at different moisture contents (40–60%). All the produced pellets were labelled Sweet Potato Leaves and Stems (SPLS) pellets.

3.3.1 Friability of sweet potato leaves and stems (SPLS) pellets

The data shown in Figure 7 demonstrates that the moisture content ranged from 0.3% to 2.31% on the friability of SPLS pellets produced by the compaction process. Friability refers to the propensity of pellets to generate dust or fracture when exposed to destructive forces. The metric quantifies the level of resistance exhibited by the pellets against breakage and abrasion (L. Wang *et al.,* 2020b). The compressive strength of pellets is assessed to prevent fracture and disintegration during handling and transportation (Zainuddin *et al*., 2014).

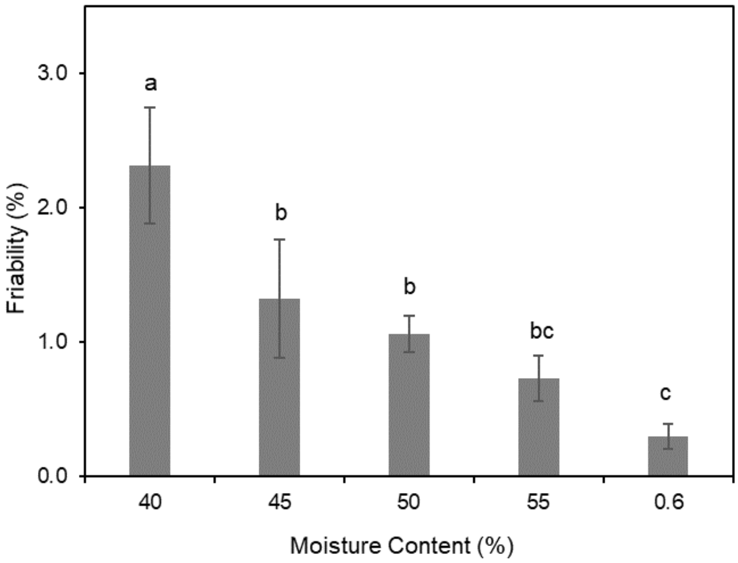

Figure 7. Influence of moisture content on the fragility of SPLS pellets.

All pellets exhibited satisfactory friability, with fines of less than 5%. In a study conducted by Karunanithy *et al*. (2012), it was proposed that fines weighing up to 5% would be deemed acceptable. However, fines beyond this threshold would diminish storage capacity and give rise to complications in flow characteristics. The low friability resulting from the compaction method suggests that the pellets can endure shear forces when exposed to mechanical attrition or shock (Zainuddin *et al*., 2014). According to Figure 7, the friability was lowest at a moisture level of 60%, followed by 55%, 50%, and 45%. The maximum friability recorded was 40%. The friability of a substance is greatly influenced by parameters such as the amount of moisture present, the level of pressure applied, and the temperature at which it is heated (Zainuddin *et al*., 2014). Upon analysis, it is evident that there is a statistically significant rise in the friability percentage when the moisture content is increased from 40% to 60%, with a p-value greater than 0.05. Therefore, the pellets produced from the compaction process with a moisture level of 60% were determined to be in the most favourable state for pellet production. This conclusion was reached based on the friability test, which showed the lowest percentage of pellet breakage compared to the other tests.

3.3.2 True density of sweet potato leaves and stems (SPLS) pellets

Figure 8 illustrates the impact of moisture on the actual pellet density generated from SPLS pellets. The proper density of the SPLS pellets for moisture content of 40% to 60% ranged between 1447.10 kg/m^3 to 1481.83 kg/m^3. The true density of SPLS pellets was inversely proportional to moisture contents. This finding is consistent with the study obtained by Zainuddin *et al*. (2014), who stated that the true density of compacted and extruded pellets shows a significant decrease at $p<0.05$ with increasing moisture content. The density depended on the feedstock type, process variables, and machines (Tan *et al*., 2017). Sufficient moisture was essential to reduce inter-partition friction, facilitating the potential to eliminate pore space. However, when high moisture contents are applied, the additional moisture occupies the space typically taken up by the plant residue, thus increasing the ability to withstand compression. Therefore, the true density of the pellets decreased (Huang *et al.*, 2017).

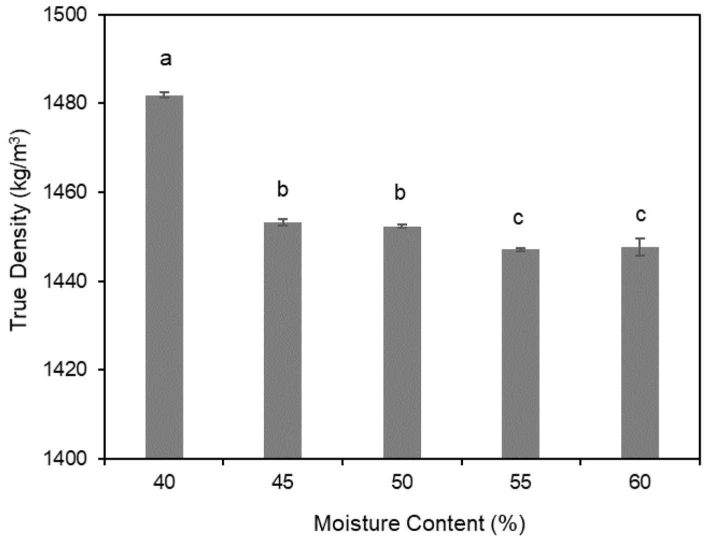

Figure 8. Effect of moisture content on the true density of SPLS pellets.

3.3.3 Bulk density of sweet potato leaves and stems (SPLS) pellets

The bulk density of the SPLS pellets with moisture ranging from 40% to 60% were measured to be 674.5 kg/m^3, 750 kg/m^3, 699.75 kg/m^3, 766 kg/m^{3,} and 629.5 kg/m^{3,} respectively. The bulk density was lowest at a moisture content of 60%, while the highest was observed at 55% (Figure 9). As the moisture content increased, the bulk density of the SPLS pellets dropped. There were noticeable variations in bulk density across different moisture levels, with statistical significance (p<0.05). Tumuluru (2018) reported that the compaction process led to the expansion of pellets, resulting in a decrease in bulk density due to the increased volume of the pellets. Zainuddin *et al*. (2014) discovered a notable disparity in the bulk density of compacted pellets as it increased. However, the bulk density of the pellets often increases by a factor of 2 to 13, depending on the feedstock type, the densification equipment used, and the process conditions (Karuranithy *et al.,* 2012). The increased bulk density can result in lower transportation expenses and improved handling when adequate storage management is implemented.

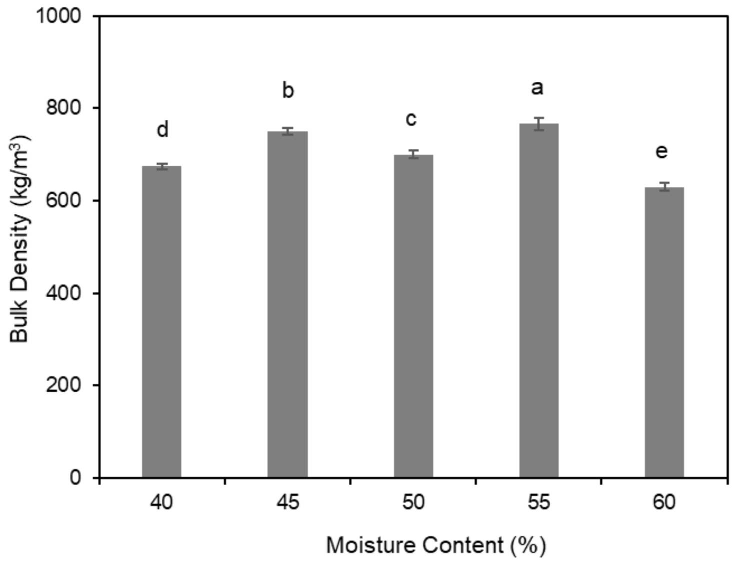

Figure 9. Effect of moisture content on the bulk density of SPLS pellets.

3.3.4 Porosity of sweet potato leaves and stems (SPLS) pellets

Porosity refers to the ratio of the volume of voids to the overall volume and void spaces of a material, typically ranging from 0 to 1. According to Figure 10, a pellet made of SPLS with a moisture content of 60% had a maximum porosity value of 56.51%. On the other hand, the pellet with a moisture level of 55% had the lowest porosity value, which was 47.07%. Nevertheless, the findings of this investigation contradicted the results of Zainuddin *et al*. (2014), who stated that porosity reduced as moisture content increased. The feedstocks' low porosity, measured at 55% moisture content, suggests less space, resulting in low compressibility within the given volume. In addition, the feedstock's high porosity at a moisture level of 60% suggests that the sample was compressed, leading to increased compressibility. The findings of this investigation were consistent with the research conducted by Mahapatra *et al*. (2010), which demonstrated that an increase in moisture content led to an increase in porosity. The augmentation in porosity and moisture content can be attributed to the diverse feedstocks, process factors, and machinery employed. Therefore, a moisture content of 60% was determined as the ideal condition for producing pellets from the stems and leaves of sweet potatoes. This resulted in a higher porosity level and required less compaction than other moisture percentages.

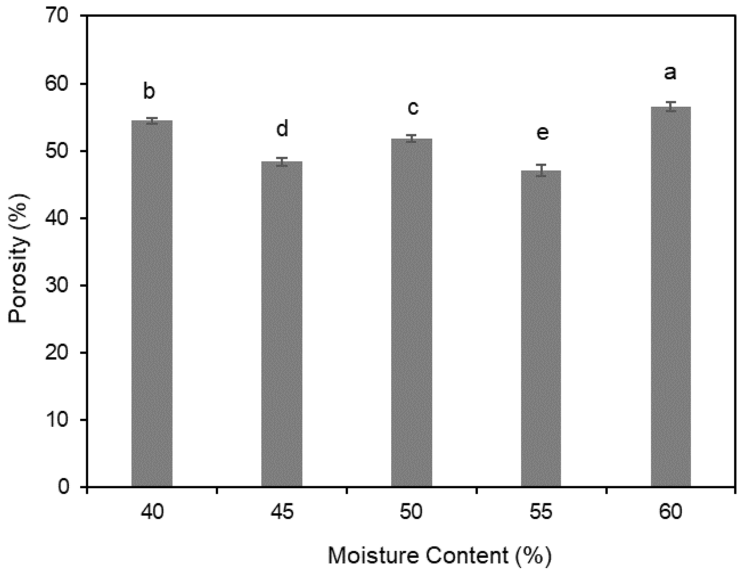

Figure 10. Effect of moisture content on the porosity of SPLS pellets.

4.3.5 Tensile strength of sweet potato leaves and stems (SPLS) pellets

Compression strength was the parameter with the most significant influence on SPLS pellet moisture contents while maintaining the quality of the SPLS pellets. The compression work values increased significantly as the moisture contents increased, ranging from 40–60% (Figure 11). The moisture content at 60% exhibited the highest work of compression, which was 303.79 kg.s, indicating that SPLS pellets were firm and did not easily tend to crack or break. Meanwhile, the lowest compression work is 40% moisture content, which is 91.29 kg.s. The breakage and decreased strength of SPLS pellets can be attributed to their low moisture content. Few studies have demonstrated that the strength of compacted products increases with increasing moisture content until optimum strength is obtained. For example, Zainuddin *et al*. (2014) stated that all the tensile strength values increased significantly for extruded and compacted pellets processed from pineapple waste (leaves and stems). Besides, a high moisture content of 19% to 23% on a wet basis has effectively reduced the resilience and flexibility characteristics of fibrous biomass materials such as sawdust, bark, and hay (Popa, 2018). This is relevant since sweet potato leaves and stems also contain a certain amount of fibres. Thus, 60% moisture content in this study was the optimum condition to produce firm and densified pellets. The moisture content, consisting of 40% to 55%, was considered low tensile strength and compression work. SPLS pellets contain high amounts of lignocellulosic components, quickly undergoing plastic deformation under specific stress. Consequently, these limitations resulted in weaker water absorption, which may cause weaker bonds to form among SPLS pellets (Lisowski *et al*., 2019). This condition causes the forming of a “Chrismas tree” shape of pellets that reduces the pellet durability and strength same case as stated by Ungureanu *et al*. (2018), where this condition results in the centre of the pellet extruding at a quicker rate than the exterior, leading to the formation of the undesired shape.

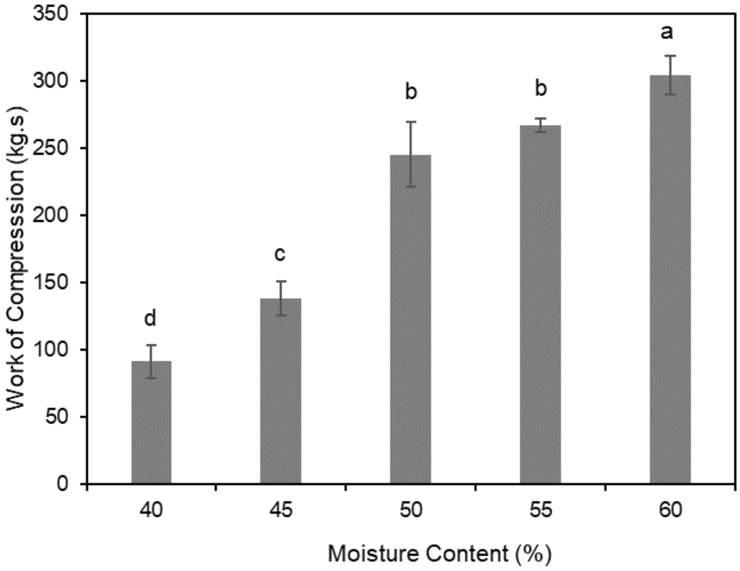

Figure 11. Effect of moisture content on the work of compression of SPLS pellets.

4. Conclusions

Incorporating sweet potato waste-based pellets (SPLS) as a supplement could better utilize nutrients in the dietary food for herbivores. The stem and leaves of Anggun 1 sweet potatoes generally contain lower cellulose, hemicellulose, and lignin than tubers and peels. In addition, leaves contained the highest crude protein content. In contrast, stems contained the highest fat, an appreciable amount of ash, and crude fibre content with other nutrients for both parts of the Anggun 1 sweet potato plant, as reflected in the proximate analysis. As for flowability, sweet potato stems, leaves, tuber, and skin powder are categorised as stable powders that are free-flowing.

Additionally, they were increasingly prone to congeal. Besides, the present results suggested that a 40% to 60% moisture content range showed a significantly different effect on the physical characteristics of the pellets. The best moisture content formulation to produce pellets in this study was found to be at 60% moisture content due to the high value of porosity and work of compression, as well as the tensile strength of SPLS pellets. Pelleting of Anggun one sweet potato stems and leaves offer several benefits, such as increasing the flexibility for feeding, reducing costs, increasing incomes, and reducing problems with handling, transportation, and storage. The agricultural industry could also benefit economically and ecologically.

Author Contributions: M.Z.M.N., R.S and N.H conceptualization and supervision; N.Z.Z., MZ.M.N., N.A.Z., M.S.M.B, M.H.H., M.N. and S.A. writing, review and editing, N.Z.Z. conducted the experiments, and collected and analysed the result data. All authors have read and agreed to the published version of the manuscript.

Funding: The authors would like to thank the Ministry of Higher Education Malaysia and Universiti Putra Malaysia for sponsoring this work under UPM Putra Grant: GPI/2023/9755100.

Acknowledgement: This research was made possible through the generous support of the Ministry of Higher Education Malaysia and Universiti Putra Malaysia, provided under the UPM Putra Grant: GPI/2023/9755100. The authors sincerely appreciate this sponsorship.

Conflicts of Interest: The authors declare no conflict of interest.

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