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Utilization of agro-industrial residues for producing pelletized soil amendments through moisture-optimized pelletization

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Abstract

Agricultural industrial residues represent an abundant yet underutilized resource for developing sustainable soil amendment products. This study investigated the conversion of three agro-industrial wastes, filter cake (FC), black rice husk ash (BRHA), and soil-rich cassava wash residue (SCR), into pelletized soil amendments through moisture-optimized pelletization. The objectives were to determine suitable moisture conditions for pellet formation, evaluate the physical and mechanical properties of the pellets, and assess their effects on maize (*Zea mays* L.) seedling growth. Physicochemical characterization indicated that FC served as the primary organic and nutrient-rich component. Individual moisture optimization revealed distinct pelletization behaviors among the materials, with the optimal moisture range for mixed formulations identified as 21.32–30.12%. Six blended formulations (F1–F6) were produced using a flat-die pellet mill. Pellet properties varied significantly among formulations, particularly in density, mechanical durability, and wettability, reflecting the influence of material composition, yielding pellets with bulk densities of 556.65–670.36 kg/m^3, mechanical durability of 47.79–90.93%, and wettability index values between 26.44% and 43.38%. Maize seedling experiments showed significant treatment effects ($P \leq 0.05$) on all growth parameters. Formulation F5 (FC60:BRHA30:SCR10) demonstrated the most balanced overall performance, achieving growth responses comparable to or exceeding those of the commercial soil amendment. These results demonstrate that agro-industrial wastes can be effectively valorized into pelletized soil amendments with favorable physicochemical properties and promising agronomic performance, offering a practical approach for transforming regional waste streams into products for circular agriculture.

Keywords: Pelletization, Soil amendment, Agricultural waste, Circular agriculture

1. Introduction

The rapid expansion of agricultural and agro-industrial production in Southeast Asia has led to a substantial increase in agricultural residues and processing by-products from activities such as sugar processing, rice milling, and cassava starch production [1]. These residues are often underutilized or disposed of through open dumping or combustion, causing environmental pollution and inefficient resource use [2, 3]. At the same time, many agricultural soils in the region are experiencing progressive degradation due to intensive cultivation, declining soil organic matter, nutrient depletion, and excessive chemical fertilizer use, which also disrupts soil microbial communities [4-6]. In 2023, the average chemical fertilizer application in Southeast Asia reached 437.4 kg/ha, with fertilizer consumption in Asia increasing by approximately 230% compared with previous decades [7]. Consequently, many soils in the region are classified as being in poor to moderate condition [8]. These challenges highlight the urgent need for sustainable strategies that simultaneously manage agro-industrial residues and improve soil quality. Recent studies suggest that agricultural waste materials can serve as effective soil amendments capable of enhancing soil fertility, improving nutrient cycling, and restoring soil structure when properly processed and applied [9-11].

Various approaches have been explored to utilize agro-industrial residues for soil improvement, including composting, direct application, and organic amendment production. Composting is widely used to stabilize residues and produce agronomically beneficial materials; for example, filter cake is valued for its high organic matter and nutrient content [12], while rice husk ash improves soil pH and supplies potassium and silica [13]. Cassava washing residues, containing soil particles and organic debris, also show potential as structural components in soil amendment formulations. However, these materials often exhibit low bulk density, heterogeneous particle size, and poor handling properties, limiting their transport, storage, and field application [14]. Their loose form further leads to uneven application and reduced efficiency, highlighting the need for improved processing technologies to produce more stable and manageable products.

Pelletization has emerged as a promising technology to improve the physical properties and usability of biomass-based materials by densifying loose feedstocks into uniform pellets with enhanced strength, bulk density, and handling characteristics [15, 16]. Pelletized products facilitate transportation, storage, and more precise application, while reducing fragmentation and dust formation

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[17, 18]. This process also promotes particle bonding and structural stability. Recent studies have demonstrated growing interest in developing pelletized soil amendments from agro-industrial residues. Sung-inthara et al. [19] established that optimal moisture content (20–30% w.b.) is critical for compost-based pellet production and quality, with the resulting pellets improving soil nutrient availability and water holding capacity. Furuhashi et al. [20] confirmed that organic matter-rich materials such as livestock manure compost function as effective natural binders during co-pelletization, enabling pellet formation without synthetic additives. Klinsukon et al. [9] developed pelletized soil amendments from sugar industry residues and demonstrated significant improvements in plant biomass and shoot height compared to the control, highlighting the agronomic potential of pelletized organic amendments. Cwalina et al. [21] reported that increasing mineral ash content in compost pellets progressively reduced mechanical strength while slightly increasing pellet density. Juntahum et al. [22] further showed that cassava industry by-products containing residual starch can enhance pellet cohesion and structural integrity when used as a formulation component.

Despite this progress, existing studies have largely focused on single-feedstock systems or homogeneous compositions such as compost–biochar mixtures. The co-pelletization of multiple agro-industrial residues with contrasting physicochemical properties, and systematic moisture optimization prior to blended formulation, remain poorly investigated. To the best of our knowledge, this is the first study to investigate the co-pelletization of filter cake, black rice husk ash, and soil-rich cassava wash residue as a blended soil amendment system, combining systematic individual moisture optimization with comprehensive evaluation of physical, mechanical, and agronomic performance across compositional variants. Therefore, the objectives of this study were to (1) evaluate the physicochemical properties of the selected agricultural residues, (2) determine suitable moisture conditions for efficient pellet formation and pelletization performance, (3) develop pelletized organic soil amendments and evaluate their physical and mechanical properties, and (4) assess their effects on plant growth through a maize seedling growth experiment. By integrating waste valorization with pelletization technology, this study seeks to provide a practical approach for transforming agro-industrial residues into functional soil amendment products that support sustainable soil management and circular resource utilization in agricultural systems.

2. Materials and methods

2.1 Collection and preparation of raw materials

Three agricultural industrial waste materials were used as feedstocks for the production of pelletized soil amendments: filter cake (FC), black rice husk ash (BRHA), and soil-rich cassava wash residue (SCR) (Figure 1). All raw materials were obtained from agro-industrial facilities in Khon Kaen Province to reflect regionally available waste streams and promote practical applicability. FC was collected from a sugar processing plant after juice clarification. BRHA was sourced from small-scale biomass combustion units using black rice husks as fuel. SCR was collected from cassava starch processing facilities, where soil and fine organic particles are separated during root washing. All raw materials were air-dried under sunlight for 5 days prior to further processing, resulting in final moisture contents of 9.28%, 5.65%, and 7.35% (w.b.) for FC, BRHA, and SCR, respectively, to ensure uniformity and reliability of subsequent analyses. Moisture content was determined by oven-drying at 105°C for 24 h (ASTM D1762-84) [23].

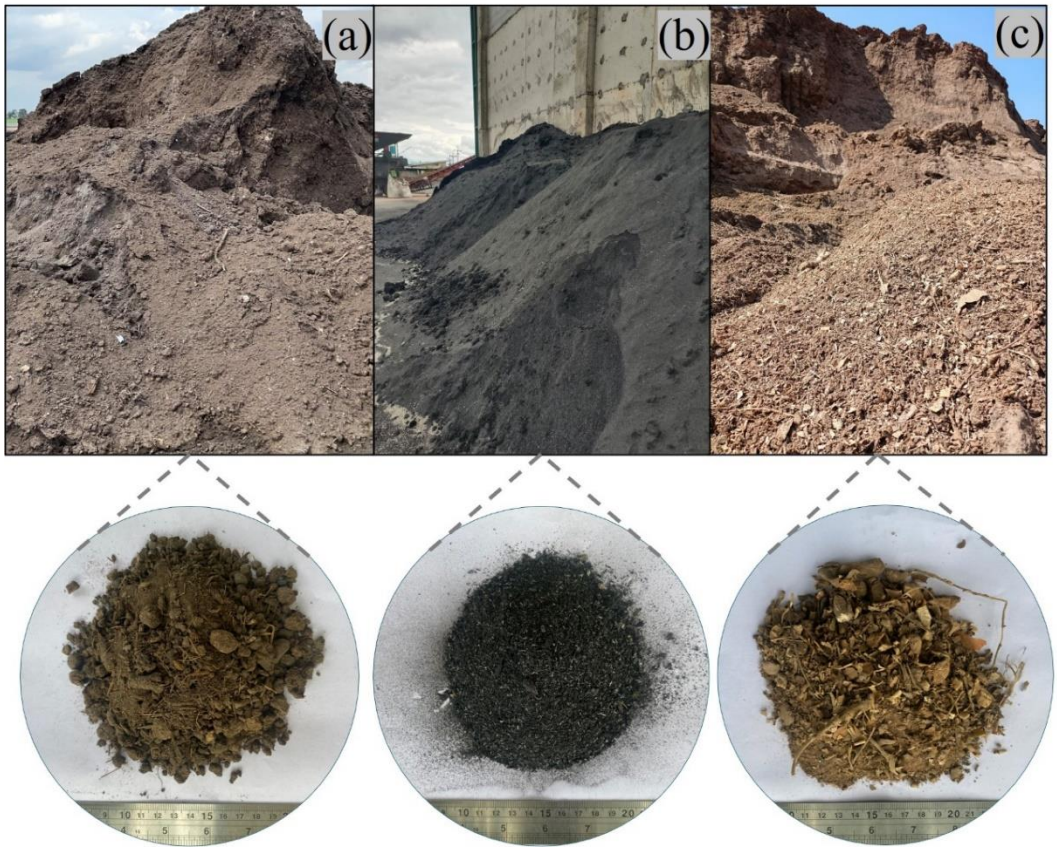


Figure 1 Raw materials used for the production of pelletized soil amendments: (a) filter cake (FC), (b) black rice husk ash (BRHA), and (c) soil-rich cassava wash residue (SCR)

2.2 Physicochemical characterization of raw materials

The three raw materials—FC, BRHA, and SCR—were analyzed for their physicochemical properties to assess their suitability for use as feedstocks in the production of pelletized soil amendments. The analyses included pH and electrical conductivity (EC), both determined in a 1 : 10 (w/v) solid-to-distilled water extract, with EC reported in dS/m. In addition, organic matter content (OM, %), total nitrogen (total N, %), carbon-to-nitrogen ratio (C/N), total phosphorus (total P, %), and total potassium (total K, %) were determined. The germination index (GI) was evaluated as an indicator of potential phytotoxicity and agricultural suitability of raw materials. All analyses were conducted at the Research and Central Laboratory Center, Faculty of Agriculture, Khon Kaen University, following established standard laboratory procedures.

2.3 Moisture adjustment

To evaluate the effect of feedstock moisture content on pelletization behavior and machine performance, the three raw materials (FC, BRHA, and SCR) were adjusted to target moisture contents ranging from 15 to 35% (MC15-MC35) on a wet basis (w.b.) prior to pelletization. This moisture range was selected based on preliminary pelletization trials and moisture levels commonly reported in biomass pelletization studies [19, 24, 25]. Moisture contents that are too low may reduce particle cohesion, whereas excessive moisture can impair pellet formation and extrusion stability. The initial moisture contents of the air-dried materials were first determined using the oven-drying method, following standard gravimetric procedures. The required amount of tap water to achieve each target moisture level was calculated using Equation (1) [26], which accounts for the initial moisture content of the sample.

$$W_w = W_s \times \frac{m_f - m_i}{100 - m_f} \tag{1}$$

Where W_w = mass of water to be added, g
W_s = mass of soil amendment (or sample), g
m_f = final moisture content (target moisture content), %
m_i = initial moisture content of the sample, %

Pre-calculated volumes of water were gradually sprayed onto weighed portions of each raw material, followed by thorough manual mixing to ensure uniform moisture distribution. The moistened samples were sealed in polyethylene bags and equilibrated for a fixed period to minimize moisture gradients within the material matrix.

2.4 Pelletization performance evaluation

The pelletization process is illustrated in Figure 2. A die diameter of 6 mm was used, as it represents the standard configuration of the flat-die pellet mill employed in this study and is widely adopted in commercial flat-die pellet mills for multipurpose biomass densification. The resulting pellet diameter also complies with the Thai Department of Agriculture's organic fertilizer regulation, which specifies a maximum particle size of 12.5 × 12.5 mm for registered organic fertilizers [27] and is consistent with pellet dimensions reported in previous studies on pelletized organic soil amendments [9, 18]. The technical specifications and operational parameters of the pellet mill provided by the manufacturer are summarized in Table 1. The feedstock was supplied manually at an approximate feed rate, ranging from 100 to 120 kg/h. The feed rate was dependent on the bulk density of the feedstock, which served as a critical factor limiting continuous feeding. Pellet mill performance was evaluated using three key indicators: pelletizing capacity (PC) (Equation 2), specific energy consumption (SEC) (Equation 3), and Pellet formation (PF) (Equation 4). Pelletizing capacity was calculated as the ratio of the total mass of pellets produced to the pelletizing time [28]. SEC was determined based on the net average power consumption during pellet production relative to the pelletizing capacity [29]. PF was determined based on the weight difference of the pellets collected directly from the pelletizer before and after sieving through a 3-mm mesh to remove fines [19]. These performance indicators were used to evaluate the pelletization efficiency of each raw material across the tested moisture range and to identify optimal moisture conditions for stable and energy-efficient pellet production.

$$PC = \frac{W_p}{t} \tag{2}$$

Where PC = pelletizing capacity of the machine (kg/h)
W_p = storage weight of pellet (kg)
t = pelletizing time (h)

$$SEC = \frac{E}{P_c} \tag{3}$$

Where SEC = specific energy consumption (Wh/kg)
E = the net average power consumption during pellet production (W)
P_c = pelletizing capacity of the machine (kg/h)

$$PF = \frac{W_p}{W_p + W_d} \times 100 \tag{4}$$

Where PF = pellet formation (%)
W_p = weight of pellets retained after sieving (g)
W_d = weight of fines/dust obtained from sieving (g)

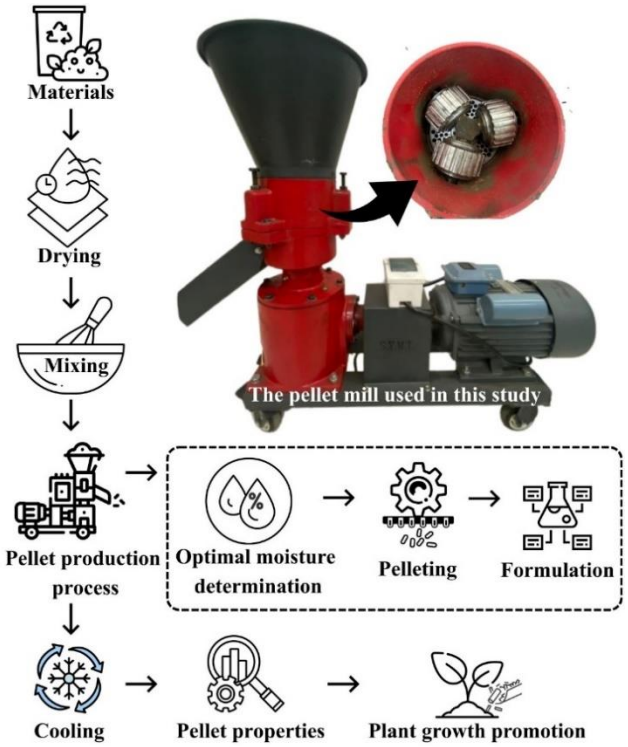


Figure 2 A process of soil amendment pellets production

Table 1 Technical specifications and operational parameters of the pellet mill from the manufacturer

Specification	Measurement unit	Parameters
Electric motor rated power	kW	4
Electric motor supply voltage	V	220
Motor rotational speed	rpm	1250
Reduction rate	-	1:4.3
Rotational speed of the shaft with rollers	rpm	290
Number of rollers	pcs.	3
Diameter of the press rollers	mm	100.2
Width of the press rollers	mm	26.9
Dimensions of the grooves on the rollers (width x depth)	mm	5 × 3
Spacing of the grooves on the press rollers	mm	5.0
Type of die	-	flat
Die diameter	mm	130
Thickness of the die	mm	22
Diameter of the holes in the die	mm	6
Number of holes in the die	pcs.	118
Capacity of the feeding hopper	dm^3	10
Dimensions of the pellet mill (length x width x height)	mm	920 × 235 × 800
Mass of the pellet mill	kg	140

2.5 Formulation and pelletization of mixed soil amendment pellets

Based on the optimal moisture contents identified for each raw material in Section 2.4, the agricultural industrial waste materials were subsequently used to formulate mixed feedstocks for pellet production. Six experimental formulations, designated F1 to F6, were prepared by combining FC, BRHA, and SCR in predetermined weight ratios. The six formulations were designed based on a systematic compositional variation approach. FC was designated as the primary component in all formulations (50–70% by weight), reflecting its superior physicochemical properties as an organic binder and nutrient source identified in Section 3.1. The formulations were organized into two groups: F1–F3, in which BRHA content was fixed at 10% while SCR content decreased progressively (40, 30, and 20%), and F4–F6, in which SCR content was fixed at 10% while BRHA content decreased progressively (40, 30, and 20%). This design allowed systematic evaluation of the effects of each component on pellet quality and agronomic performance while maintaining FC as the dominant fraction. A minimum inclusion level of 10% was maintained for both BRHA and SCR across all formulations to ensure that the contribution of each material could be assessed while maintaining the optimal moisture conditions established for efficient pelletization.

F1: (FC50: BRHA10: SCR40); F2: (FC60: BRHA10: SCR30); F3: (FC70: BRHA10: SCR20)
F4: (FC50: BRHA40: SCR10); F5: (FC60: BRHA30: SCR10); F6: (FC70: BRHA20: SCR10)

Each formulation was thoroughly mixed to ensure homogeneity prior to pelletization. The blended materials were then pelletized using the same flat-die pellet machine and operating conditions described in Section 2.3 to ensure comparability across formulations. The produced pellets were air-cooled at ambient conditions for 7 days, subsequently sieved to remove fines, and stored in sealed containers for further physical, mechanical, and agronomic evaluations.

2.6 Evaluation of pelletized soil amendment properties

The characterization of the physical and mechanical properties of pelletized soil amendment includes the measurement of their moisture content (MC), bulk density (BD), true density (TD), wettability index (WI), and mechanical durability (MD) were measured.

The BD was determined following ASTM D6683–19 standards and the method described by Hwangdee et al [30], using a test kit consisting of the IL.60607 Seedburo filling hopper and stand (Seedburo Equipment, USA). In brief, materials were free poured into a 1,000 cm³ cylindrical container until it overflowed to its maximum height. Any excess material was then removed, leveling it to the top edge of the container. The mass of the materials was measured by subtracting the mass of the empty container. BD was calculated using Equation 5.

$$BD = \frac{m}{v} \tag{5}$$

Where BD = the bulk density of pellets (kg/m^3)
m = the mass of pellets in a cylindrical container (kg)
v = the volume of the cylindrical container (m^3)

Pelletized soil amendments were randomly collected, and the diameter and length of the samples were measured using a digital vernier caliper with an accuracy of 0.01 mm (Mitutoyo, Japan).

The TD of pelletized soil amendments was determined by weighing the samples using a balance (Ohaus, USA) with an accuracy of 0.0001 g. The dimensions of each pellet (diameter and length) were measured and used to calculate their volume. Based on the measured mass and calculated volume (Equation 6), the TD of the pellets was determined and expressed in kg/m^3 [31].

$$TD = \frac{m}{v} \tag{6}$$

Where TD = true density (kg/m^3)
m = the mass of pellet (kg)
v = the volume of pellet (m^3)

The WI was determined using a modified version of the method described by Papandrea et al. [32]. Pellets were randomly selected from each batch and prepared for analysis. All weight measurements were recorded using an analytical balance with a precision of 0.0001 g. Each pellet was first weighed in its dry state (Dry Weight) and then carefully immersed in distilled water for 30 s. After immersion, excess surface water was gently removed using a standardized procedure. The wetted pellets were immediately weighed (Wet Weight). The WI was calculated using Equation (7).

$$WI = [\frac{W_w - D_w}{D_w}] \times 100 \tag{7}$$

Where WI = wettability index (%)
W_w = wet weight (g)
D_w = dry weight (g)

The MD was evaluated according to EN 15210-1 standard and the method described by Yılmaz et al. [31] by placing 500 g of pellets in a durability tester and shaking them at 50 rpm for 10 min. The tester consisted of a 30 × 30 × 12.5 cm box with a 5 × 23 cm plate diagonally positioned inside. After testing, the pellets were sieved using a 3 mm sieve, and durability was determined based on the measured weight loss. The MD was calculated using Equation (8).

$$MD = \frac{W_a}{W_b} \times 100 \tag{8}$$

Where MD = mechanical durability (%)
W_a = the initial mass of pellets before the durability test (g)
W_b = the mass of pellets retained on the sieve after the durability test (g)

2.7 Plant growth promotion by pelletized soil amendments

A plant growth experiment was conducted using a randomized complete block design (RCBD) to evaluate the agronomic performance of pelletized soil amendments. Eight treatments were tested, including six pellet formulations (F1–F6), a control without amendment (F0), and a commercial amendment (FCO). Maize (*Zea mays* L.) was grown in a commercial growing medium, with amendments applied at a fixed ratio of 100:10 (w/w) (250 g medium and 25 g amendment per 7-inch planting bag; total 275 g). The control contained no amendment but maintained the same total mass, while the commercial treatment was applied at an equivalent rate. Seeds were sown prior to amendment application and irrigated regularly for three weeks. Growth parameters, including shoot height, stem diameter, root length, shoot fresh weight, and shoot dry weight, were measured. Shoot dry weight was determined after oven-drying at 105 °C for 24 h to constant weight.

2.8 Statistical analysis

All statistical analyses were performed using Statistix (version 8.0), with results expressed as mean values of replicates. For moisture adjustment and pelletization performance (Sections 2.3–2.4), data from three subsamples were averaged and analyzed separately for each raw material using a completely randomized design (CRD), with moisture content as the treatment factor. Analysis of variance (ANOVA) followed by Fisher's LSD test ($p \leq 0.05$) was applied, and a scoring approach was used to determine optimal moisture levels. Data from mixed pellet formulation and pellet property evaluation (Sections 2.5–2.6) were also analyzed using ANOVA under CRD with LSD for mean comparison. The plant growth experiment (Section 2.7) followed a randomized complete block design (RCBD), with growth parameters analyzed by ANOVA and treatment means compared using Fisher's LSD test at $p \leq 0.05$.

3. Results and discussion

3.1 Physicochemical properties of soil amendments

The feedstocks exhibited distinct physicochemical characteristics reflecting their origins and suitability for pelletized soil amendments (Table 2). FC showed near-neutral pH, low EC, high organic matter (29.24%) and nutrient content (N = 1.12%, P = 0.83%, K = 0.28%), with an optimal C/N ratio (15.07) and high germination index (GI = 129%), indicating strong agronomic potential and absence of phytotoxicity [33]. In contrast, BRHA was alkaline (pH 8.91) with low OM and N but contributed mineral nutrients, particularly K, and exhibited high GI (107%), supporting its role as a mineral amendment [34]. SCR presented moderate OM, low nutrient content, and a high C/N ratio (36.84), suggesting limited nutrient availability if used alone, although its high GI (117%) confirmed biological safety. Compared with conventional composts [19, 34], FC performed similarly to mature organic amendments, while BRHA and SCR functioned primarily as mineral and structural components. According to Thai compost standards, FC met all criteria, whereas BRHA and SCR require formulation adjustments. Overall, their complementary properties support combined use, with FC as the main nutrient source, BRHA providing alkalinity and potassium, and SCR contributing structural carbon, aligning with the development of co-formulated soil amendments.

Table 2 Biological, chemical, and physical properties of raw materials

Raw materials	pH (1:10)	EC (1:10) (dS/m)	OM (%)	Total N (%)	Total P (%)	Total K (%)	C/N	GI (%)	APS (mm)	Ref.
FC	7.41	0.41	29.24	1.12	0.83	0.28	15.07	129	0.34	This study
BRHA	8.91	0.13	0.8	0.03	0.27	0.2	14.02	107	0.30	
SCR	6.95	0.29	10.78	0.17	0.02	0.13	36.84	117	1.04	
Sugar industry waste	5.7-7.4	2.2-3.0	16.46-44.26	0.77-2.07	0.22-0.61	1.26-1.88	15.78-31.82	86-96	-	Klinsukon et al. [9]
Cow manure compost	7.37	1.57	20.18	1.82	0.53	0.68	14.27	93.7	0.23	Sung-inthara et al. [19]
Compost	6.89-7.64	0.46-2.58	15.84-20.18	0.65-0.82	0.29-0.61	0.13-1.68	14.19-15.71	95.76-97.76	-	Juntahum et al. [22]
	5.5–8.5	<6	>20	>1	>0.5	>0.5	<20	-	<12.5	Compost standard [35] (In Thai)

3.2 Moisture-dependent pellet formation behavior of individual raw materials

Moisture optimization revealed distinct pelletization behaviors among the raw materials (Table 3). FC exhibited a wide moisture tolerance (20–35%) with stable production capacity, while higher moisture significantly reduced SEC and improved pellet formation (PF), with MC35 identified as optimal. In contrast, BRHA required higher moisture for pellet formation due to its ash-rich composition; no pellets formed at low moisture, while PF increased with moisture despite relatively low efficiency, and MC35 was selected as optimal. SCR showed a narrower operational range (15–25%), with higher moisture inhibiting pellet formation; within this range, increasing moisture reduced SEC and improved PF, with MC25 identified as optimal. At optimal conditions (FC: MC35; BRHA: MC35; SCR: MC25), the materials exhibited complementary roles: FC provided high cohesion and stability, SCR contributed high production capacity, and BRHA functioned as a mineral component under higher moisture conditions. These results define a practical moisture range of 25–35% for blended formulations and highlight the importance of moisture balance for efficient pelletization and process stability.

Based on the moisture-dependent pellet formation behavior of individual raw materials (Section 3.2), the optimal moisture contents of blended soil amendment formulations were determined by moisture balancing according to formulation ratios (Table 4). The calculated optimum moisture contents of the formulations ranged from 21.32% to 30.12%, falling within the viable pellet formation window identified for the individual materials. These formulation-specific moisture setpoints provided the basis for subsequent pelletization trials to evaluate pellet quality of the blended soil amendments.

Table 3 Evaluation of optimal moisture levels for machinery performance in pelletizing agricultural industrial waste

Materials	Moisture	PC (kg/h)	SEC (Wh/kg)	PF (%)	Total score	Rank
FC	MC15	×				
	MC20	78.99 A^3	47.07 A^1	79.33 B^3	7	3
	MC25	73.39 A^3	48.07 A^1	91.27 A^3	7	3
	MC30	70.71 A^3	38.70 B^2	95.27 A^3	8	2
	MC35	76.89 A^3	32.75 C^3	94.46 A^3	9	1
BRHA	MC15	×				
	MC20	61.69 C^1	76.48 A^1	22.92 C^1	3	4
	MC25	81.16 A^3	38.30 C^3	23.00 C^1	7	2
	MC30	57.31 C^1	50.19 B^2	51.82 B^2	5	3
	MC35	67.54 B^2	39.42 C^3	63.84 A^3	8	1
SCR	MC15	111.19 A^3	26.88 A^1	85.21 C^1	5	2
	MC20	151.78 A^3	16.58 C^3	88.52 B^2	8	1
	MC25	137.86 A^3	18.18 B^2	92.28 A^3	8	1
	MC30	×				
	MC35	×				

Note: Different uppercase letters within each raw material in the same column indicate significant differences among moisture levels at $P \leq 0.05$.
The symbol × indicates that pellet formation was not possible due to inadequate or excessive moisture content.
Superscript numbers show the ranking within each material column, where the highest value was 3 and the lowest was 1.

Table 4 Optimum water addition and moisture content of soil amendment formulations for pelletization

Formulation ratio (by weight)	Water addition (g/1,000 g of feedstock)	Optimum moisture content (%)	Code
FC50: BRHA10: SCR40	213.22	21.32	F1
FC60: BRHA10: SCR30	218.36	21.84	F2
FC70: BRHA10: SCR20	223.50	22.35	F3
FC50: BRHA40: SCR10	301.21	30.12	F4
FC60: BRHA30: SCR10	277.02	27.70	F5
FC70: BRHA20: SCR10	252.83	25.28	F6

3.3 Properties of soil amendment pellets

The physical and mechanical properties of the soil-amendment pellets produced from different formulations were evaluated to assess pellet quality and structural stability. The results are presented in Figure 3, while the physical appearance of the pellets is shown in Figure 4.

Moisture content: MC of pelletized soil amendments ranged from 5.03% to 7.95% (w.b.) across all formulations (Figure 3a), indicating effective moisture reduction during pelletization and subsequent air-cooling. These values fall within the generally acceptable moisture range (<10%) for stabilized pellet products, ensuring improved storage stability, reduced microbial reactivation, and enhanced mechanical integrity [36, 37]. The lowest MC values were observed in F1 (5.03 ± 0.41%) and F4 (5.19 ± 0.18%), which did not differ significantly from each other but were significantly lower than the other formulations ($p \leq 0.05$). From an agronomic standpoint, Excessive residual moisture could promote microbial reactivation during storage, reduce pellet durability, and increase the risk of structural degradation and caking.

Density and pellet dimensions: BD and TD showed consistent trends across formulations, indicating that pellet compactness was primarily governed by composition (Figure 3b–c). BD ranged from 556.65–670.36 kg/m³ and TD from 948.97–1,303.70 kg/m³, with significant differences ($p \leq 0.05$). The highest densities were observed in F1 and F2, while F4 exhibited the lowest. Higher densities in F1–F3 were associated with lower BRHA (10%) and higher FC and SCR contents, which enhanced particle packing and inter-particle bonding due to their organic matter and adhesive biopolymers [38, 39]. In contrast, the high BRHA content in F4 reduced densification due to its rigid, mineral-dominated structure and limited compressibility [40]. Density increased progressively from F4 to F6 with increasing FC, confirming the role of organic matter in pellet consolidation. The BD values were comparable to or slightly higher than those reported for compost- or biochar-based pellets (450–650 kg/m³) [18, 21], suggesting advantages in transport and storage. Pellet dimensions also differed significantly ($p \leq 0.05$) (Figure 3d–f), with diameters slightly exceeding the 6-mm die due to elastic recovery. Pellet length varied more markedly, with F1–F3 and F6 producing longer pellets (15.07–15.61 mm), while BRHA-rich formulations (F4–F5) yielded shorter pellets due to reduced strand cohesion and structural integrity.

Mechanical durability: MD varied significantly among formulations (47.79–90.93%; $p \leq 0.05$) (Figure 3g), with the highest values in F6 and F3 (>90%), followed by F2 and F1, while F4 showed the lowest durability. The observed variation in MD among formulations was also consistent with the pellet formation behavior of the individual raw materials presented in Table 3. FC and SCR exhibited relatively high pellet formation percentages, indicating favorable binding and consolidation behavior during compression, whereas BRHA showed substantially lower pellet formation ability. Therefore, formulations containing higher BRHA proportions likely developed weaker inter-particle bonding and lower structural integrity, resulting in reduced mechanical durability. The higher MD observed in F3 and F6 enhanced resistance to abrasion and fragmentation [9]. However, durability was not solely dependent on density, as F1 exhibited high TD but lower MD, indicating that optimal performance requires appropriate interaction between organic binders and mineral fractions [28]. From a practical perspective, high MD reduces dust generation and improves handling, transport, and application efficiency, whereas low MD increases fragmentation risk and uneven nutrient distribution. Agronomically, adequate durability ensures pellet integrity during handling while allowing gradual disintegration in soil; thus, F3 and F6 demonstrated the most balanced performance among all formulations.

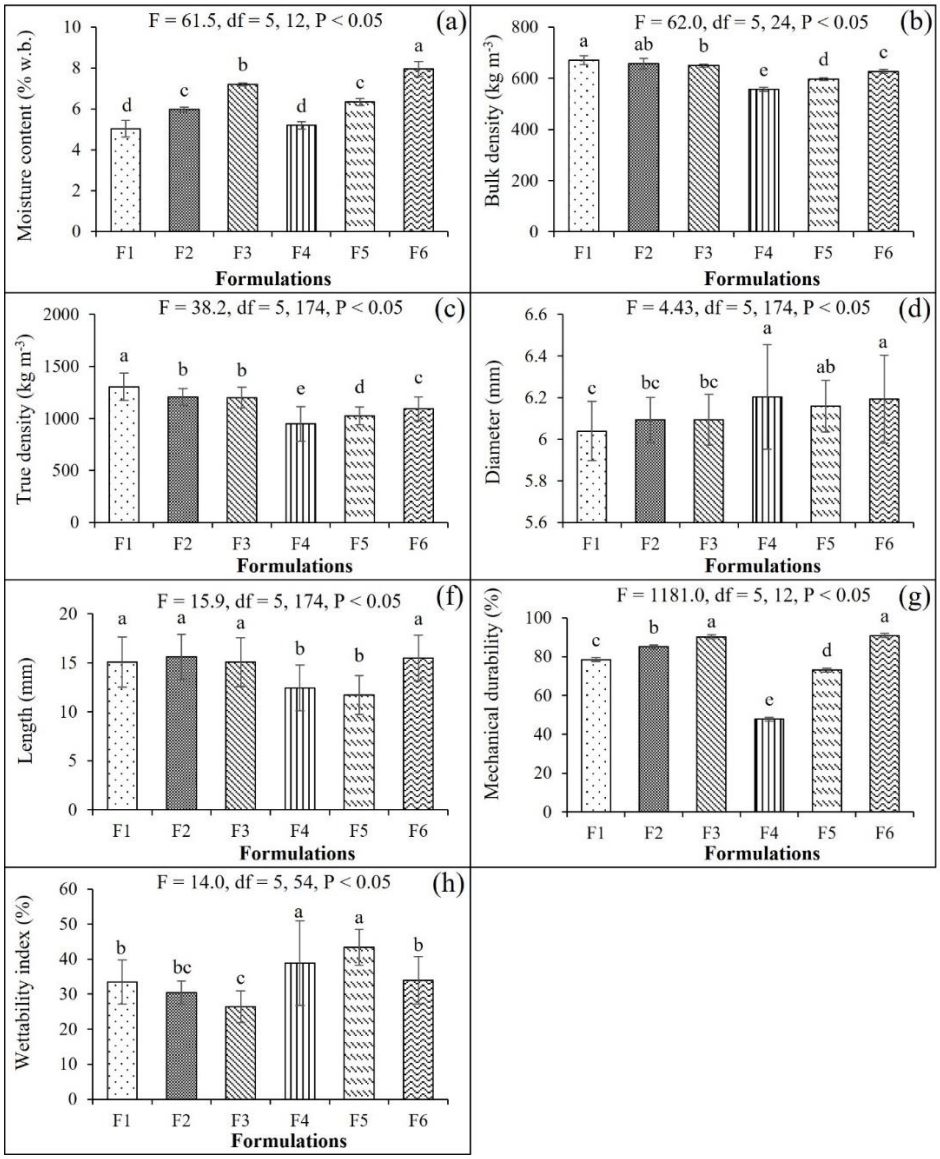


Figure 3 Effects of various soil-amendment pellet formulations on physical and mechanical properties. Different lowercase letters in the individual subfigures indicate significant differences at $P \leq 0.05$. Error bars represent standard deviation (SD)

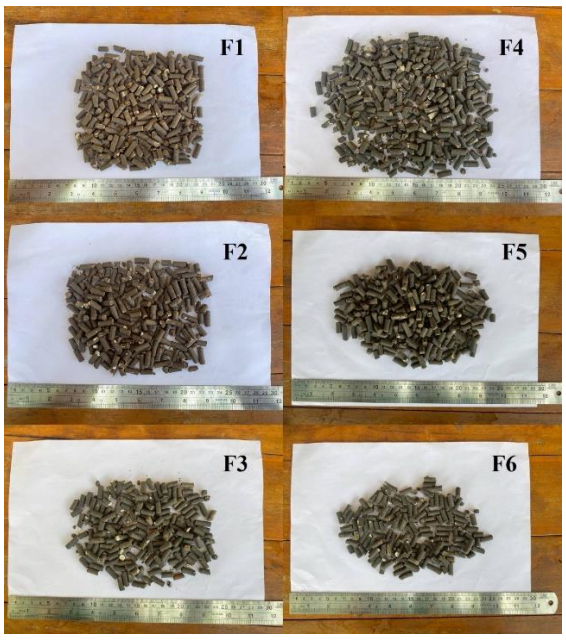


Figure 4 Physical appearance of soil-amendment pellet formulations

Wettability index: Wettability index (WI) ranged from 26.44–43.38% ($p \leq 0.05$) (Figure 3h), with the highest value in F5 and the lowest in F3. Formulations with higher BRHA content (F4–F5) exhibited greater water uptake due to lower density and increased porosity, facilitating rapid water penetration [41]. In contrast, F3 and F6, which had high mechanical durability (>90%) and higher density, showed lower WI, likely due to stronger particle bonding and reduced pore space. The WI values were comparable to those reported pelletized soil amendments produced from sugar industry waste (25.83–45.79%) [9]. As noted by Podlaski et al. [42], WI is a key parameter influencing structural stability and nutrient release; excessively high WI may reduce storage stability, whereas low WI may delay water infiltration and nutrient availability. Therefore, optimal WI should balance stability and functional performance under specific conditions.

3.4 Plant growth parameters

Pelletized soil amendments significantly affected maize growth ($p \leq 0.05$) across all parameters (Table 5). Shoot height ranged from 264.67–405.67 mm, with FCO producing the tallest plants, comparable to F5, while F2 showed the lowest values. Several pelletized formulations (F1, F4, F5) achieved comparable shoot growth to the commercial treatment. Shoot diameter was highest in F4, F5, and F1, indicating improved vegetative growth. Root length ranged from 103.49–150.22 mm, with F4 and F5 exceeding the commercial treatment, suggesting enhanced root development and improved growing medium conditions. Shoot fresh weight (0.90–1.61 g) was highest in F1 and F5, while shoot dry weight (0.0733–0.1533 g) was highest in F5 and F6.

Tabel 5 Effects of different soil-amendment pellet formulations on the growth parameters of maize (*Zea mays* L.) seedlings after 21 days of cultivation

Formulations	Shoot height (mm)	Shoot diameter (mm)	Root length (mm)	Shoot fresh weight (g)	Shoot dry weight (g)
F0	294.67 ± 15.50 c	2.21 ± 0.04 abc	114.53 ± 8.89 bc	1.09 ± 0.07 cd	0.13 ± 0.02 bc
F1	365.00 ± 18.52 b	2.29 ± 0.12 a	117.07 ± 11.14 bc	1.61 ± 0.07 a	0.11 ± 0.01 cd
F2	264.67 ± 12.34 d	1.96 ± 0.22 cd	108.04 ± 13.35 c	0.90 ± 0.11 e	0.07 ± 0.02 e
F3	290.00 ± 16.82 cd	2.24 ± 0.06 ab	118.72 ± 4.14 bc	1.00 ± 0.03 de	0.09 ± 0.02 de
F4	370.67 ± 15.18 b	2.38 ± 0.11 a	150.22 ± 5.83 a	1.37 ± 0.06 b	0.12 ± 0.02 c
F5	391.33 ± 17.21 ab	2.33 ± 0.08 a	140.17 ± 9.15 a	1.55 ± 0.10 a	0.15 ± 0.01 a
F6	311.67 ± 2.52 c	1.79 ± 0.13 d	103.49 ± 6.68 c	1.21 ± 0.13 c	0.15 ± 0.01 ab
FCO	405.67 ± 13.87 a	2.01 ± 0.27 bcd	123.52 ± 8.06 b	1.13 ± 0.07 cd	0.10 ± 0.01 cd
F	34.39	5.2	9.79	25.21	9.74
df	7, 14	7, 14	7, 14	7, 14	7, 14
P	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05

The strong performance of F5 may be attributed to its relatively high wettability index, which promotes rapid water interaction, pellet disintegration, and early nutrient availability. This likely contributed to improved maize growth during the short experimental period. However, performance may vary with crop type and growth duration, as lower wettability may be advantageous for longer cycles. Despite using a high-quality growing medium, several formulations outperformed the control (F0) and commercial amendment (FCO) at a low application rate (10%), highlighting their effectiveness. These benefits may be more pronounced in low-fertility soils and warrant further investigation.

The WI emerged as a key determinant of early seedling growth. F5, which exhibited the highest WI (43.38%), produced the greatest growth responses. This finding is consistent with Sung-inthara et al. [19], who reported that pellets with higher water absorption capacities released nutrients more rapidly and enhanced early plant growth. Conversely, F3 and F6, despite superior mechanical durability (>90%), showed lower shoot dry weight, suggesting that highly durable pellets may have delayed water penetration and nutrient release during the short three-week evaluation period. Formulations with moderate bulk density (F4 and F5) supported the longest root lengths (150.22 and 140.17 mm), which may be associated with more favorable pellet disintegration and water distribution characteristics within the growing medium, as reported by Abbas et al. [43]. The relatively poor performance of F2 and F3 may also be partly attributed to the high C/N ratio of SCR (36.84), which may have contributed to temporary nitrogen immobilization during early seedling establishment. Furthermore, increasing BRHA content reduced mechanical durability, consistent with the observations of Cwalina et al. [21], who reported that ash-rich particles weaken inter-particle bonding and promote void formation during pellet densification. The shoot height increases observed for F5 and F4 were comparable to the 27.5% increase reported by Klinsukon et al. [9] for pelletized sugar industry amendments. Overall, F5 demonstrated the most balanced performance among all formulations, achieving growth comparable to or exceeding the commercial amendment (FCO), indicating that both nutrient composition and pellet physical properties play important roles in determining agronomic effectiveness.

4. Conclusions

This study demonstrated the potential of utilizing filter cake, black rice husk ash, and soil-rich cassava wash residue as feedstocks for pelletized soil amendments. The physicochemical characterization revealed complementary properties among the materials, with FC serving as the primary nutrient-rich component, BRHA contributing mineral content, and SCR providing structural support. Moisture optimization identified a suitable pelletization range of 21.32–30.12%, enabling stable pellet formation and efficient processing. The resulting pellets exhibited acceptable physical and mechanical properties, although pellet quality varied according to formulation composition. Plant growth experiments confirmed the agronomic effectiveness of the developed products, with several formulations performing comparably to or better than the commercial amendment. Among them, F5 (FC60:BRHA30:SCR10) showed the most favorable combination of pellet properties and plant growth performance, with growth responses comparable to or exceeding the commercial soil amendment. Overall, the findings support the development of pelletized soil amendments from agro-industrial residues as a practical strategy for converting regional waste streams into value-added agricultural products.

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