

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/395174052>

# Valorization of Sugar Industry Waste into Pelletized Soil Amendments for Enhanced Plant Growth and Soil Improvement

Article in Results in Engineering · September 2025

DOI: 10.1016/j.rineng.2025.107068

CITATIONS

0

READS

17

4 authors, including:



**Chaiya Klinsukon**

Khon Kaen University

5 PUBLICATIONS 77 CITATIONS

[SEE PROFILE](#)



**Suchat Juntahum**

Khon Kaen University

10 PUBLICATIONS 92 CITATIONS

[SEE PROFILE](#)



**Kittipong Laloon**

Khon Kaen University

34 PUBLICATIONS 208 CITATIONS

[SEE PROFILE](#)



# Valorization of sugar industry waste into pelletized soil amendments for enhanced plant growth and soil improvement

Chaiya Klinsukon<sup>a,d</sup>, Sophon Boonlue<sup>b</sup>, Suchat Juntahum<sup>d,e</sup>, Kittipong Laloon<sup>c,d,e,\*</sup> 

<sup>a</sup> Department of Innovative Agriculture, Faculty of Agriculture, Khon Kaen University, Khon Kaen, 40002, Thailand

<sup>b</sup> Department of Microbiology, Faculty of Science, Khon Kaen University, Khon Kaen, 40002, Thailand

<sup>c</sup> Department of Agricultural Engineering, Faculty of Engineering, Khon Kaen University, Khon Kaen, 40002, Thailand

<sup>d</sup> GMS Food, Energy, Water Security Research Institute, Khon Kaen University, Khon Kaen, 40002, Thailand

<sup>e</sup> Postharvest Technology Innovation Center, Science, Research and Innovation Promotion and Utilization Division, Office of the Ministry of Higher Education, Science, Research and Innovation, Bangkok, 10400, Thailand

## ARTICLE INFO

### Keywords:

Pelletized organic fertilizer  
Sugar industry waste  
Soil health  
Nutrient availability  
Circular agriculture  
*Capsicum annuum* L.

## ABSTRACT

Overreliance on synthetic fertilizers in high-input agriculture has led to soil degradation and environmental pollution, necessitating sustainable alternatives. This study developed pelletized organic soil amendments from sugar industry residues, vinasse sludge, molasses wastewater, and bio-organic compost and assessed their physicochemical properties and agronomic performance. Six formulations were produced through aerobic fermentation in ventilated containers and pelletized under controlled moisture and particle size. Among them, F2 (sludge + vinasse sludge + molasses wastewater) exhibited superior characteristics, including high organic matter (43.06 mg kg<sup>-1</sup>), total nitrogen (2.07 mg kg<sup>-1</sup>), phosphorus (0.61 mg kg<sup>-1</sup>), potassium (1.88 mg kg<sup>-1</sup>), bulk density (714.60 kg m<sup>-3</sup>), and wettability index (45.79 %), significantly outperforming other formulations ( $p \leq 0.05$ ). To further evaluate nutrient dynamics, the formulations were combined with sand (sand + F1 - F6). SF2 showed the highest early availability of N, P, and K compared with other treatments. Greenhouse trials with *Capsicum annuum* L. showed that plants treated with F2 (ChF2) significantly enhanced shoot height, biomass, and chlorophyll content. ChF2 achieved 27.5 % greater shoot height and 31.2 % more biomass than the control. Soil amended with F2 also demonstrated improved water retention and nutrient availability during early growth stages. The pelletized format provided practical advantages, such as ease of handling, controlled nutrient release, and compatibility with mechanized application. These findings indicate that F2 is an effective organic alternative to synthetic fertilizers, contributing to improved soil fertility and sustainable nutrient cycling. Further research should explore long-term field performance, microbial interactions, and economic feasibility to support large-scale adoption.

## 1. Introduction

Global agriculture is undergoing a paradigm shift as the sustainability of conventional farming practices is increasingly questioned. Excessive reliance on synthetic fertilizers has led to widespread soil degradation, loss of organic matter, environmental pollution, and rising greenhouse gas (GHG) emissions [1,2]. These challenges are particularly pronounced in high-input agricultural systems, where intensified production often compromises long-term soil health and environmental stability [3]. Consequently, there is growing interest in sustainable alternatives capable of recycling organic waste and restoring soil fertility while maintaining high crop productivity [4,5].

Organic soil amendments have emerged as effective tools for enhancing soil structure, nutrient availability, water retention, and microbial activity [6,7]. Recent studies confirm that the application of sludge and organic waste-derived compost can significantly improve soil fertility, water retention, and crop productivity, particularly in semi-arid environments. For example, treated wastewater sludge has been shown to enhance soil organic matter, microbial activity, and grain yield in wheat cultivation [8,9]. Moreover, low-dose municipal sludge composts were found to be associated with increased K<sub>2</sub>O, P<sub>2</sub>O<sub>5</sub>, and nitrate content, and modest microbial enzyme activity improvement [10,11]. These findings support the sustainable use of sludge as a beneficial amendment for improving both soil quality and nutrient

\* Corresponding author.

E-mail addresses: [chaikl@kku.ac.th](mailto:chaikl@kku.ac.th) (C. Klinsukon), [bsopho@kku.ac.th](mailto:bsopho@kku.ac.th) (S. Boonlue), [jsuchat@kkumail.com](mailto:jsuchat@kkumail.com) (S. Juntahum), [kittila@kku.ac.th](mailto:kittila@kku.ac.th) (K. Laloon).

<https://doi.org/10.1016/j.rineng.2025.107068>

Received 16 April 2025; Received in revised form 29 August 2025; Accepted 1 September 2025

Available online 1 September 2025

2590-1230/© 2025 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

cycling. Recent studies have demonstrated the feasibility of producing pelletized substrates from sugarcane residues, which enhance seedling establishment and nutrient availability [12]. Furthermore, biochar integration into compost has been widely recognized to improve soil physical properties, nutrient retention, and long-term stability [13,14]. Derived primarily from agro-industrial waste, these amendments not only valorize organic residues but also play a critical role in carbon sequestration and the advancement of climate-smart agriculture [15, 16]. Of particular interest is the use of revalorized by-products from the sugar industry such as vinasse sludge, molasses wastewater, and bio-organic compost owing to their abundance, nutrient richness, and renewability nature [17,18].

Numerous studies have demonstrated the agronomic and environmental potential of organic amendments. For instance, Piash et al. [19] reported that chicken manure biochar retains 76.4 % of nitrogen during processing and releases nearly 100 % in plant-available form, outperforming compost and hydrochar. Aguirrebengoa et al. [20] showed that vermicompost derived from olive mill waste enhances root microbiome diversity and activates plant defense mechanisms. Similarly, Jaffar et al. [21] found that orange peel-derived biochar mitigated salinity stress in maize, whereas Kisekka et al. [22] observed improved water infiltration and soil aggregation using almond hull-based compost. These findings highlight the versatility and adaptability of organic amendments derived from diverse biomass sources.

In addition to enhancing crop performance, compost and vermicompost amendments also contribute to the mitigation of GHG emissions. Organic amendments can reduce methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) emissions while enhancing soil organic carbon (SOC) storage [23–25]. Composting and vermicomposting techniques, particularly when optimized, are highly effective for nutrient stabilization and gaseous emission suppression. Wang et al., Fionore et al., Li et al. and Gaspar et al. [26–29] highlighted recent technological advances, including thermophilic inoculants, microbial consortia, and controlled aeration, which enhance decomposition efficiency. Abioye et al. [30] demonstrated that applying vermicompost significantly reduced methane and nitrous oxide emissions in agricultural fields, reinforcing its role in low-emission farming systems.

Nevertheless, conventional compost and vermicompost face limitations, such as bulkiness, inconsistent nutrient content, and logistical challenges in field applications. Pelletization offers a promising engineering solution by improving the physical characteristics of organic amendments such as bulk density, durability, and nutrient retention, thereby facilitating storage, handling, and field application. This growing interest in pelletized formulations is part of a broader trend toward the valorization of agricultural waste, which seeks to convert low-value byproducts into high-performance inputs through sustainable technologies. Recent reviews emphasize that valorization strategies ranging from composting and pelletization to integrated biorefineries can transform agro-industrial residues into biofertilizers, bioenergy, and other value-added products, supporting the circular economy [31–33]. These advances also reduce reliance on chemical fertilizers while promoting rural development and environmental sustainability. While these innovations demonstrate the potential of compost pelletization and waste valorization technologies, few studies have specifically explored the integration of multiple sugar industry residues into pelletized formulations tailored for both nutrient enhancement and greenhouse gas (GHG) mitigation.

Emerging studies have demonstrated the feasibility of pelletizing sugar industry waste into durable and energy-efficient biomass pellets. For instance, Sanchumpu et al. [34] successfully formulated pellets from sugarcane bagasse and filter cake with bulk densities exceeding 600 kg/m<sup>3</sup> and durability above 97.5 % by making use of optimal moisture content and particle size. These findings highlight the engineering viability of valorizing sugar-derived residues through pelletization. Additionally, Singh et al. (2025) [35] showed that the integration of sugar industry by-products such as press mud compost, bagasse, and

treated wastewater significantly improved soil organic carbon by up to 85.7 %, microbial population, and sugarcane yield while reducing dependency on chemical fertilizers. However, challenges related to the bulkiness and field logistics of traditional compost applications remain.

Therefore, this study aimed to: (1) develop pelletized organic soil amendments using vinasse sludge, molasses wastewater, and bio-organic compost; (2) characterize their physicochemical properties and essential nutrients; and (3) evaluate their effects on the early seedling growth of *Capsicum annuum* L. under greenhouse conditions.

## 2. Materials and methods

To illustrate the overall experimental framework, a workflow diagram (Fig. 1) is provided to visualize the sequential steps involved in the production and evaluation of the pelletized soil amendments. The process began by selecting and collecting sugar industry waste materials to serve as raw inputs. These materials were characterized for their physicochemical properties and then formulated into compostable mixtures. The mixtures were subject to controlled fermentation, followed by pelletization. The physicochemical and mechanical properties of the resulting pellets, including their durability, density, and wettability, were assessed. Finally, the agronomic performance of pelleted soil amendments was evaluated through seed germination and seedling growth trials under greenhouse conditions.

### 2.1. Preparation of organic amendment materials

Agricultural waste materials were sourced from the Kaset Thai International Sugar Corporation (KTIS) in Nakhon Sawan, Thailand. These sugar production by-products are available in large quantities, making them suitable for development into soil amendments that can be produced at scale and utilized by farmers for soil improvement or commercial distribution. The materials used included: (1) vinasse sludge, high K content, and humic substances that enhance cation exchange capacity (CEC) and root proliferation [36,37]; (2) molasses wastewater which provides readily available carbon to stimulate microbial activity [38]; (3) sludge (solid waste from wastewater treatment), which contains high organic matter and essential nutrients required for plant growth, including both macronutrients and micronutrients [39]; (4) bio-organic compost produced from filter cake mixed with ash from power generation processes; and (5) effluent from the biogas production process, which is a habitat for microbial communities that contains nutrients and secondary metabolites [40]. Samples of the collected sugar industry by-products were analyzed to determine their organic matter content using the Walkley and Black method [41]. Key macronutrients were assessed, including nitrogen (N) using the Kjeldahl method and analyzed the FLA method [42], phosphorus (P) using spectrophotometry [43], and potassium (K) using atomic absorption spectrophotometry [44]. Additionally, secondary nutrients were quantified, including sulfur (S) (measured by turbidity spectrophotometry) [45], calcium (Ca), magnesium (Mg), and iron (Fe) (measured by atomic absorption spectrophotometry) [44]. Heavy metal contaminants, specifically arsenic (As) and cadmium (Cd), were analyzed using inductively coupled plasma atomic emission spectroscopy (ICP-OES) [46]. These analyses were conducted at the Center for Research and Laboratory Studies, Faculty of Agriculture, Khon Kaen University.

### 2.2. Formulation and fermentation

Agricultural waste materials were subjected to a fermentation process designed to produce bio-organic soil amendments. Six experimental formulas (F1 to F6) were formulated by combining the different materials in specific ratios of 1:1:2 (W:W:V).

F1: Sludge + vinasse sludge + biogas effluent

F2: Sludge + vinasse sludge + molasses wastewater

F3: Bio-organic compost + vinasse sludge + molasses wastewater

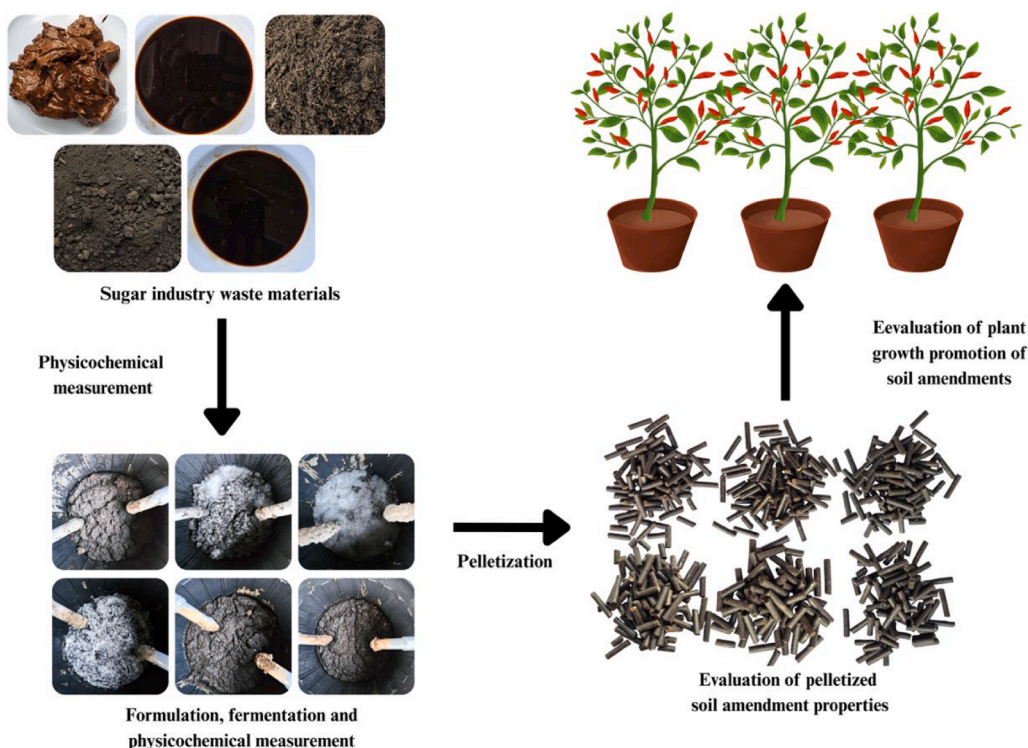


Fig. 1. Workflow diagram of the overall experimental design.

F4: Bio-organic compost + vinasse sludge + biogas effluent

F5: Bio-organic compost + sludge + molasses wastewater

F6: Bio-organic compost + sludge + biogas effluent

Fermentation was performed in plastic containers equipped with ventilation tubes for aeration. The fermentation period lasted 45 days, with aeration facilitated by turning the compost pile. At the end of the fermentation process, the chemical and physical properties of the compost and the essential nutrients for plant growth were analyzed.

### 2.3. Germination test

The effects of the soil amendments on maize (*Zea mays* L.) seed germination were evaluated, following the method by Zucconi et al. [47] using a germination test. A 1:10 (w/v) solution was prepared by mixing each soil amendment with distilled water. Corn seeds were then sown in sterile trays and incubated for 3–7 days. The experiment was conducted in triplicate and the data analyzed using a completely randomized design (CRD).

### 2.4. Palletization

The pelletization and drying process followed the optimum conditions method and pellet properties of Sung-Inthara et al. [48].

Before the pelleting process, the soil amendment materials were required to be appropriately sized. Materials that are too large for pelleting, such as branches, stones, and gravel, can cause clogging or result in inconsistent pellets. Therefore, all soil amendment materials were pre-processed using a hammer mill crusher equipped with 12 beating blades and a 6 mm sieve to reduce the particle size. The feed rate was set to 120 kg h<sup>-1</sup>.

The drying process was carried out to standardize the moisture content across all formulations to an optimal level for effective pelletization. The target final moisture content was set at 20 % because excessive moisture can hinder pellet formation by reducing particle cohesion, leading to deformation or mechanical instability. All six soil amendment formulations were subjected to a controlled drying regime

using a parabolic dome dryer at ambient temperatures ranging from 42–50 °C. The drying process was performed continuously over 7 days during May 2024 in the Northeastern region of Thailand. Moisture content was monitored via random sampling using a digital moisture meter, and drying continued until all treatments consistently approached the target moisture level of 20 %.

The pelleting process shapes the materials into pellets of specified dimensions (diameter and length). A flat die pellet machine with a 6 mm die was used to form the pellets, with a manual feed rate of approximately 120 kg h<sup>-1</sup>. After pelleting, the soil amendment pellets were cooled to balance the moisture content, sieved through a 3 mm mesh, and weighed. The pellet formation percentage was calculated using equation (1):

$$\text{Pellet Formation Percentage} = \frac{\text{Dry Weight of Pellets (kg)}}{\text{Dry Weight of Pressed Material (kg)}} \times 100 \quad (1)$$

### 2.5. Evaluation of pelletized soil amendment properties

Samples (10 g) were taken from each pellet batch in triplicate to evaluate the physical properties of the soil amendment pellets. The surface morphology of the pelletized soil amendment formulations was examined under a stereo microscope (Nikon SMZ 745T). The length and diameter of the soil amendment pellets were measured using a Vernier caliper with an accuracy of 0.01 mm. True density is a fundamental physical property that represents the actual mass per unit volume of a material, excluding any void spaces or pores. This parameter is essential for assessing the compactness and structural integrity of the pelletized materials. The true density of the pellets was determined by precisely measuring their mass and volume [34,49]. The mass of each pellet was recorded using an analytical balance (Ohaus, USA) with a high accuracy of 0.0001 g to ensure precise measurements. The geometric dimensions of each pellet, including its diameter and length, were carefully measured using a high-precision digital calipers. These dimensions were used to calculate the volume of the pellets, assuming a cylindrical shape,

using equation (2):

$$\text{True Density} = \frac{\text{Weight of Pellets (kg)}}{\text{Volume of Pellets (m}^3\text{)}} \quad (2)$$

Bulk density was determined according to the ASTM C29 standard procedure [50]. To ensure consistency in measurement, the pellets were gently poured into a cylindrical container with a fixed volume of 0.001 m<sup>3</sup>. The pouring process was conducted without compaction, which allowed the pellets to settle naturally under the influence of gravity. After filling, the top layer was carefully leveled to align with the container's edge, ensuring a uniform and reproducible volume measurement. The total weight of the container, including that of the pellets, was recorded using an analytical balance with an accuracy of 0.0001 kg. The weights of the empty containers were also measured separately. Bulk density was calculated using equation (3):

$$\text{Bulk Density} = \frac{\text{Total Weight (kg)} - \text{Container Weight (kg)}}{\text{Container Volume (m}^3\text{)}} \quad (3)$$

The mechanical durability of the pellets was determined according to EN ISO 17,831-1 for pellets (EN ISO, 2025). Samples of 500 g were subjected to agitation at 50 rpm for 10 min using a custom durability testing device, a 30 × 30 × 12.5 cm box equipped with a 5 × 23 cm plate. After tumbling, the remaining pellets were separated using a 3 mm sieve, and the weight loss was recorded. The experiment was conducted using a completely randomized design (CRD) with three replications for each formulation.

The wettability index was determined using a modified version of the method described by Papandrea et al. [51]. Pellets were randomly selected from the sample batches and prepared for analysis. To ensure accurate measurements, all weight recordings were performed using an analytical balance with a precision of 0.0001 g. Each pellet was initially weighed in its dry state (denoted as the Dry Weight). Subsequently, the sample was carefully immersed in distilled water for 30s, ensuring complete submersion while minimizing external disturbances that could impact water absorption. After the immersion period, excess surface water was gently removed using a standardized blotting technique to prevent overestimation due to surface adhesion. The wet pellets were then immediately weighed (Wet Weight). The wettability index was calculated using equation (4):

$$\text{Wettability Index} = \frac{\text{Wet Weight} - \text{Dry Weight}}{\text{Dry Weight}} \times 100 \quad (4)$$

## 2.6. Evaluation of the effect of pelletized soil amendments on soil physicochemical properties

The experiment was conducted using a completely randomized design (CRD) with a factorial arrangement, consisting of seven treatments with three replicates. The control treatment (S) comprised a sand-based medium without any soil amendments. This study was conducted in a greenhouse at the Faculty of Agriculture, Khon Kaen University, Thailand (16°28'01.1 N, 102°48'43.1 E). The experiment utilized cylindrical polyethylene terephthalate (PET) pots with a capacity of 1.5 L. Each pot was filled with washed river sand (particle size < 2 mm) to minimize external contamination. Each pelletized soil amendment formulation (F1-F6) was incorporated into the sand at a rate of 10 % by weight (100 g kg<sup>-1</sup> of sand). Sand was mixed with each amendment formulation (F1-F6). These combined treatments were denoted as SF1 - SF6, where SF1 = sand + F1, SF2 = sand + F2, SF3 = sand + F3, SF4 = sand + F4, SF5 = sand + F5, and SF6 = sand + F6. The mixtures were thoroughly homogenized to ensure uniform distribution. Following the amendment application, 250 g of sterilized distilled water was added to each pot to facilitate hydration. Each pot was then sealed with a dome lid and wrapped with parafilm to maintain controlled environmental conditions. The pots were incubated under dark conditions for 10 days to allow for interactions between the amendments and the soil matrix

before sample collection. The nutrient content of nitrogen (N), phosphorus (P), and potassium (K) were measured daily over the 10 days using a BGT-SNPK RS485 Soil NPK Sensor (BGT, China). Measurements were conducted in situ within the pots and readings were recorded at 10 different points per pot to ensure representative data collection. Data acquisition and processing were carried out using Modbus Pol software to facilitate real-time monitoring of soil nutrient dynamics. At the end of the incubation period, soil samples were randomly collected from each pot using a hand-held soil auger. Samples were taken from a depth of 0–10 cm and subjected to further physicochemical analysis. The soil texture was separated using the fraction of sand, silt, and clay particles in the jar test, followed by identification of the soil type by using the USDA soil texture triangle [52]

Water holding capacity (WHC) was determined using a modified gravity drainage method, adapted from Jenkinson and Powlson [53]. This method quantifies the ability of soil to retain water after saturation and subsequent drainage. Soil samples were collected from the study site using a soil sampler probe at a depth of 0–15 cm. The collected soil samples were then air-dried before being subjected to oven drying at 105 °C for 48 h to remove residual moisture. After complete drying, 50 g of soil was accurately weighed and placed in a funnel lined with Whatman No 2 filter paper. A total of 100 mL of distilled water was gradually added to each soil sample to ensure complete saturation. The funnel was then placed vertically on a collection container to allow free drainage of excess water under the influence of gravity. The drainage process was allowed to continue for 1 h. Subsequently, the volume of drained water was measured using a graduated cylinder. The WHC was calculated as the difference between the total volume of water added and the volume of drained water, accounting for the water retained by the filter paper (3.08 mL ± 0.22). The WHC (%) was determined using equation (5):

$$\text{WHC (\%)} = \frac{100 \text{ mL} - \text{water drained} - 3.08 \text{ mL}}{50\text{g}} \times 100 \quad (5)$$

## 2.7. Plant growth promotion of soil amendments

The greenhouse experiment was conducted using chili (*Capsicum annuum* L.), an economically significant widely cultivated vegetable and spice crop which has a high nutrient demand and sensitivity to soil fertility [54]. 45-day-old chili seedlings were cultivated in pot trays. The seedlings were transferred to 7-inch diameter plastic pots under greenhouse conditions at 24 - 26 °C and 60 % humidity. The experiment was carried out using a randomized complete block design (RCBD) consisting of seven treatments: Chili untreated with soil amendment control (C); chili treated with 150 g soil amendment (ChF1); chili treated with 150 g soil amendment F2 (ChF2); chili treated with 150 g soil amendment (ChF3); chili treated with 150 g soil amendment F4 (ChF4); chili treated with 150 g soil amendment F5 (ChF5); and chili treated with 150 g soil amendment F6 (ChF6). The plants were cultivated for 60 days, from transplantation to data collection. Plant growth parameters, including shoot height, shoot diameter, fresh and dry weight of shoot and root, and SPAD chlorophyll content (using SPAD 502 Plus Chlorophyll Meter), were analyzed at 45 days to evaluate plant growth performance for each treatment.

## 2.8. Data analysis

Statistical analysis of the data was carried out using the Statistix 10 software. Significant differences among the mean values at  $p < 0.05$  were analyzed using Fisher's least significant difference (LSD) test to identify significant differences.

### 3. Results and discussion

#### 3.1. Physicochemical properties of raw materials

The analysis of raw materials used for bio-organic soil amendment development revealed significant variability in their nutrient composition and heavy metal content. Table 1 presents the concentrations of primary and secondary nutrients including organic matter (OM), total nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and iron (Fe). Among the materials analyzed, vinasse sludge exhibited the highest organic matter content ( $58.23 \text{ mg kg}^{-1}$ ), total nitrogen ( $4.89 \text{ mg kg}^{-1}$ ), and potassium ( $1.97 \text{ mg kg}^{-1}$ ). Molasses wastewater had a low organic matter content ( $3.15 \text{ mg kg}^{-1}$ ) and minimal nitrogen ( $0.09 \text{ mg kg}^{-1}$ ), phosphorus ( $0.02 \text{ mg kg}^{-1}$ ), and potassium ( $1.04 \text{ mg kg}^{-1}$ ). Sludge, bio-organic compost, and biogas effluent contained moderate to high organic matter content ( $33.93$ ,  $54.55$ , and  $1.39 \text{ mg kg}^{-1}$ , respectively), with varying levels of essential nutrients. Notably, bio-organic compost had the highest phosphorus content ( $0.75 \text{ mg kg}^{-1}$ ), whereas sludge exhibited higher calcium ( $1.65 \text{ mg kg}^{-1}$ ) and magnesium ( $0.35 \text{ mg kg}^{-1}$ ) concentrations. The iron content was highest in vinasse sludge ( $2.32 \text{ mg kg}^{-1}$ ) and sludge ( $1.20 \text{ mg kg}^{-1}$ ), whereas biogas effluent exhibited the lowest organic matter content ( $1.39 \text{ mg kg}^{-1}$ ). Heavy metal analysis (Table 1) indicated that all tested materials contained arsenic (As) and cadmium (Cd) concentrations well below the safety thresholds established for organic fertilizers by the Land Development Department of Thailand. Vinasse sludge exhibited the highest arsenic concentration ( $2.32 \text{ mg kg}^{-1}$ ), whereas sludge and bio-organic compost contained  $0.83$  and  $0 \text{ mg kg}^{-1}$ , respectively. Cd concentrations remained within acceptable limits, with the highest value observed in bio-organic compost ( $1.49 \text{ mg kg}^{-1}$ ).

The nutrient composition and heavy metal profile of the raw materials used in this study demonstrated considerable variability, emphasizing the critical role of material selection on the formulation of effective organic soil amendments. Vinasse sludge exhibited superior organic matter content ( $58.23 \text{ mg kg}^{-1}$ ) and total nitrogen ( $4.89 \text{ mg kg}^{-1}$ ), whereas molasses wastewater although low in OM ( $3.15 \text{ mg kg}^{-1}$ ) contained moderate potassium levels ( $1.04 \text{ mg kg}^{-1}$ ). Bioorganic compost had the highest phosphorus content ( $0.75 \text{ mg kg}^{-1}$ ). These findings support the strategic blending of organic waste streams to optimize nutrient profiles. Compared to previous studies, such as Piash et al. [19] which highlighted chicken-manure biochar's high nitrogen retention and release efficiency, our results align with the notion that proper selection of organic waste can lead to enhanced nutrient recovery and soil enrichment. Moreover, the arsenic and cadmium concentrations were all within safety limits defined by Thai agricultural standards [55], ensuring that the raw inputs are environmentally safe. This is consistent with the findings of Vollmer et al. [6] which reported similarly low heavy metal levels in composted horticultural waste. One unique feature of the present study is the integration of vinasse sludge, a sugar-industry byproduct less commonly used in Thailand, suggesting region-specific valorization strategies.

The variation in elemental composition across the raw materials likely reflects the differences in their origins and processing stages. For instance, the high nitrogen content in vinasse sludge may stem from

protein-rich fermentation residues, whereas the lower OM content in molasses wastewater could be attributed to its aqueous nature and prior sugar extraction processes. Compared to other composting studies involving tomato residues or animal manure [7], our raw materials provided a broader range of macronutrient concentrations, suggesting a more diverse nutrient source for composting. A key strength of our approach lies in the comprehensive characterization of both macro- and micronutrients along with heavy metals, which provides a holistic evaluation of material suitability. However, this study is limited by the lack of microbial profiling, which would have complemented the chemical data with biological potential insights, as suggested by Aguirrebengoa et al. [19] which linked microbial diversity in raw materials with enhanced soil functionality.

The characterization of raw materials in this study aligns directly with the primary research objective of developing nutrient-rich, safe, and effective organic pelleted amendments from sugar industry waste. This demonstrated nutrient diversity supports the hypothesis that waste blending can be tailored to specific agronomic needs. In a broader context, our findings highlight the importance of valorizing regional agro-industrial byproducts, not only to close nutrient cycles but also to reduce reliance on synthetic fertilizers and promote sustainable waste management. These insights provide foundational data to justify subsequent composting and formulation strategies in this study.

#### 3.2. Fermentation process

During the composting process for soil amendments, temperature, pH, electrical conductivity (EC), and moisture content were monitored at regular intervals for 45 days (Fig.1). The initial temperature of the composting materials was recorded at  $27.6 \text{ }^\circ\text{C}$ , followed by a rapid increase during the first 7 days, reaching a peak of  $47.2 \text{ }^\circ\text{C}$ , indicating active microbial decomposition. The temperature then gradually declined, reaching approximately  $38 \text{ }^\circ\text{C}$  by day 21, and continued to decrease until stabilizing at  $28.2 \text{ }^\circ\text{C}$  on day 45 (Fig. 2a). The pH of the composting materials initially ranged from 5.7 to 7.4, showing a steady increase throughout the first 28 days, reaching a maximum range of 7.8 to 8.2. During the final stages, particularly on days 42 and 45, the pH values gradually declined, stabilizing at neutral to slightly alkaline levels (Fig. 2b). The initial EC values ranged between 2.2 and 3.0 dS/m, showing an increasing trend between days 7 and 28, peaking at approximately 3.8 dS/m, before gradually decreasing. By the end of the composting process, the final EC values ranged from 2.0 to 2.6 dS/m (Fig. 2c). The moisture content of the composting materials started between 45 % and 55 %, slightly decreasing during the first 14 days.

The final soil amendments after the 45-day fermentation period exhibited distinct and observable physical transformations, indicating successful compost maturation. All formulations (F1–F6) developed a dark brown to black coloration, signifying increased humification and organic matter stabilization. This color change, together with a uniformly granular and crumbly texture and reduced particle size, reflects a high degree of organic matter decomposition and microbial activity. These characteristics suggest the production of a stable and mature compost product suitable for agricultural application, as visually presented in Fig. 3. The moisture content was found to be well-balanced

**Table 1**

Concentrations of primary and secondary nutrients in raw materials, organic matter (OM), total nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe).

Samples	OM	Total N	P	K	Ca ( $\text{mg kg}^{-1}$ )	Mg	Fe	As	Cd
VS	58.23	4.89	0.13	1.97	2.13	0.31	2.32	2.32	0.39
MW	3.15	0.09	0.02	1.04	0.27	0.18	0.02	0.03	0.09
S	33.93	1.18	0.32	0.20	1.65	0.35	1.20	0.83	1.13
BC	54.55	0.42	0.75	0.67	0.95	0.54	1.44	0	1.49
BE	1.39	0.09	0.02	0.97	0.02	0.17	0.02	0.21	0.09

VS, Vinasse sludge; MW, Molasses wastewater; S, Sludge; BC, Bio-organic compost; BE, Biogas effluent.

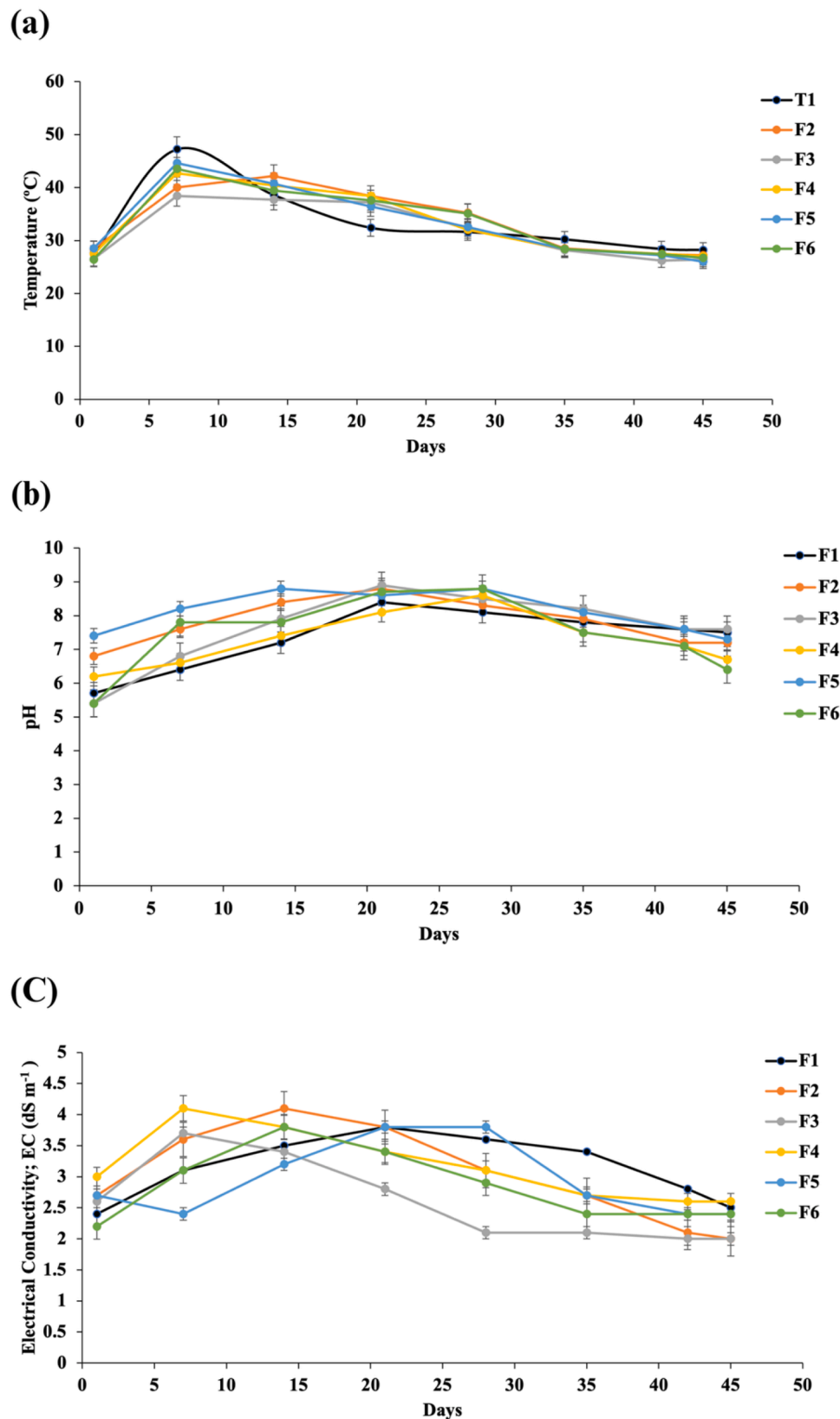
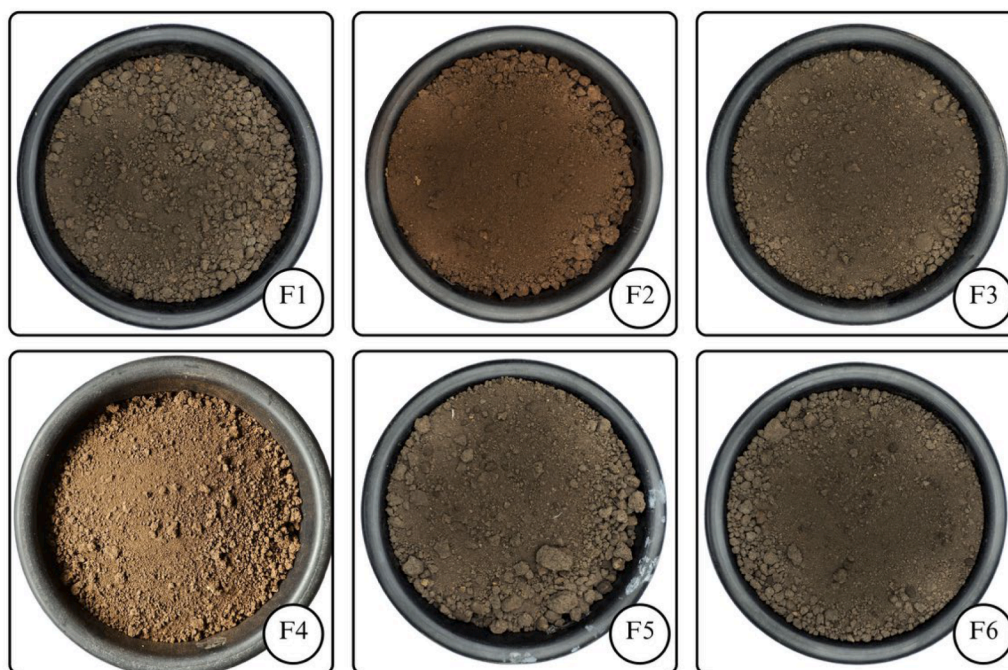


Fig. 2. Change in (a) temperature, (B) pH, and (C) electroconductivity (EC) throughout the composting process of organic soil amendment.

across all formulations, supporting adequate aeration and microbial viability. Importantly, no unpleasant odors were detected, indicating the effective degradation of volatile organic compounds. The disappearance of fungal mycelia, previously observed during the early composting

stages, further confirmed the completeness of the decomposition process. Among the formulations, those containing sludge and vinasse sludge (F1 and F2) showed slightly higher moisture retention and denser texture, whereas those incorporating bio-organic compost (F3-F6)



**Fig. 3.** Soil amendments in the final 45 days. F1: Sludge + vinasse sludge + biogas effluent, F2: Sludge + vinasse sludge + molasses wastewater, F3: Bio-organic compost + vinasse sludge + molasses wastewater, F4: Bio-organic compost + vinasse sludge + biogas effluent, F5: Bio-organic compost + sludge + molasses wastewater, F6: Bio-organic compost + sludge + biogas effluent.

exhibited greater porosity and aeration, likely enhancing their utility in improving soil structure.

### 3.3. Physicochemical properties and essential nutrients for plant growth of soil amendments

The analysis of organic matter (OM) and macronutrient concentrations for the six compost formulas revealed substantial variations in nutrient enrichment and compost maturity (Table 2). Formula 2 (F2), composed of sludge, vinasse sludge, and molasses wastewater, demonstrated the highest OM ( $43.06 \text{ mg kg}^{-1}$ ), total nitrogen ( $2.07 \text{ mg kg}^{-1}$ ), phosphorus ( $0.61 \text{ mg kg}^{-1}$ ), and potassium ( $1.88 \text{ mg kg}^{-1}$ ) levels, suggesting a synergistic effect of combining nutrient-rich and carbonaceous waste streams. Formula 1 (F1), also sludge-based, showed similarly high OM ( $39.53 \text{ mg kg}^{-1}$ ) and nitrogen ( $1.76 \text{ mg kg}^{-1}$ ), although with lower phosphorus ( $0.22 \text{ mg kg}^{-1}$ ). These results reflect the effective transformation of sugar industry byproducts into nutrient-rich amendments,

**Table 2**

Organic matter (OM) and primary nutrient content, including nitrogen (N), phosphorus (P), potassium (K), and carbon to nitrogen (C/N) ratio in soil amendments for each treatment after 45 Days.

Treatments	OM ( $\text{mg kg}^{-1}$ )	Total N ( $\text{mg kg}^{-1}$ )	Total P ( $\text{mg kg}^{-1}$ )	Total K ( $\text{mg kg}^{-1}$ )	C/N ratio
F1	39.53b	1.76b	0.22d	1.68a	22.44c
F2	43.06a	2.07a	0.61a	1.88a	20.81c
F3	15.26d	0.97c	0.42b	1.49b	15.78d
F4	16.46d	1.01c	0.45b	1.48b	16.29d
F5	24.74c	0.85c	0.34c	1.45b	28.96b
F6	24.39c	0.77d	0.36c	1.26c	31.82a
% CV	44.26	52.62	56.52	48.46	52.42

Means followed by the same letter within the same column are not significantly different at  $P \leq 0.05$ , according to the LSD test. F1: Sludge + vinasse sludge + biogas effluent; F2: Sludge + vinasse sludge + molasses wastewater; F3: Bio-organic compost + vinasse sludge + molasses wastewater; F4: Bio-organic compost + vinasse sludge + biogas effluent; F5: Bio-organic compost + sludge + molasses wastewater; F6: Bio-organic compost + sludge + biogas effluent.

particularly when vinasse sludge and molasses wastewater are used. This finding supports the hypothesis that molasses wastewater, despite its low initial OM, contributes bioavailable carbon that stimulates microbial activity and enhances nutrient mineralization, as reported by Piash et al. [19] in the context of nitrogen release from chicken manure-derived biochar. The superior C/N ratio in F2 (20.81) further indicates an advanced stage of decomposition and suitability for soil application, consistent with the recommendations by Li et al. [7] which noted that organic amendments with C/N ratios between 15–25 promote nutrient availability while minimizing nitrogen immobilization. This observation also aligns with synergistic compost quality assessments, which emphasize that a combination of chemical indices (e.g., C/N ratio) together with stability and biological activity indicators provides a more holistic evaluation of compost maturity and agronomic effectiveness [56]. The disparity in nutrient content among the formulas can be attributed to the intrinsic chemical properties of the raw materials and their relative biodegradability. For instance, the higher N and K in F2 may stem from the nitrogenous nature of the sludge and the potassium-rich profile of the molasses wastewater. F5 and F6, incorporating bio-organic compost with sludge or biogas effluent, showed moderate nutrient content but higher C/N ratios (28.96 and 31.82), potentially due to the recalcitrant organic matter in compost or the dilution effect from biogas effluent with low OM ( $1.39 \text{ mg kg}^{-1}$ ). Notably, F3 and F4, despite containing bio-organic compost, recorded the lowest OM ( $15.26$  and  $16.46 \text{ mg kg}^{-1}$ ), possibly due to microbial competition or inhibitory compounds present in the feedstock. When compared to a similar composting study by Vollmer et al. [6], which reported high P and K levels from tomato plant residues, our formulations achieved comparable or higher macronutrient values, with waste sources more prevalent in the sugar industry. These findings reinforce the research objective of producing organic soil amendments with enhanced nutrient profiles suitable for high-input cropping systems. The superior nutrient levels in F2 highlight the feasibility of customizing waste-based formulations to target specific nutrient deficiencies. Furthermore, the C/N ratio analysis provides a critical indicator of compost maturity and application readiness.

### 3.4. Germination test

Germination test results for maize (*Zea mays* L.) seeds indicated varying levels of seedling establishment across different soil amendment treatments. F2 exhibited the highest germination index (GI) of 96 %, suggesting optimal conditions for seed germination. This was followed by F1 with a GI of 92 % and F5 with a GI of 90 % (Table 3), both of which demonstrated favorable conditions for seedling growth. The other formulas recorded slightly lower germination indices, with F3 at 87 %, F6 at 88 %, and F4 at 86 %. The coefficient of variation (CV) was 46.56 %, indicating some variability in seed germination performance across formulas. Statistical analysis showed that significant differences were observed among the formulas, with F2 demonstrating the highest germination success and F4 exhibiting the lowest GI. These findings suggest that the composition of each soil amendment had a measurable effect on the ability of maize seeds to germinate, as summarized in Table 3.

The GI of maize seeds varied significantly across treatments, with F2 achieving the highest GI at 96 %, followed by F1 (92 %) and F5 (90 %), indicating the favorable seedbed conditions created by these soil amendments. These results suggest that the amendments derived from sludge, vinasse sludge, and molasses wastewater (F2) promoted rapid and uniform seed germination, likely due to balanced nutrient availability, optimal moisture retention, and a near-neutral pH-factors known to influence seed physiology. Rashid et al. [2] emphasized the critical role of soil pH in modulating both seed germination and microbial activity, highlighting that near-neutral pH enhances nutrient solubility and minimizes phytotoxicity. The moderate to low GI in F3, F4, and F6 (86–88 %) may be due to residual compounds from biogas effluent or suboptimal nutrient availability. These patterns are consistent with those reported by Vollmer et al. [6], who noted that compost derived from certain plant residues can initially release ammonia or organic acids that inhibit germination if not fully stabilized. The strong performance of F2 supports the concept of well-balanced microbial decomposition and low levels of phytotoxicity in mature composts.

The differences in germination indices can be partially explained by variations in C/N ratios, total nitrogen, and organic matter content among the formulas. F2, with the lowest C/N ratio (20.81) and highest nitrogen content (2.07 %), likely offered readily available nutrients that supported early seed metabolic activation and radicle emergence. Additionally, molasses wastewater may have provided easily decomposable sugars that fueled microbial respiration during the early composting phase, hastened maturation, and reduced residual phytotoxicity by the time of germination testing. In contrast, treatments such as F4, which included biogas effluent, might have retained incomplete degradation products or volatile fatty acids, consistent with the findings of Galamini et al. [57], which reported elevated CO<sub>2</sub> emissions and

microbial imbalance in early-stage digestate-amended soils. However, a limitation lies in the exclusive use of maize seeds, as maize is a reliable test species, but further validation with diverse crops would enhance generalizability. The germination test results directly align with the research objective of evaluating the bioavailability and agronomic effectiveness of the produced pelleted soil amendments. The high GI values for F2 and F1 indicate their readiness for application or capacity to support initial plant establishment in cropping systems.

### 3.5. Pelleting process and soil amendment properties

The moisture reduction process of all soil amendment materials exhibited a consistent decrease across all formulas (F1-F6) over the first three days. On day 1, the initial moisture levels ranged from approximately 50 % to 75 %, with F1 exhibiting the highest moisture content. By day 2, moisture levels were significantly reduced to a range of 30 % to 40 %, and by day 3, they further declined to approximately 20 %, indicating a steady downward trend. The results showed that all of formulas were able to form pellets, as shown in Fig. 4. The pelletization performance of the soil amendments varied significantly, with F2 exhibiting the highest pellet formation percentage (92.65 %), followed by F5 at 91.32 %, and F3 and F1 had the lowest values at 82.55 % and 83.24 %, respectively. The pellet dimensions also differed, with F2 producing the longest pellets (7.54 mm) and the largest diameter (5.75 mm), whereas F3 generated comparably long pellets (7.36 mm) but with a smaller diameter (5.12 mm). Density characteristics showed that F3 had the highest true density (1172.1 kg m<sup>-3</sup>), whereas F2 exhibited slightly lower true density (1142.6 kg m<sup>-3</sup>) but had the highest bulk density (714.60 kg m<sup>-3</sup>), suggesting superior compaction and durability. The bulk densities of F5 and F6 followed closely with bulk densities of 702.34 kg m<sup>-3</sup> and 694.65 kg m<sup>-3</sup>, respectively.

The mechanical durability of the pelletized soil amendment formulations varied significantly ( $P \leq 0.05$ ), ranging from 92.91 % (F1) to 96.41 % (F5) as shown in Table 4. Formulations F4 and F5, both of which contained bio-organic compost in combination with vinasse sludge and either biogas effluent (F4) or molasses wastewater (F5), exhibited the highest durability values (96.22 % and 96.41 %, respectively). In contrast, the lowest durability was observed for F1, which contained only sludge, vinasse sludge, and biogas effluent without compost. These findings suggest that the presence of bio-organic compost plays a critical role in enhancing the structural integrity of the pellets. The fibrous and humified organic matter in compost likely acted as a natural binder, improving the cohesion between particles during the pelletization process. This observation is consistent Juntahum et al. [58] which reported that compost-based pellets formulated with cassava starch binder achieved high mechanical durability (up to 95.88 %) due to enhanced inter-particle bonding and moisture retention capacity. Moreover, the use of molasses wastewater in F5 may have further contributed to pellet robustness by acting as an adhesive agent during pellet formation, promoting compactness and reducing micro-fractures within the pellet matrix. Similar mechanisms have been reported by Papandrea et al. [51] which emphasized the role of organic binders and moisture-regulating constituents in improving the resistance to mechanical stress during handling and transport. It is noteworthy that all formulations exceeded the commonly accepted threshold of 90 % durability, indicating their potential suitability for commercial-scale storage and transportation.

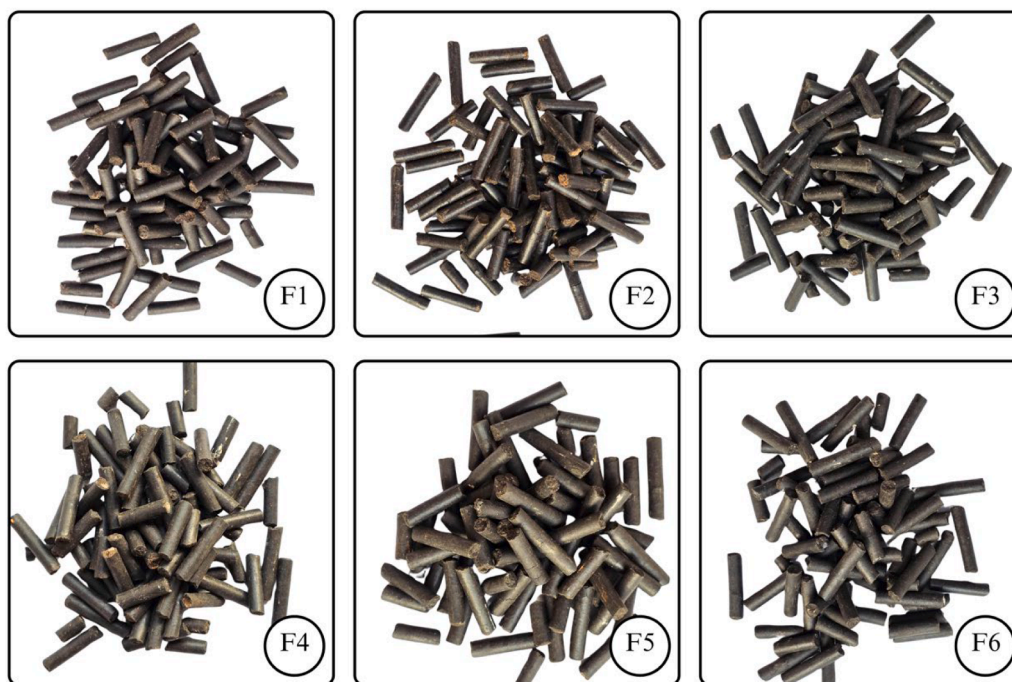
The wettability index, indicating moisture absorption capacity, was highest in F2 (45.79 %), followed by F4 (42.92 %), while F1 had the lowest wettability index (25.83 %), suggesting lower water absorption potential. These findings highlight variations in moisture reduction, pellet formation efficiency, physical dimensions, and density characteristics across the formulas, as summarized in Table 4.

The drying and pelleting results revealed critical differences between formulas in terms of moisture reduction efficiency, pellet quality, density, and wettability. All formulas followed a similar trend of sharp

**Table 3**  
Germination index (GI) of maize seed on soil amendments.

Treatments	Germination Index; GI ( % )
F1	92b
F2	96a
F3	87c
F4	86d
F5	90b
F6	88c
% CV	46.56

Means followed by the same letter within the same column are not significantly different at  $P \leq 0.05$ , according to the LSD test. F1: Sludge + vinasse sludge + biogas effluent; F2: Sludge + vinasse sludge + molasses wastewater; F3: Bio-organic compost + vinasse sludge + molasses wastewater; F4: Bio-organic compost + vinasse sludge + biogas effluent; F5: Bio-organic compost + sludge + molasses wastewater; F6: Bio-organic compost + sludge + biogas effluent.



**Fig. 4.** Pellets of soil amendments from F1–F6 formulations. F1: Sludge + vinasse sludge + biogas effluent, F2: Sludge + vinasse sludge + molasses wastewater, F3: Bio-organic compost + vinasse sludge + molasses wastewater, F4: Bio-organic compost + vinasse sludge + biogas effluent, F5: Bio-organic compost + sludge + molasses wastewater, F6: Bio-organic compost + sludge + biogas effluent.

**Table 4**

Effects of different soil Amendment formulations on pellet gormation percentage, pellet length, pellet diameter, true density, bulk density, durability, and wettability Index.

Formulas	Factors						
	percentage of pellets forming (%)	Length of pellets (mm)	Diameter of pellets (mm)	True density ( $\text{kg m}^{-3}$ )	Bulk density ( $\text{kg m}^{-3}$ )	Durability (%)	Wettability index (%)
F1	83.24c	5.47d	4.69c	935.7e	574.77e	92.91d	25.83e
F2	92.65a	7.54a	5.75a	1142.6b	714.60a	93.62c	45.79a
F3	82.55d	7.36a	5.12b	1172.1a	621.07d	95.26b	34.75d
F4	83.45c	6.43b	5.74a	964.3d	672.04c	96.22a	42.92b
F5	91.32a	5.98c	5.12b	1024.3c	702.34b	96.41a	32.74d
F6	86.66b	6.44b	4.87c	1124.5b	694.65b	94.34b	40.12c
% CV	26.32	40.24	42.62	60.32	46.42	26.42	32.64

Means followed by the same letter within the same column are not significantly different at  $P \leq 0.05$  level according to the LSD test. F1: Sludge + vinasse sludge + biogas effluent, F2: Sludge + vinasse sludge + molasses wastewater, F3: Bio-organic compost + vinasse sludge + molasses wastewater, F4: Bio-organic compost + vinasse sludge + biogas effluent, F5: Bio-organic compost + sludge + molasses wastewater, F6: Bio-organic compost + sludge + biogas effluent.

moisture reduction from 50–75 % on day 1 to approximately 20–30 % by day 3, confirming that the drying conditions applied were effective and suitable for pellet formation. Among the six formulations, F2 achieved the highest pellet formation rate (92.65 %) and optimal physical attributes, including the longest pellet length (7.54 mm), largest diameter (5.75 mm), highest bulk density ( $714.60 \text{ kg m}^{-3}$ ), and superior wettability index (45.79 %). These properties suggest that the combination of sludge, vinasse sludge, and molasses wastewater yields a formulation with excellent pellet cohesion, compaction, and water absorption characteristics. This observation is consistent with the findings of Piash et al. [19], which demonstrated that biochar derived from chicken manure exhibited high bulk density and water retention when pyrolyzed and incorporated into fertilizer pellets. Furthermore, the high wettability of F2 may reflect its well-balanced organic composition, which enhances the pore structure and capillary action, facilitating rapid rehydration when applied to soil.

The observed differences in pellet quality can be attributed to variations in the physical and chemical compositions of the feedstocks. F2's superior performance is likely due to its higher organic matter and

nitrogen content, which may act as natural binders, enhancing compaction and pellet integrity. In contrast, F1, despite its high OM content, exhibited lower pellet formation efficiency (83.24 %) and wettability (25.83 %), possibly due to excessive moisture at the onset or an unbalanced carbon-to-nitrogen ratio affecting pellet stability. The relatively high true density of F3 ( $1172.1 \text{ kg m}^{-3}$ ) compared to its bulk density suggests that while individual pellets were compact, they lacked sufficient inter-pellet porosity, which may hinder aeration or lead to compaction in field applications. These findings are supported by Gyanwali et al. [15], which emphasized the importance of achieving both a high true density and optimal pore structure for soil amendment pellets. A notable strength of this study is the holistic evaluation of multiple physical parameters-including bulk and true density, pellet dimensions, and water absorption-ensuring that the formulations meet both agronomic and handling standards.

These results substantiate the research objective of developing organic pelleted soil amendments with favorable physical characteristics for ease of application, storage, and field performance. The high bulk density and wettability of the best-performing formulations suggest

their practical viability for mechanized field applications and soil incorporation. Furthermore, this demonstrates the potential for optimizing pellet formulations using specific combinations of sugar industry waste materials, thereby enhancing the circular economy of in agricultural production systems. From a broader perspective, such high-quality pellets not only simplify nutrient delivery but also represent a scalable and sustainable alternative to conventional chemical fertilizers in cropping. Furthermore, this research can be used for commercial production, particularly parabolic drying and manual pelletization, which can be replaced by mechanized systems. For instance, the moisture reduction step can be efficiently conducted using a rotary drum dryer, which offers continuous, high capacity drying under controlled temperature and airflow conditions. After drying, the material was transferred directly via a conveyor belt system into a pelletizer machine.

### 3.6. Effect of pelletized soil amendments on soil physicochemical properties

The water holding capacity (WHC) of the soil amendments varied significantly among treatments, demonstrating the effects of different organic materials on soil moisture retention. The control treatment (S), consisting solely of sand, exhibited the lowest WHC of 26.36 %, indicating minimal water retention capacity. In contrast, the highest WHC was observed in SF3 at 46.82 %, followed by SF2 at 42.56 % and SF1 at 41.24 %. SF5 and SF4 displayed moderate WHC values of 40.26 % and 36.86 %, respectively, whereas SF6 had the lowest WHC among the amended treatments at 35.28 %.

Soil texture analysis revealed that all amended treatments were classified as loamy sand, whereas the control treatment (C) was classified as pure sand. The sand content in the amended treatments ranged from 82.24 % (SF5) to 87.15 % (SF4), whereas silt content varied between 12.28 % (SF4) and 17.69 % (SF5). Clay content remained low across all treatments, with the highest value recorded in SF6 (0.62 %) and the lowest in SF5 (0.07 %). Variations in soil texture composition contributed to differences in WHC, as treatments with higher silt and organic matter content generally retained more moisture than those dominated by sand. These findings illustrate the influence of organic amendments on soil physical properties, as summarized in Table 5.

The application of pelletized soil amendments resulted in variations in nitrogen (N), phosphorus (P), and potassium (K) availability across treatments. Nitrogen content increased during the first three days, reached peak concentrations by day 5, and then gradually declined towards day 10. The highest nitrogen availability was recorded in SF2, followed by SF1 and SF5. The control (C) exhibited minimal nitrogen fluctuations throughout the study period. Phosphorus (P) concentrations increased steadily during the first five days of incubation, with the highest values observed in SF2, followed by SF4 and SF5. Treatments incorporating bio-organic compost demonstrated sustained phosphorus release, whereas the control treatment consistently maintained low

**Table 5**  
Effect of applying soil amendment pellets on soil properties after 10 days.

Treatments	WHC ( % )	Soil Textures			Soil type
		Sand ( % )	Silt ( % )	Clay ( % )	
C	26.36d	100	–	–	sand
SF1	41.24b	84.72	15.16	0.12	Loamy sand
SF2	42.56b	82.46	17.46	0.08	Loamy sand
SF3	46.82a	85.26	14.56	0.18	Loamy sand
SF4	36.86c	87.15	12.28	0.57	Loamy sand
SF5	40.26b	82.24	17.69	0.07	Loamy sand
SF6	35.28c	83.36	16.02	0.62	Loamy sand
% CV	36.25				

Means followed by the same letter within the same column are not significantly different at  $P \leq 0.05$ , level according to the LSD test. C: sand (control), SF1: sand + F1, SF2: sand + F2, SF3: sand + F3, SF4: sand + F4, SF5: sand + F5, SF6: sand + F6.

phosphorus levels. Potassium (K) content increased gradually, peaking between days 5 and 7 before stabilizing towards on day 10. The highest K levels were observed in SF2, followed by SF1 and SF5, whereas the control treatment maintained the lowest K levels. Treatments containing sludge-based amendments exhibited enhanced K retention. The data indicated differences in nutrient retention and release among the treatments, with varying concentrations of nitrogen, phosphorus, and potassium measured throughout the incubation period. These trends are illustrated in Fig. 5.

The application of pelletized soil amendments significantly enhanced WHC and altered the soil texture profile compared with the control. These results demonstrate the positive influence of organic amendments on the physical quality of soil. The increased WHC can be attributed to the higher organic matter content and finer textural composition, which enhance soil porosity and capillarity. This observation is consistent with previous studies reporting that composted sludge amendments significantly enhance water retention by improving aggregate stability and microporosity [39,59,60], particularly higher silt proportions in treatments SF2 and SF5, which aids in moisture retention. Soil texture modification from pure sand to loamy sand signifies the capacity of amendments to improve soil structure by introducing finer particles and organic matrices.

The differences in WHC across treatments can be explained by variations in the organic matter content, pellet porosity, and nutrient composition. SF3 has superior performance, despite lower OM and N content compared to SF2, potentially due to better physical pellet structure and higher silt content (14.56 %), which are known to enhance capillary water retention. Conversely, SF6, despite moderate OM and nutrient levels, showed the lowest WHC among amended soils, possibly due to its lower silt and higher sand fraction (86.54 %). The ability of organic amendments to improve WHC is also influenced by their decomposition products, such as humic substances, which enhance soil aggregation and micropore formation.

These findings are in line with those of Komal et al. [5] which found that the addition of biochar significantly improved water retention and microporosity under different irrigation regimes. Likewise, Vollmer et al. [5] noted that composted plant residues enhanced WHC and soil aggregation, contributing to better water use efficiency. Li et al. [7], in a meta-analysis, confirmed that organic amendments increase soil water retention by enhancing organic carbon levels and reducing bulk density.

The present study included both WHC and detailed soil textural classification, offering comprehensive insights into the structural impact of the pelletized amendments. However, one limitation is the short assessment window of 10 days, which may not fully capture the long-term stabilization and physical restructuring effects of organic amendments. These findings confirm the potential of the developed pelletized soil amendments to improve the key physicochemical properties of degraded sandy soils. These results reinforce the role of pelletized organic amendments as viable tools for sustainable soil management, particularly in regions that experience water scarcity or erratic rainfall. Furthermore, by improving soil structure and water retention, such amendments can reduce the need for frequent irrigation, contributing to more resilient and resource-efficient agriculture in the context of climate change adaptation.

### 3.7. Influence of soil amendments on plant growth parameters

The effect of pelletized soil amendments on the growth of *Capsicum annuum* L. was assessed by evaluating multiple morphological and physiological parameters after 45 days of cultivation. The treatments exhibited significant variation in shoot diameter (D), shoot height (H), SPAD values, root fresh weight (RFW), root dry weight (RDW), shoot fresh weight (SFW), and shoot dry weight (SDW) (Table 6). Among all treatments, the ChF2 plants treated with 150 g of soil amendment F2 exhibited the highest values across nearly all parameters. Specifically, ChF2 achieved the largest shoot diameter (4.2 mm), highest shoot height

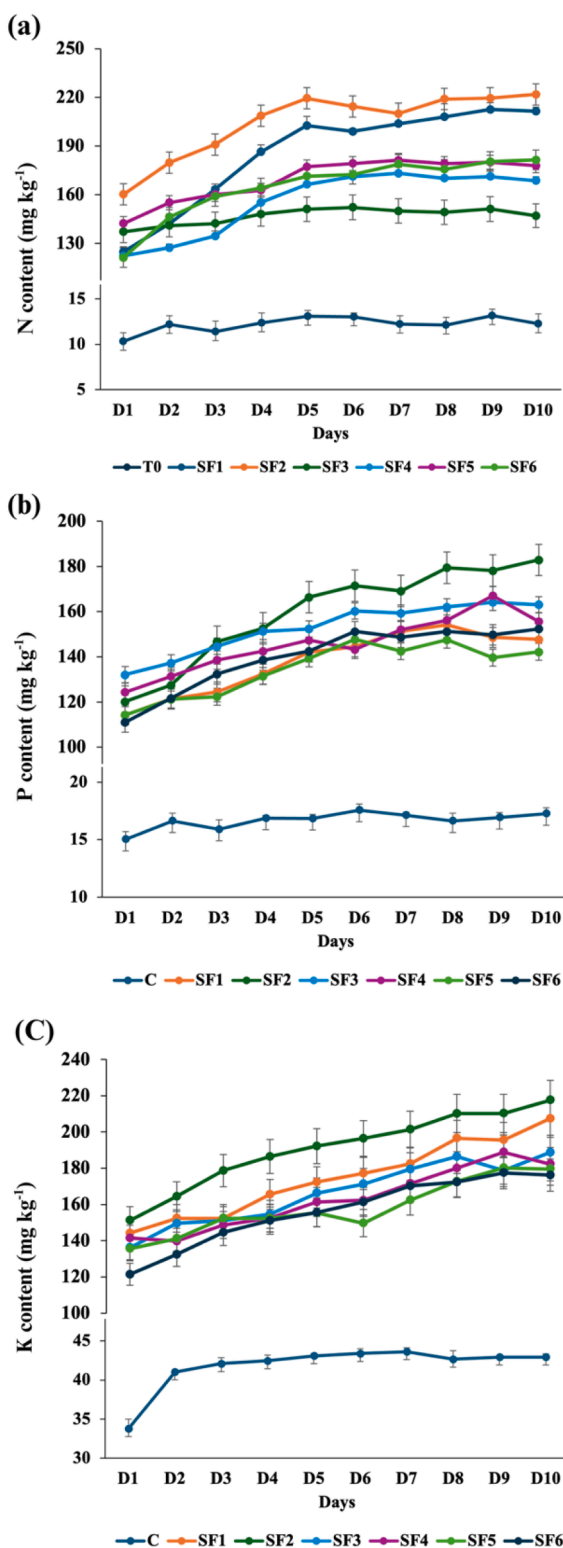


Fig. 5. Effect of applying soil amendment pellets on nitrogen (N), phosphorus (P), and potassium (K), C: sand (control), SF1: sand + F1, SF2: sand + F2, SF3: sand + F3, SF4: sand + F4, SF5: sand + F5, SF6: sand + F6.

(54.6 cm), and the highest SPAD reading (34.3), indicating enhanced chlorophyll content. Furthermore, ChF2 recorded the highest biomass, with a root fresh weight of 22.6 g and root dry weight of 10.1 g, along with shoot fresh weight and dry weight of 19.0 g and 8.6 g, respectively. ChF1 also demonstrated significant growth improvement over the control, with a shoot diameter of 3.8 mm, shoot height of 52.0 cm, and root

Table 6

Influence soil amendments on plant growth parameters, including shoot diameter (D), shoot height (H), root fresh weight (RFW), root dry weight (RDW), shoot fresh weight (SFW), and shoot dry weight (SDW) of chili (*Capsicum annuum* L.) seedlings after cultivation for 45 days.

Treatments	D (mm)	H (cm)	SPAD	RFW (g)	RDW (g)	SFW (g)	SDW (g)
C	3.1d	41.7d	27.1d	16.0d	6.9c	16.6c	7.2b
ChF1	3.8b	52.0a	31.4b	22.5a	8.2b	17.5b	8.1a
ChF2	4.2a	54.6a	34.3a	22.6a	10.1a	19.0a	8.6a
ChF3	3.3b	43.6	26.8d	16.1d	5.9d	16.4c	7.0b
ChF4	4.1a	49.7b	29.7c	20.2b	7.4c	16.4c	7.2b
ChF5	3.3c	46.7c	26.4d	22.4a	8.0b	15.2d	6.7c
ChF6	3.5c	45.2c	24.2e	19.8c	6.1d	16.1c	6.8c
% CV	24.6	42.4	48.6	58.5	68.7	28.4	26.2

Means followed by the same letter within the same column are not significantly different at  $P \leq 0.05$  level according to the LSD test. C: chili untreated with soil amendment control (a control), ChF1: chili treated with 150 g soil amendment F1, ChF2: chili treated with 150 g soil amendment F2, ChF3: chili treated with 150 g soil amendment F3, ChF4: chili treated with 150 g soil amendment F4, ChF5: chili treated with 150 g soil amendment F5 and ChF6: chili treated with 150 g soil amendment F6.

fresh weight of 22.5 g. Conversely, treatments ChF3, ChF5, and ChF6 showed lower performance, with shoot diameters ranging from 3.3 to 3.5 mm, and shoot heights between 43.6 cm (ChF3) and 46.7 cm (ChF5). Biomass accumulation was also reduced in these treatments, as indicated by lower shoot fresh weight (15.2–16.4 g) and shoot dry weight (6.7–6.8 g). The control treatment, which received no amendment, had the lowest values across all metrics, including the smallest shoot diameter (3.1 mm) and the shortest height (41.7 cm), confirming the substantial benefits of soil amendment application.

The application of pelletized soil amendments had a pronounced impact on the growth performance of *Capsicum annuum* L., as evidenced by variations in shoot and root growth, leaf chlorophyll content, and overall biomass among the treatments. F2, which combined sludge, vinasse sludge, and molasses wastewater, consistently demonstrated superior performance. The high total nitrogen ( $2.07 \text{ mg kg}^{-1}$ ), phosphorus ( $0.61 \text{ mg kg}^{-1}$ ), and potassium ( $1.88 \text{ mg kg}^{-1}$ ) contents in F2 likely contributed to the enhanced vegetative development, as these macronutrients play critical roles in chlorophyll synthesis, energy transfer, and root elongation. These results align with Piash et al. [19] which reported that nutrient-enriched biochar derived from animal waste significantly improved nutrient availability and plant uptake. Additionally, F2's favorable C/N ratio (20.81) suggests a well-stabilized compost capable of sustaining microbial activity and nutrient mineralization, both essential for early-stage plant growth.

In contrast, formulas with lower nutrient concentrations or higher C/N ratios, such as F6 and F3, exhibited limited plant development, reaffirming the importance of compost maturity and nutrient balance in organic amendments. These findings are further supported by Hallman et al. [61] which observed improved citrus growth in soils enriched with organic matter.

The disparity in plant performance among treatments can also be traced to differences in soil physicochemical properties shaped by each amendment. F2 and F1 not only provided ample nutrient availability, but also improved soil texture and water holding capacity, creating favorable rhizosphere conditions. However, treatments such as F4 and F6, which incorporated biogas effluent, may have introduced inhibitory compounds or suffered nutrient leaching due to incomplete organic matter stabilization. This phenomenon was similarly noted by Galamini et al. [57] which highlighted the potential negative effect of improperly stabilized digestate on microbial dynamics and plant development.

The present study used a holistic approach, integrating both soil quality and plant response metrics to comprehensively assess the efficacy of waste-derived organic amendments. However, a key limitation was the relatively short experimental duration under greenhouse

conditions, which may not fully reflect the long-term agronomic performance of these amendments under field conditions.

Although direct measurements of microbial activity were not performed in this study, recent studies have demonstrated that organic amendments significantly enhance soil microbial biomass, enzymatic activity, and nutrient cycling, which in turn promote plant growth and yield [62–64]. For instance, compost application has been shown to increase microbial biomass carbon and dehydrogenase activity both reliable indicators of soil biological health [65]. Moreover, microbial activity profiles have been reported to explain up to 50 % of yield variation in *Capsicum annuum* under compost fertilization [66]. These findings suggest that the improvements in plant growth and soil properties observed in this study may also be partially attributed to microbial-mediated processes stimulated by the sugar industry waste-based amendments. Future studies could benefit from integrating smart composting technologies, such as IoT-enabled monitoring systems, to enhance process control and provide more precise insights into nutrient transformation and microbial dynamics over extended periods.

### 3.8. Economic feasibility and cost competitiveness

The economic feasibility assessment considered material costs (1 BHT = 0.03 USD). The total production cost of formulation F2, excluding packaging, shipping, and distribution, was estimated at 2900 THB ton<sup>-1</sup> (2.90 THB kg<sup>-1</sup>). This competitive cost is primarily due to the efficient utilization of low-cost sugar industry by-products, combined with solar-assisted drying and optimized pelletizing conditions that minimize electricity consumption. Although packaging costs were not included in this calculation, the production cost remains substantially lower than the prevailing retail prices of commercial granular organic fertilizers in Thailand, which typically range from 7 to 12 THB kg<sup>-1</sup>. This significant cost advantage highlights the strong market potential of waste-derived pelletized fertilizers as a profitable and sustainable alternative for agricultural industries.

## 4. Conclusion

This study successfully developed and evaluated organic pelleted soil amendments derived from sugar industry waste, highlighting their potential to improve soil properties and promote plant growth under greenhouse conditions. All pelleted formulations were found to enhance soil physicochemical properties, particularly by increasing water-holding capacity and altering soil texture from sandy to loamy sand, a condition more favorable for crop cultivation. Among the tested treatments, Formula F2 which was composed of sludge, vinasse sludge, and molasses wastewater exhibited superior nutrient content (2.07 mg kg<sup>-1</sup> N, 0.61 mg kg<sup>-1</sup> P, 1.88 mg kg<sup>-1</sup> K) along with an ideal C/N ratio of 20.81. These attributes contributed to its outstanding performance in promoting seed germination and chili seedling growth. Specifically, treatments with F2 significantly improved shoot diameter, plant height, and biomass accumulation in *Capsicum annuum* L., thereby confirming the agronomic effectiveness of this amendment in stimulating early-stage plant development. Furthermore, the findings affirm that sugar industry byproducts can be effectively transformed into nutrient-rich soil inputs, offering a sustainable alternative to synthetic fertilizers. This approach not only supports organic waste valorization but also contributes to the restoration of soil health and enhances resource-use efficiency.

This research supports the practical application of pelletized organic soil amendments in cropping, particularly in regions with degraded soils or limited access to chemical inputs. Field-scale validation is recommended to further explore long-term benefits and adaptability under diverse agro-environment conditions.

A limitation of this study is the lack of microbial activity and diversity assessment, which are crucial components of soil health and nutrient cycling. Future research should incorporate microbial profiling

or enzymatic activity analyses to provide a more comprehensive evaluation of the effects of pelletized organic amendments.

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT, Grammarly, and Claude to improve language. After using this tool/service, the author(s) reviewed and edited the content as needed and took(s) full responsibility for the content of the publication.

## Funding

This research has received financial support from Post Doctoral Training for Frontier Research 2024, Khon Kaen University.

**Research involving human participants or animals:** This article does not include studies involving human participants or animals.

**Informed consent:** Informed consent was obtained from all the participants included in the study.

## CRediT authorship contribution statement

**Chaiya Klinsukon:** Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sophon Boonlue:** Writing – review & editing, Methodology, Conceptualization. **Suchat Juntahum:** Writing – review & editing, Methodology. **Kittipong Laloon:** Writing – original draft, Supervision.

## Declaration of competing interest

The authors declare no competing interests related to this work.

## Acknowledgements

This research was financially supported by the Post Doctoral Training for Frontier Research 2024, Khon Kaen University. The authors also gratefully acknowledge the invaluable support provided by the GMS Food, Energy, Water Security Research Institute, the Postharvest Technology Innovation Center, and the Faculty of Agriculture, Khon Kaen University. These institutions contributed significantly by offering access to research laboratories, analytical equipment, greenhouse facilities, and essential field tools, all of which were critical to the successful implementation of this study.

## Data availability

No data was used for the research described in the article.

## References

- [1] P.M. Islam, T.I. Kazusa Abe, K. Iwabuchi, Superior nutrient recovery and release by Chicken Manure-derived biochar over hydrochar and compost for soil fertilization, *Geoderma Regional* 40 (2025) e00906, <https://doi.org/10.1016/j.geodrs.2024.e00906>.
- [2] A. Rashid, S. Sanogo, E.A. Lehnhoff, L. Beck, B.J. Schutte, Soil pH is an underappreciated influence on germination- and microbial-based methods for reducing weed seedbanks in croplands, *Weed. Res.* (2025) 65, <https://doi.org/10.1111/wre.70002>.
- [3] S.J.C. Galgo, S.Y. Kim, T.K. Oh, H.C. Park, R.C. Canatoy, K.M. Sohn, I.B. Song, P. J. Kim, Contribution of silicate fertilizer application to reducing CH4 emission and increasing productivity in Korean rice paddies, *Field. Crops. Res.* 322 (2025) 109711, <https://doi.org/10.1016/j.fcr.2024.109711>.
- [4] T. Li, S. Wang, S. Liu, X. Zhang, H. Dong, S. Dai, L. Chai, H. Li, Y. Lv, T. Li, Q. Gao, G. Li, X. Ma, 2025. Trade-offs of organic amendment input on soil quality and crop productivity in Saline-Alkali land globally: a meta-analysis, *Eur. J. Agronomy* 164 (2025) 127471, <https://doi.org/10.1016/j.eja.2024.127471>.
- [5] L. Komal, S. Jahan, A. Kamran, A. Hashem, G.D. Avila-Quezada, E.F. Abd Allah, Optimizing soil health through activated acacia biochar under varying irrigation regimes and cultivars for sustainable wheat cultivation edited by D. Abd El-Moneim, *PeerJ.* 13 (2025) e18748, <https://doi.org/10.7717/peerj.18748>.

- [6] A. Vollmer, U. Schmidt, C. Ulrichs, D. Dannehl, Closing the loop: utilization of composted tomato plant residues as fertilizer and soil amendment, *Sci. Hortic.* 342 (2025) 114028, <https://doi.org/10.1016/j.scienta.2025.114028>.
- [7] X. Li, Z. Guo, Y. Ma, P.A.M. Leite, Z. Li, G. Wu, Incorporating cattle manure improves hydraulic properties and enhances infiltration rates of low-infiltrability saline-sodic soils, *Land. Degrad. Dev.* 36 (2024) 945–953, <https://doi.org/10.1002/ldr.5404>.
- [8] L.A. Jaoude, R.H. Mohtar, F. Kamaledine, R. Dbaibo, R.B. Said, I. Keniar, S. F. Yanni, Impact of treated wastewater sludge on soil and wheat growth characteristics in a semi-arid climate, *Sci. Total Environ.* 974 (2025) 179166, <https://doi.org/10.1016/j.scitotenv.2025.179166>.
- [9] A. Farsang, I. Babcsányi, Z. Ladányi, K. Perei, A. Bodor, K.T. Csányi, K. Barta, Evaluating the effects of sewage sludge compost applications on the microbial activity, the nutrient and heavy metal content of a chernozem soil in a field survey, *Arabian J. Geosci.* 13 (2020) 982, <https://doi.org/10.1007/s12517-020-06005-2>.
- [10] O. Mabrouk, H. Hamdi, S. Sayadi, M.A. Al-Ghouti, M.H. Abu-Dieyeh, N. Zouari, Reuse of sludge as organic soil amendment: insights into the current situation and potential challenges, *Sustainability.* 15 (2023), <https://doi.org/10.3390/su15086773>.
- [11] E.A.L. Paganini, R.B. Silva, L.R. Roder, I.A. Guerrini, G.F. Capra, E. Grilli, A. Ganga, A systematic review and meta-analysis of the sustainable impact of sewage sludge application on soil organic matter and nutrient content, *Sustainability.* 16 (2024), <https://doi.org/10.3390/su16229865>.
- [12] H. Gahrouei, M. Ghasemi-Nejad-Raeini, N. Kazemi, B.K. Moghadam, M. Reza Zare Bavan, Production of jiffy pellets from sugarcane waste as a novel substrate: evaluation of chemical properties and its application in seedling production, *Results. Eng.* (2025) 106855, <https://doi.org/10.1016/j.rineng.2025.106855>.
- [13] M. Ebrahimi, S. Gholipour, G. Mostafaei, F. Yousefian, Biochar-amended food waste compost: a review of properties, *Results. Eng.* 24 (2024) 103118, <https://doi.org/10.1016/j.rineng.2024.103118>.
- [14] M. Afshar, S. Mofatteh, Biochar for a sustainable future: environmentally friendly production and diverse applications, *Results. Eng.* 23 (2024) 102433, <https://doi.org/10.1016/j.rineng.2024.102433>.
- [15] P. Gyanwali, R. Khanal, S. Pokhrel, K. Adhikari, Exploring the benefits of Biochar: a review of production methods, characteristics, and applications in soil health and environment, *Egyptian J. Soil Sci.* 64 (2024) 855–884, <https://doi.org/10.21608/ejss.2024.270380.1725>.
- [16] Xi. Xia, Z. Zhao, Y. Ding, X. Feng, S. Chen, Q. Shao, X. Liu, K. Cheng, R. Bian, J. Zheng, L. Li, G. Pan, Crop residue biochar rather than manure and straw return provided short term synergism among grain production, carbon sequestration, and greenhouse gas emission reduction in a paddy under rice-wheat rotation, *Food Energy Secur.* 13 (5) (2024) e70009, <https://doi.org/10.1002/fes3.70009>.
- [17] G. Imwinkelried, L. Bonetto, C. Saux, M.B. Blanco, High-value products from Chickpea residues by thermal pyrolysis and its environmental impacts, *Biomass Bioenergy* 193 (2025) 107584, <https://doi.org/10.1016/j.biombioe.2024.107584>.
- [18] H. Zhao, Z. Zhu, X. Wang, M. Xu, N. Huang, Impacts of nitrogen fertilization on CO<sub>2</sub> efflux with and without organic amendments in a high-PH soil, *Land. Degrad. Dev.* 35 (16) (2024) 4853–4863, <https://doi.org/10.1002/ldr.5262>.
- [19] M.I. Piash, T. Itoh, K. Abe, K. Iwabuchi, Superior nutrient recovery and release by Chicken Manure-derived biochar over hydrochar and compost for soil fertilization, *Geoderma Regional* 40 (2025) e00906, <https://doi.org/10.1016/j.geodrs.2024.e00906>.
- [20] Martin Aguirrebengoa, Beatriz Moreno, Nuria Guirado, Rafael Núñez, M. L. Fernández-Sierra, Fernando Reyes, Jesús Martín, Emilio Benítez, Microbe-mediated organic fertilization increases insect predator attraction upon fruit damage in olive trees, *Soil Ecol. Lett.* 7 (1) (2025) 240281, <https://doi.org/10.1007/s42832-024-0281-z>.
- [21] M.T. Jaffar, S. Zhen, J. Han, J. Zhang, A.r Dar, Z. Mushtaq, H. Q. Z. Ahmad Zahir, K.H.M. Siddique, Orange Peel biochar: an effective amendment to improve the maize resilience by regulating the soil enzymatic activities, nutrient uptake, and ionic homeostasis under salinity stress, *Ind. Crops. Prod.* 222 (2024) 120081, <https://doi.org/10.1016/j.indcrop.2024.120081>.
- [22] I. Kisekka, S.R. Peddinti, D. Vanella, E. Andrews, P.H. Brown, S.D.S. Khalsa, Organic soil amendment effects on soil hydrology in an almond orchard evaluated using time-lapse electrical resistivity tomography, *Agric. Water. Manage.* 302 (2024) 108979, <https://doi.org/10.1016/j.agwat.2024.108979>.
- [23] M.C. Enebe, R.L. Ray, R.W. Griffin, Carbon sequestration and soil responses to soil amendments – A review, *J. Hazardous Mater. Adv.* 18 (2025) 100714, <https://doi.org/10.1016/j.hazadv.2025.100714>.
- [24] R. Rubin, E. Oldfield, J. Lavallee, T. Griffin, B. Mayers, J. Sanderman, Climate mitigation through Soil Amendments: quantification, evidence, and uncertainty, *Carbon. Manage.* 14 (1) (2023) 2217785, <https://doi.org/10.1080/17583004.2023.2217785>.
- [25] K. Peltokangas, S. Kalu, K. Huusko, J. Havisalmi, J. Heinonsalo, K. Karhu, L. Kulmala, J. Liski, M. Pihlatie, Ligneous amendments increase soil organic carbon content in fine-textured boreal soils and modulate N<sub>2</sub>O emissions, *PLoS. One* 18 (8 August) (2023), <https://doi.org/10.1371/journal.pone.0284092>.
- [26] L. Wang, Y. Li, X. Li, Microbe-aided thermophilic composting accelerates manure fermentation, *Front. Microbiol.* 15 (2024), <https://doi.org/10.3389/fmicb.2024.1472922>.
- [27] I. Finore, A. Feola, L. Russo, A. Cattaneo, P.d. Donato, B. Nicolaus, A. Poli, I. Romano, Thermophilic bacteria and their thermozymes in composting processes: a review, *Chem. Biol. Technol. Agric.* 10 (1) (2023) 7, <https://doi.org/10.1186/s40538-023-00381-z>.
- [28] J.3. Li, J. Li, R. Yang, P. Yang, H. Fu, Y. Yang, C. Liu, Construction of microbial consortium to enhance cellulose degradation in corn straw during composting, *Agronomy* 14 (9) (2024), <https://doi.org/10.3390/agronomy14092107>.
- [29] S.S. Gaspar, L.L.R. Assis, C.A. Carvalho, V.H. Buttrós, G.M.d.R. Ferreira, R. F. Schwan, M. Pasqual, F.A. Rodrigues, E.C. Rigobelo, R.P. Castro, J. Dória, Dynamics of microbiota and physicochemical characterization of food waste in a new type of composter, *Front. Sustain. Food Systems* Volume 6 (2022), <https://doi.org/10.3389/fsufs.2022.960196>.
- [30] O.M. Abioye, M.F. Amodu, D.O. Raphael, D.A. Olasehinde, M.M. Aniobi, K. O. Yusuf, A.I. Olosho, An overview of the role of vermicompost in reducing green house gas emissions, improving soil health, and increasing crop yields, *Appl. Sci. Eng. Progress* 18 (2) (2025) 7586, <https://doi.org/10.14416/j.asep.2024.09.011>.
- [31] A. Sarker, R. Ahmmed, S.M. Ahsan, J. Rana, M.K. Ghosh, R. Nandi, A comprehensive review of food waste valorization for the sustainable management of global food waste, *Sustain. Food Technol.* 2 (1) (2024) 48–69, <https://doi.org/10.1039/D3FB00156C>.
- [32] M.S. Wagh, S. Sowjanya, P.C. Nath, A. Chakraborty, R. Amrit, Bi. Mishra, A. K. Mishra, Y.K. Mohanta, Valorisation of Agro-industrial wastes: circular bioeconomy and biorefinery process – A sustainable symphony, *Process Safety Environ. Protect.* 183 (2024) 708–725, <https://doi.org/10.1016/j.psep.2024.01.055>.
- [33] I. Prado-Acebo, J. Cubero-Cardoso, T.A. Lu-Chau, G. Eibes, Integral Multi-valorization of Agro-Industrial wastes: a review, *Waste Manag.* 183 (2024) 42–52, <https://doi.org/10.1016/j.wasman.2024.05.001>.
- [34] P. Sanchumpu, W. Suaili, S. Nonsawang, C. Junsiri, P. Ansuree, K. Laloon, Biomass pellet processing from sugar industry byproducts: a study on pelletizing behavior and energy usage, *Sustainability.* 16 (14) (2024), <https://doi.org/10.3390/su16146035>.
- [35] P. Singh, P. Kumar, M. Singh, K. Kumar, S. Awasthi, Utilization of sugarcane and sugar industry wastes for sustainable sugarcane production and post-harvest quality management, *Sugar. Tech.* (2025), <https://doi.org/10.1007/s12355-025-01593-3>.
- [36] M. Tejada, A.M. García-Martínez, J. Parrado, Effects of a vermicompost composted with beet vinasse on soil properties, soil losses and soil restoration, *Catena (Amst)* 77 (3) (2009) 238–247, <https://doi.org/10.1016/j.catena.2009.01.004>.
- [37] A. Maffia, M. Oliva, F. Marra, C. Mallamaci, S. Nardi, A. Muscolo, Humic substances: bridging ecology and agriculture for a greener future, *Agronomy* 15 (2) (2025), <https://doi.org/10.3390/agronomy15020410>.
- [38] L. Meng, W. Li, X. Zhang, Y. Zhao, L. Chen, S. Zhang, Influence of spent mushroom substrate and molasses amendment on nitrogen loss and humification in sewage sludge composting, *Heliyon.* 6 (9) (2020), <https://doi.org/10.1016/j.heliyon.2020.e04988>.
- [39] D. Ma, Y. Wang, Y. Ye, X. Ge, X. Lu, Effects of three sludge products from Co-treatment of wastewater on the soil properties and plant growth of silty loam, *Int. J. Environ. Res. Public Health* 19 (7) (2022), <https://doi.org/10.3390/ijerph19074385>.
- [40] A. Mukhtiar, A. Mahmood, Mu.A. Zia, M. Ameen, R. Dong, Y. Shoujun, M. M. Javid, B.A. Khan, M.A. Nadeem, Role of biogas slurry to reclaim soil properties providing an eco-friendly approach for crop productivity, *Bioresour. Technol. Rep.* 25 (2024) 101716, <https://doi.org/10.1016/j.biteb.2023.101716>.
- [41] A.J. Walkley, I.A. Black, An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method, *Soil. Sci.* 37 (1) (1934) 29–38.
- [42] M.L. Jackson, *Soil Chemical Analysis*, Prentice-Hall, Englewood Cliffs, NJ, USA, 1967.
- [43] C.H. Fiske, Y. Subbarow, The colorimetric determination of phosphorus, *J. Biol. Chem.* 66 (2) (1925) 375–400.
- [44] D.A. Skoog, F.J. Holler, S.R. Crouch, *Textbook “principles of instrumental analysis, Cengage Learn.* 6 (2019).
- [45] Alessandra Rossette, José Bendassolli, Paulo Trivelin, Organic sulfur oxidation to sulfate in soil samples for total sulfur determination by turbidimetry R, *Revista Brasileira de Ciência Do Solo (Brasil)* (2008), <https://doi.org/10.1590/S0100-06832008000600031>. Num.6 Vol.32.
- [46] B.H. Abdelmonem, L.T. Kamal, Rana M. Elbaz, M.R. Khalifa, A. Abdelnaser, From contamination to detection: the growing threat of heavy metals, *Heliyon.* 11 (1) (2025) e41713, <https://doi.org/10.1016/j.heliyon.2025.e41713>.
- [47] F. Zucchini, A. Pera, M. Forte, M. Bertoldi, Evaluating toxicity of immature compost, *Biocycle* 2 (1981) 54–57.
- [48] T. Sung-inthara, S. Juntahum, K. Senawong, S. Katekaew, K. Laloon, Pelletization of Soil Amendment: optimizing the production and quality of soil amendment pellets from compost with water and biochar mixtures and their impact on soil properties, *Environ. Technol. Innov.* 33 (2024) 103505, <https://doi.org/10.1016/j.eti.2023.103505>.
- [49] C. Igathinathane, J.S. Tumuluru, S. Sokhansanj, X. Bi, C.J. Lim, S. Melin, E. Mohammad, Simple and inexpensive method of wood pellets macro-porosity measurement, *Biores. Tech.* 101 (16) (2010) 6528–6537, <https://doi.org/10.1016/j.biortech.2010.03.034>.
- [50] ASTM International. ASTM C29/C29M-17a: standard test method for bulk density (“unit weight”) and voids in aggregate. ASTM International, West Conshohocken, PA, USA, 2017.
- [51] S.F. Papandrea, F.C. M, A. Palma, F. Gallucci, G. Zimbalatti, A.R. Proto, Pelletization of compost from different mixtures with the addition of exhausted extinguishing powders, *Agronomy* 11 (7) (2021), <https://doi.org/10.3390/agronomy11071357>.
- [52] Soil Survey Staff. *Soil Survey Manual. USDA Handbook No. 18*, U. S. Government Printing Office, Washington, D. C., 1951.

- [53] D.S. Jenkinson, D.S. Powlson, The effects of biocidal treatments on metabolism in soil-V: a method for measuring soil biomass, *Soil Biol. Biochem.* 8 (3) (1976) 209–213, [https://doi.org/10.1016/0038-0717\(76\)90005-5](https://doi.org/10.1016/0038-0717(76)90005-5).
- [54] A. Pedroza-Sandoval, J.R. Minjares-Fuentes, R. Trejo-Calzada, I. Gramillo-Avila, Physiological and productivity responses in two chili pepper morphotypes (*Capsicum Annuum* L.), under different soil moisture contents, *Horticulturae* 10 (1) (2024), <https://doi.org/10.3390/horticulturae10010092>.
- [55] Department of Agriculture, announcement of the Department of Agriculture request for registration issue of registration certificate request to amend the registration list and the amendment of the organic fertilizer registration list B. E (in Thai). <https://www.doa.go.th/ard/wp-content/uploads/2019/11/FEDOAS.pdf>, 2012. (Accessed 1 April 2025).
- [56] E.E.Y. Amuah, B. Fei-Baffoe, K. Miezah, Y.A. Sarpong, K. Obiri-Danso, Synergistic assessment of compost quality using a multifaceted approaches and machine learning: a research protocol, *Results. Eng.* 27 (2025) 105786, <https://doi.org/10.1016/j.rineng.2025.105786>.
- [57] G. Galamini, G. Ferretti, C. Rosinger, S. Huber, A. Mentler, E. Diaz-Pines, B. Faccini, K.M. Keiblinger, Potential for agricultural recycling of struvite and zeolites to improve soil microbial physiology and mitigate CO<sub>2</sub> emissions, *Geoderma* 453 (2025) 117149, <https://doi.org/10.1016/j.geoderma.2024.117149>.
- [58] S. Juntahum, C. Klinsukon, K. Senawong, S. Katekaew, N. Sokudlor, K. Laloon, Assessing the potential for producing compost pellets with binders from Cassava industry by-products and supplemented with trichoderma, *Case Studies Chem. Environ. Eng.* 11 (2025) 101221, <https://doi.org/10.1016/j.csee.2025.101221>.
- [59] A. Simoes-Mota, R.M. Poch, A. Enrique, L. Orcaray, I. Virto, Soil quality assessment after 25 years of sewage sludge vs. Mineral Fertilization in a Calcareous Soil. *Land* 10 (7) (2021), <https://doi.org/10.3390/land10070727>.
- [60] C. Bondi, M. Castellini, M. Iovino, Compost amendment impact on soil physical quality estimated from hysteretic water retention curve, *Water. (Basel)* 14 (7) (2022), <https://doi.org/10.3390/w14071002>.
- [61] L.M. Hallman, J.-P. Fox, P.P. Joseph, K. Hussain, A.L. Wright, L. Rossi, Soil organic matter influences citrus growth, nutrient uptake, and root system architecture, *HortScience* 59 (12) (2024) 1781–1788, <https://doi.org/10.21273/HORTSCI18225-24>.
- [62] A. Aguilar-Paredes, G. Valdés, N. Araneda, E. Valdebenito, F. Hansen, M. Nuti. Microbial community in the composting process and its positive impact on the soil biota in sustainable agriculture. 2023. <https://doi.org/10.3390/agronomy13020542>.
- [63] D. Xu, Xi. Yu, J. Chen, X. Li, J. Chen, J.H. Li, Effects of compost as a Soil amendment on bacterial community diversity in Saline-Alkali Soil, *Front. Microbiol.* 14 (2023), <https://doi.org/10.3389/fmicb.2023.1253415>.
- [64] L.E. Fels, A. Naylo, M. Jemo, N. Zrikam, A. Boularbah, Y. Ouhdouch, M. Hafidi, Microbial enzymatic indices for predicting composting quality of recalcitrant lignocellulosic substrates, *Front. Microbiol.* 15 (2024), <https://doi.org/10.3389/fmicb.2024.1423728>.
- [65] A.B. Mastiholi, B. Sowmya, H.P. Maheswarappa, V. Dasar, T. Shantappa, D. L. Rudresh, R.T. Patil, Organic and natural farming practices effect on microbial population, dehydrogenase activity and microbial biomass carbon in the rhizosphere soil of cabbage, *Commun. Soil. Sci. Plant Anal.* 55 (8) (2024) 1236–1247, <https://doi.org/10.1080/00103624.2024.23031023>.
- [66] C.A. Zeiner, M.N. Kisch, E.D. Lynch, P. Shrestha, G.E. Small, Soil microbial activity profiles associated with organic compost fertilizers in an urban garden, *Urban Agric. Regional Food Syst.* 9 (1) (2024) e20059, <https://doi.org/10.1002/uar.2.20059>.