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Development of High-Quality Organic Fertilizer from Biomass Waste and the Application of Biochar in Local Areas of Sakon Nakhon Province, Northeastern Thailand

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Abstract

This study investigates the production of high-quality organic fertilizers from biomass waste in the Ban Wa Yai community of Sakon Nakhon Province, Northeastern Thailand, aimed at promoting sustainable agricultural practices amidst challenges such as soil degradation and reliance on chemical fertilizers. The primary objective was to develop organic fertilizers that enhance soil health and support plant growth while utilizing locally sourced biomass materials, including cow and buffalo manure, finely ground fermented leaf scraps, and weed debris. A fermentation process lasting 15 to 30 days was used, integrating biochar to improve nutrient profiles and microbial activity. Results showed optimal pH levels of 8.04 after 15 days and 7.94 after 30 days of fermentation, beneficial for addressing the region's acidic soil conditions (pH 4.67 - 5.38). The germination index (GI) was notably high at 129 ± 1.86 after 30 days, indicating effective growth promotion potential. Analytical assessments confirmed nitrogen (N), phosphorus (P), and potassium (K) concentrations in the organic fertilizers met or exceeded organic standards, supporting plant nutrition and fostering healthy microbial ecosystems. The organic matter (OM) and organic carbon (OC) content were approximately 40 - 60 % higher than commercial alternatives, enhancing soil structure, aeration, and water retention. Additionally, calcium (Ca) and magnesium (Mg) levels improved the nutrient profile, with Ca slightly exceeding standard limits, which helps ameliorate soil acidity. Economic analysis indicated a 40 % reduction in fertilizer costs for local farmers, promoting a shift towards organic practices. Overall, this study emphasizes the significance of self-reliance and the sufficiency economy philosophy in fostering sustainable agriculture practices within the Ban Wa Yai community. By utilizing local

resources and transitioning from chemical fertilizers to high-quality organic fertilizers, the community enhances agricultural productivity while promoting economic independence and resilience. Such initiatives exemplify the potential for integrating traditional practices with modern agricultural methods to ensure a sustainable future.
Keywords: Organic fertilizer, Biomass waste, Biochar application, Sakon Nakhon Province, Sustainable agriculture, Waste management, Soil improvement

Introduction

As of 2023, approximately 30 % of Thailand's population remains actively engaged in agriculture, with 43 % of the country's total land area is dedicated to agricultural activities. Agriculture continues to play a significant role, particularly in rural regions, despite a gradual decline due to industrialization and urban migration. The sector has diversified, focusing on crops such as rice, sugarcane, and rubber, which form the backbone of Thailand's agricultural output. Technological advancements have driven farming modernization, with the adoption of machinery and agricultural chemicals enhancing productivity. However, this shift has introduced notable challenges, particularly the environmental and health risks associated chemical residues. These residues not only affect the health of farmers but also raise concerns among consumers, highlighting the need for sustainable agricultural practices and immediate interventions to address these critical issues [1-5]. Consumers are increasingly seeking sustainable, safe, and environmentally friendly agricultural practices, which is motivating farmers to transition from chemical-based farming to organic methods, reminiscent of traditional practices [6,7].

Chemical fertilizers play a crucial role in Thai agriculture, with N-based fertilizers, particularly urea, being a dominant choice. In 2023, nitrogenous fertilizer consumption in Thailand was reported at over 705,000 metric tons, largely driven by the demands of rice farming. The fertilizer market's value reached approximately USD 3.1 billion in 2022 and is projected to continue expanding, fueled by the need to enhance crop yields and bolstered by government initiatives aimed at supporting farmers. This trend underscores the heavy reliance on synthetic fertilizers to meet agricultural productivity demands in the country, despite ongoing shifts towards more sustainable practices [8-10]. Organic farming reduces the use of chemical fertilizers and pesticides by utilizing animal manures from livestock farming, such as cow, buffalo, chicken, and pig manure. In particular, cow and buffalo manure are abundant in Thailand, as these animals are commonly raised by farmers as a secondary source of income. However, various research reports indicate that cow and buffalo manure contain relatively low levels of essential mineral nutrients for plants, with N content ranging from approximately 0.8 - 1.2 %, P from 0.5 - 0.9 %, and K from 0.5 - 1.0 %. It was also found that the amount of essential minerals like Ca and Mg in cow and buffalo manure is relatively small, generally not exceeding 0.5 %. The concentrations of primary and secondary minerals necessary for plant growth in cow and buffalo manure fertilizers vary by region, influenced by factors such as local farming practices and the animals' diets [11-13]. Therefore, the direct use of cow and buffalo manure as fertilizer has several limitations. One major issue is the low availability of minerals that plants can immediately absorb and utilize. Additionally, applying fresh or partially decomposed manure may trigger fermentation processes in the soil, which can lead to soil acidification. This practice can also introduce diseases caused by microorganisms and fungi from the manure, posing risks to plant health [11,12,14].

Sakon Nakhon Province, located in the northeastern region of Thailand, is an area with extensive agricultural land. The main crops cultivated in the province are rice, rubber, and oil palm. To achieve high yields, these crops require sufficient mineral nutrients. Consequently, fertilizer expenses account for nearly 40 % of each household's agricultural production costs. This information is based on a 2024 survey of farmers in Ban Wa Yai community, Wa Yai Sub-district, Akat Amnuai District, Sakon Nakhon Province, which is the focus area of this research study. The findings align with previous studies by Kaufman and Watanasak [15], Virochsaengaroon *et al*. [16], Inthasin *et al*. [17], and Yothong *et al*. [18], who investigated fertilizer use and its economic impacts on rice, rubber, and oil palm cultivation by farmers in the northeastern region of Thailand, including Sakon Nakhon Province.

Consequently, developing high-quality, low-cost organic fertilizers is a practical approach to promoting sustainable and safe agriculture while also reducing production costs for farmers. The primary objective of this research is to develop high-quality organic fertilizer using locally available materials. The main components include cow and buffalo manure, composted leaf and weed debris, which provide essential N and OM, and biochar made from tree branches, which has more pores than regular charcoal. Additional materials include shell and eggshell debris, which supply Ca and Mg, essential secondary nutrients for plants, as well as other amendments (e.g., bio-fermented water, dolomite powder, phosphate, molasses, etc.). These materials are readily available locally, inexpensive, and most importantly, environmentally friendly. Furthermore, using these materials to produce high-quality organic fertilizers not only reduces costs but also adds value to biomass waste while helping to address community pollution problems caused by burning this waste.

In addition, this research analyzes the properties of each main raw material before using it to produce high-quality organic fertilizers. The resulting organic fertilizers are then compared with high-quality inorganic fertilizers and with commercially available organic fertilizers. The analysis is conducted according to the organic fertilizer standards established by the Department of Agricultural Science, Ministry of Agriculture and Cooperatives, Thailand, in 2005. The comparison criteria included pH, electrical conductivity (EC), soil organic matter (OM), total nitrogen (Total N), P, K, total calcium (Total Ca), total magnesium (Total Mg), and the GI. Moreover, this research also analyzed the secondary components used to produce high-quality organic fertilizers. Biochar was examined for surface morphology using Scanning Electron Microscopy (SEM), while surface area and porosity were assessed through the Brunauer-Emmett-Teller (BET) method, along with iodine adsorption efficiency. Additionally, shell and eggshell debris were analyzed for mineral composition using X-ray Fluorescence (XRF) techniques. This data will serve as a valuable database for the production of high-quality organic fertilizers. The final phase of this research involves testing the high-quality organic fertilizer produced with farmers in the target area, Ban Wa Yai community, Wa Yai Sub-district, Akat Amnuai District, Sakon Nakhon Province, specifically for rice cultivation. The rice cultivation area was divided into 2 groups: One utilizing conventional chemical fertilizers and the other using the high-quality organic fertilizer produced in this study. Data were collected over 3 rice cultivation seasons. The results of this research will be invaluable for farmers seeking to reduce their dependence on chemical fertilizers by using high-quality organic fertilizers they can produce themselves. This initiative promotes sustainable and safe agriculture by creatively applying scientific knowledge, innovation, and technology.

Materials and methods

Materials

The materials used to produce high-quality organic fertilizers consist primarily of cow and buffalo dung, along with fermented leaf and weed residues, maintaining a moisture content of no more than 40 %. Secondary components include crushed shells and eggshells. Biochar powder is prepared by burning a mixture of tree branches using the biomass incinerator innovation developed by the Appropriate Technology Center, Faculty of Science and Technology, Sakon Nakhon Rajabhat University. These materials are sourced and collected from the Ban Wa Yai community, Wa Yai Sub-district, Akat Amnuai District, Sakon Nakhon Province. Additional organic fertilizer enhancers, such as bio-fermented water, rice bran and molasses (for use as microbial food), dolomite powder (for adjusting the pH value of fertilizers), and phosphate, are also incorporated. In addition, the production of high-quality organic fertilizer involves the use of PD.1 as an accelerator. PD.1 is a group of microorganisms with a high capacity to decompose agricultural waste materials, enabling the production of compost in a short period of time. It consists of bacteria, actinomycetes, and fungi, sourced from the Agriculture Office of Akat Amnuay District, Sakon Nakhon Province [19,20]. These microorganisms, along with bio-fermented water, work together to accelerate the decomposition process in the production of high-quality organic fertilizer.

The chemicals used in this study, including potassium dichromate ($K_2Cr_2O_7$), ferrous ammonium sulfate [$(NH_4)_2Fe(SO_4)_2\cdot 6H_2O$], concentrated sulfuric acid (H_2SO_4), *o*-phenanthroline ($C_{12}H_8N_2$), potassium chloride (KCl), boric acid (H_3BO_3), sodium hydroxide

(NaOH), Bray II extractant solution (typically a mixture of ammonium fluoride (NH_4F) and hydrochloric acid (HCl)), potassium standard solution (K^+ solution), magnesium standard solution (Mg^{2+} solution), and strontium chloride ($SrCl_2$), were all of analytical grade (AR) and were sourced from Fluka, Sigma-Aldrich, Carlo Erba, QRëC, Merck, LabScan, and Acros Chemical Co. Ltd. In addition, the chemicals, organic solvents, and other materials used in this research study are readily available in standard chemistry laboratories.

Evaluation of biochar powder and crushed shells and eggshells as precursors for high-quality organic fertilizer production

Biochar powder, one of the main ingredients used in the production of high-quality organic fertilizer at a proportion of 10 %, can be produced by burning tree branches using an innovative biomass incinerator. This incinerator can achieve temperatures of 600 - 800 °C. During the combustion process at these high temperatures, the resulting charcoal exhibits higher porosity compared to regular charcoal, thereby classifying it as biochar. To obtain comprehensive information on the properties of the produced high-quality organic fertilizer, it is essential to analyze the characteristics of one of its key components—biochar powder. In this research, the surface area, pore volume, and average pore diameter of biochar were evaluated using the BET technique. Additionally, iodine adsorption efficiency was measured, and morphology was examined using the SEM technique. All experimental procedures followed the research methodology outlined by Roschat *et al*. [21]. Crushed shells and eggshells were incorporated as ingredients in the production of high-quality organic fertilizer at a proportion of 5 %. These materials serve as sources of Ca and Mg, which are secondary nutrients essential for plant growth. In this research, the composition of the crushed shells and eggshells was analyzed using the Energy-Dispersive X-ray Spectroscopy (EDX) technique, following the experimental procedures described by Roschat *et al*. [22].

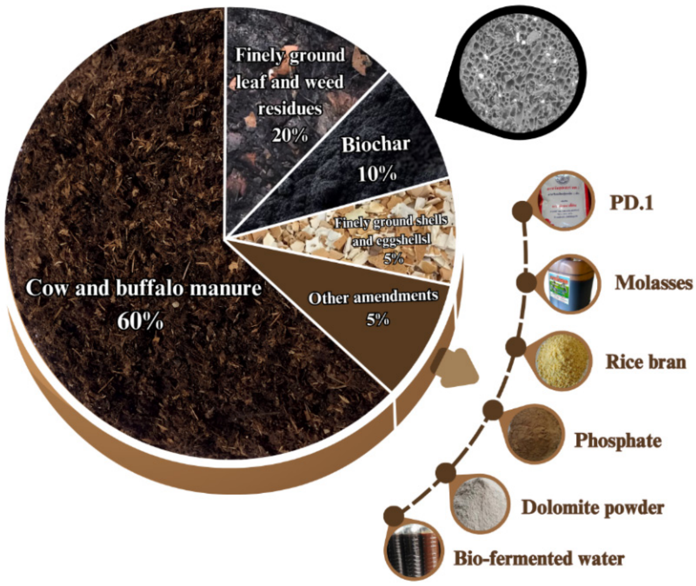

Figure 1 Composition of starting materials for the production of high-quality organic fertilizer.

Production process of high-quality organic fertilizer

The production process of high-quality organic fertilizer from biomass materials in this research was based on a mixing ratio of 60 % cow and buffalo manure, 20 % finely ground leaf and weed residues, 10 % biochar, 5 % finely ground shells and eggshells, and 5 % other amendments (including bio-fermented water, molasses, rice bran, dolomite powder, and phosphate) as shown in **Figure 1**. In this research, approximately 10 tons of high-quality organic fertilizer was produced at the Ban Wa Yai Community Organic Farming Enterprise, located in Wa Yai Sub-district, Akat Amnuay District, Sakon Nakhon Province. The process of making high-quality organic fertilizer begins by spreading cow and buffalo manure in a square shape as the 1st layer. Fermented leaf and weed residues are then spread on top to form the 2nd layer. Next, a layer of biochar powder is applied as the 3rd layer, followed by finely ground shells and eggshells. Finally, additional improvers such as dolomite lime powder, phosphates, molasses, and rice bran are added. The rice bran and molasses serve as a food source for the microorganisms involved in the composting process. The next step involves dissolving the bio-fermented water with PD.1. All ingredients are mixed thoroughly, after which the bio-fermented water solution containing PD.1 is sprayed evenly over the mixture. The ingredients are then mixed repeatedly to ensure that the organic fertilizer mixture is thoroughly combined. Afterward, the ingredients should be gathered into a pile and covered with a burlap cloth. The high-quality compost mixture should be left to compost in a shaded area. Humidity must be monitored using a field moisture meter every 3 days to prevent excessive drying of the compost pile. The ideal humidity for the composting process of high-quality organic fertilizer is between 50 and 60 %. Excessive humidity can lead to spoilage and methane gas production, whereas insufficient humidity may hinder the composting process and decrease efficiency. Humidity can be assessed by squeezing the composted material; if no water is released, the humidity level is considered appropriate. Verification can also be conducted using a field moisture meter [23,24]. The fermentation period for the high-quality organic fertilizer was set at 30 days to allow microorganisms to fully decompose the ingredients. Samples of the fertilizer, fermented for 15 and 30 days, were randomly collected and analyzed for quality following the standard methods established by the Department of Agricultural Science, Ministry of Agriculture and Cooperatives, Thailand, in 2005 [25-28]. The flow diagram of the high-quality organic fertilizer production process is shown in **Figure 2**.

Figure 2 Process flow diagram for high-quality organic fertilizer production.

Quality analysis of organic fertilizers produced

In this study, 10 samples were analyzed, including 4 samples of cow and buffalo manure from the Ban Wa Yai Community; 1 sample of fermented leaf litter, primarily from the rain tree (*Samanea saman*); 1 sample of weed debris from the Nong Harn wetlands, comprising water hyacinth, Grail of duckweed, and other weeds; 2 samples of high-quality organic fertilizer produced after fermentation for 15 and 30 days; and 2 samples of commercial organic fertilizer.

Quantification of soil organic matter using the Walkley and Black method

Weigh 1 g of the sample and place it in a 250 mL Erlenmeyer flask. Pipette 10 mL of 1 nitrogen potassium dichromate solution into the flask. Add 15 mL of concentrated sulfuric acid and shake the flask gently for 1 - 2 min. Allow the mixture to stand for 30 min. Then, add approximately 50 mL of distilled water and let it cool. After cooling, add 5 drops of *o*-phenanthroline indicator. Titrate with 0.5 N ferrous ammonium sulfate solution to determine the amount of potassium dichromate remaining from the reaction, stopping when the color of the solution changes from green to red-brown at the endpoint. Record the volumes of potassium dichromate and ferrous ammonium sulfate used. Prepare a blank using the same method as the sample analysis. Calculate the amount of OM using the formula below:

$$Organic\ Matter\ (\%) = \frac{(B-T)\times N}{B} \times \frac{100}{77} \times \frac{100}{58} \times \frac{3}{1000} \times \frac{100}{W} \times 10 \qquad (1)$$

where N is the concentration of potassium dichromate (N), B is the volume of ferrous ammonium sulfate solution titrated with the blank (mL), T is the volume of ferrous ammonium sulfate solution titrated with the sample (mL), and W is the weight of the sample (g) [19,21,26]. The calculation of OC values in the studied samples can be performed by dividing the OM (%) by 1.724, as described in the research of Finore *et al*. [19], Makan *et al*. [24] and Lee *et al*. [26].

Electrical conductivity (EC) analysis

The EC analysis of all samples in this research was conducted following the experimental method described by Finore *et al*. [19], Gurusamy *et al*. [23], and Carmo *et al*. [29]. The experimental procedure begins by weighing 10 g of the sample and placing it in a 125 mL Erlenmeyer flask. Then, add 50 mL of distilled water and shake the flask for 2 h. After shaking, allow the mixture to stand for about 30 min until the solution separates, or filter the solution. Before measuring the conductivity of the sample solution with a conductivity meter, calibrate the meter using 0.01 and 0.1 M KCl solutions. The 0.01 M KCl standard solution should read approximately 1413 µS/cm at 25 °C, while the 0.1 M KCl standard solution should read approximately 129 dS/cm at 25 °C. Finally, dilute the sample solution at a ratio of 1:5 and measure the EC using the conductivity meter.

pH analysis

The pH analysis was conducted using the experimental method described in the research report by Makan *et al*. [24] and Ernest *et al*. [30]. The procedure involved weighing 10 g of the sample and placing it into a 50 mL beaker. Next, 10 mL of distilled water was added, and a glass rod was used to stir the mixture several times. The mixture was allowed to sit for at least 30 min to enable precipitation. A portion of the sample solution was then taken to measure the pH with a pH meter, using standard buffer solutions of pH 7 and pH 4 for calibration. The pH meter was adjusted before each experiment.

Total nitrogen (Total N) analysis Kjeldahl method

The total nitrogen (Total N) analysis by the Kjeldahl method was performed in accordance with the AOAC standard method 955.04 [31] and referenced the method from the research report by Finore *et al*. [19] and Gurusamy *et al*. [23]. The Kjeldahl method is a commonly applied analytical technique for determining total nitrogen (Total N) in organic fertilizer samples. The procedure starts by weighing about 1 - 2 g of the fertilizer and placing it into a Kjeldahl digestion flask. To initiate the digestion, 10 mL of concentrated sulfuric acid (H_2SO_4) is added, along with a catalyst mixture, typically potassium sulfate (K_2SO_4) and copper sulfate ($CuSO_4$). These catalysts accelerate the decomposition of OM, which is achieved by heating the mixture. The heating continues until the solution turns clear, indicating the complete conversion of organic N into ammonium sulfate ($(NH_4)_2SO_4$). After digestion, the solution is cooled and transferred to a distillation apparatus. At this point, a strong base such as sodium hydroxide (NaOH) is introduced to neutralize the acid, releasing ammonia gas (NH_3) from the ammonium ions. The ammonia is then distilled into a receiving flask containing a boric acid (H_3BO_3) solution, where it forms ammonium borate.

The final step involves titrating the ammonium borate solution with a standardized HCl solution. An indicator, such as methyl red, is used to detect the titration endpoint, indicated by a color change. The volume of acid required is recorded and used to calculate the Total N content in the sample. The formula used for this calculation takes into account the normality of the acid and the molecular weight of N. This method provides a precise and reliable measurement of the Total N present in organic fertilizer, which is essential for understanding its nutrient content and effectiveness. The Kjeldahl method remains the standard for N analysis due to its accuracy and its ability to handle complex organic matrices in fertilizers. The formula for calculating Total N using the Kjeldahl method is as follows:

$$Total\ Nitrogen\ (\%) = \frac{V_{acid} \times N_{acid} \times 14.007}{W_{sample}} \times 100 \quad (2)$$

where V_{acid} is the volume of acid used in titration (mL), N_{acid} is the normality of the acid used in titration, 14.007 is the atomic weight of N (g/mol), and W_{sample} is the weight of the sample (g).

Analysis of available phosphorus (P)

The analysis of plant-available P was conducted using standard methods as reported by Finore *et al*. [19], Lee *et al*. [26]. The experimental procedure began with weighing a 1.0 g sample and placing it in a 50-milliliter Erlenmeyer flask. Then, 10 mL of Bray II extract solution was added, and the mixture was shaken for 1 min before being filtered through No. 5 filter paper (11.0 cm). The resulting solution was then diluted in a 1:16 ratio (equivalent to 17 times using an Auto-dilutor) into a glass cuvette, left for half an hour, and the concentration was read using a spectrophotometer at a wavelength of 882 nanometers. Additionally, a blank sample set and standard solution sets with varying concentrations were prepared for comparison. The calculation of the amount of P available to plants can be performed using the following equation:

$$Available\ phosphorus\ (mg/kg) = \frac{B \times df(sample) \times R}{A \times df(standard)} \quad (3)$$

where A is the weight of the sample (g), B is the volume of the extract solution (mL), R is the reading measured against the standard set, and df is the dilution factor. The calculated results are expressed in milligrams per kilogram of sample and are then converted to percentages to facilitate comparison with other mineral contents.

Analysis of available potassium (K)

Analysis of available K for plants was conducted following standard experimental procedures, as outlined in the research reports of Yothong *et al*. [18] and Finore *et al*. [19]. The experimental analysis of available K in the fertilizer samples was conducted by weighing approximately 2.5 g of the sample into an Erlenmeyer flask. Then, 25 mL of ammonium acetate or another extraction solution was added. The mixture was shaken for about 30 min and subsequently filtered. The filtrate was analyzed, and if the K concentrations were high, the extract was diluted before measuring the K content. The flame photometer was set to a wavelength appropriate for K, typically around 766.5 nm, and the results were compared with a K standard curve. The calculation of the amount of K available to plants can be performed using the following equation:

$$Available\ potassium\ (mg/kg) = \frac{D \times df(sample) \times B}{A} \quad (4)$$

where A is the weight of the sample (g), B represents the volume of ammonium acetate solution used for extraction (mL), D denotes the K concentration relative to the standard concentration, and df is the dilution factor. The calculated results are expressed in milligrams per kilogram of sample and are then converted to percentages to facilitate comparison with other mineral contents.

Total calcium (Total Ca) analysis by atomic absorption spectrophotometry

Total Ca is essential for optimal plant growth, making accurate measurement of its levels in organic fertilizers critical for effective nutrient management. The Atomic Absorption Spectrophotometric (AAS) method is widely employed for this purpose due to its high sensitivity and accuracy. The analytical process starts with the preparation of the sample, where 1 - 5 g of the organic fertilizer is weighed and then dissolved in a strong acid, such as nitric acid (HNO_3) or hydrochloric acid (HCl). To ensure complete dissolution, gentle heating can be applied. Once dissolved, the solution is filtered to eliminate any solid residues. Subsequently, the prepared solution is analyzed using AAS, with the instrument calibrated to the appropriate wavelength for Ca detection, typically around 422.7 nm. The absorbance of the solution is recorded and compared to a standard calibration curve to ascertain the Ca concentration. Results are expressed in milligrams per kilogram of the sample or as a percentage of the total weight. This analysis is instrumental in evaluating the Ca content, thereby aiding in the assessment of the quality and efficacy of organic fertilizers in enhancing plant health and productivity [18,19].

Total magnesium (Total Mg) analysis by atomic absorption spectrophotometry

Total Mg is a crucial nutrient for plant growth, and accurately assessing its levels in organic fertilizers is vital for effective nutrient management. The AAS method is widely employed for this analysis due to its high sensitivity and precision. The sample preparation involves acid digestion, which follows a procedure similar to that used for Ca analysis. However, for Mg detection, the instrument is set to a wavelength of approximately 285.2 nm. The absorbance readings obtained are then compared to a standard calibration curve to calculate the Mg concentration. Results are expressed in milligrams per kilogram of sample or as a percentage of the total weight. This analysis method is a standard general method based on the research reports by Bekele *et al*. [32] and Tangga *et al*. [33].

Germination Index (GI) analysis

The GI measures seed quality and germination ability, assessing both the rate and uniformity of germination. It provides insights into the seed's growth potential and is often used to compare different seed lots or evaluate the impact of various treatments. For compost producers, the GI test is essential as it measures phytotoxic substances resulting from incomplete decomposition. This method involves extracting organic compounds from compost samples with water to dissolve salts, organic acids, and other water-soluble toxic substances. High levels of these toxic substances can adversely affect germination and the radicle length of seedlings used for testing [18,24]. The germination test was conducted using a solution of organic fertilizer mixed with water at a ratio of 1:10 (weight/volume) compared to filtered water. Seeds were planted and left to grow for 48 h. The percentage of germination and the root length of the plants were then measured and calculated using the following formula:

$$Germination\ Index = \frac{Seed\ germination\ (\%) \times Root\ length\ of\ treatment}{Seed\ germination\ (\%) \times Root\ length\ of\ control} \times 100 \quad (5)$$

High-quality organic fertilizer standards typically require a GI value of at least 80. This threshold indicates the fertilizer's quality and safety for use with plants, as determined by the Department of Agriculture, Ministry of Agriculture and Cooperatives. However, specific GI values may vary depending on the standards established by various agencies or organizations in different countries [4,15,18,24].

Results and discussion

Analysis of starting materials for use in the production of high-quality organic fertilizers

Analysis of cow and buffalo manure, finely ground fermented leaf scraps, and weed debris from the Nong Harn wetlands

The results of the analysis of raw materials for producing high-quality organic fertilizers are presented in **Table 1**. The cow and buffalo manure samples, labeled as 1, 2, 3, and 4, were collected from 4 different farms within the Ban Wa Yai Community Organic Farming Enterprise, located in Wa Yai Sub-district, Akat Amnuay District, Sakon Nakhon Province. These samples were randomly selected for analysis to assess their chemical and physical properties, including the levels of essential minerals that promote plant growth. The experimental results indicated that the cow and buffalo manure from all 4 farms were of similar quality, with pH values exceeding 8.5, suggesting relatively strong base properties. This is attributed to the ongoing fermentation of the manure, primarily due to the excretion of ammonia (NH_3) from the cows and buffaloes. These experimental results align with the findings of Ali *et al*. [12], Loss *et al*. [13], and Rayne and Aula [14], who reported that animal manure exhibits alkaline properties due to the release of ammonia (NH_3) during the fermentation process. This release affects soil fertility and helps reduce nutrient loss. When considering sample 5, finely ground fermented leaf scraps, the pH value is quite neutral. In contrast, the weed debris from the Nong Harn wetlands (sample 6) has a pH value of 4.91, indicating that it is relatively acidic. This acidity in the weed debris may be attributed to the fermentation process of the debris and sediment that accumulated in the Nong Harn water source. As the material was drawn up from the water source, the fermentation process continued, resulting in increased acidity.

The pH values of these starting materials directly influenced the seed germination rate, as measured by the GI analysis, illustrated in **Figure 3(a)**. The results from the GI analysis revealed that samples A1, A2, A3, and A4, which consisted of cow and buffalo manure from 4 different farms, exhibited GI values lower than the specified standard criteria. Similarly, sample A6, which comprised weed debris from the Nong Harn wetlands, also had a value below the standard criteria of 80. This indicates that the fermentation processes occurring in both the cow and buffalo manure samples and the weed debris from the Nong Harn wetlands resulted in pH values that exhibited excessive acidity or basicity. Consequently, this may lead to low seed germination rates, suggesting that these materials may still be toxic to plants [6,14,20]. In contrast, sample A5, consisting of finely ground fermented leaf scraps, achieved a GI value of 82 ± 0.89, which meets the standard criteria. This aligns with the analyzed pH value of 7.16, indicating that it is neutral. Therefore, based on this information, it can be concluded that the direct use of fertilizer starting materials from cow and buffalo dung, as well as weed debris from the Nong Harn wetlands, may have adverse effects on plants. This is because these materials exhibit an incomplete fermentation process, resulting in the presence of substances that may be harmful to plants.

Table 1 The results of analysis of cow and buffalo dung and finely ground leaf and weed debris.

Sample	pH (1:10)	EC (mS/cm)	OM (%)	OC (%)	Total N (%)	P (%)	K (%)	Ca (%)	Mg (%)
Cow and buffalo manure 1	8.71	1.62	28.12	16.31	0.98	0.08	0.43	1.76	0.50
Cow and buffalo manure 2	8.60	1.58	26.78	15.53	0.87	0.14	0.35	1.82	0.43
Cow and buffalo manure 3	8.64	1.44	28.85	16.73	1.02	0.11	0.12	2.06	0.74
Cow and buffalo manure 4	8.48	1.37	28.23	16.37	0.95	0.09	0.28	1.94	0.57
Finely ground fermented leaf scraps	7.16	0.30	15.26	8.85	0.86	0.10	0.14	3.62	0.26
Weed debris from the Nong Harn wetlands	4.91	1.38	56.84	32.97	2.12	0.09	0.42	0.69	0.14

Note: All of the results in **Table 1** were averaged from the repeats analytical 3 times and the standard deviation was within 3 %.

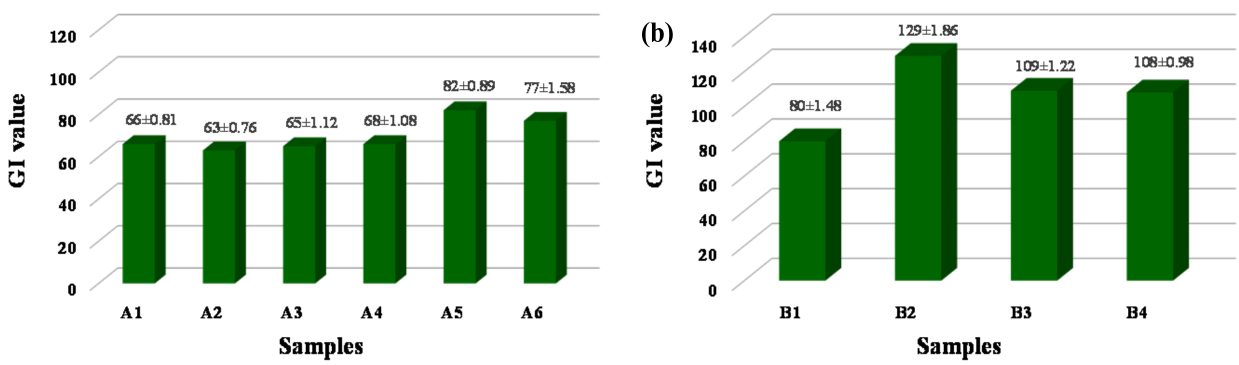

Figure 3 GI analysis of (a) cow and buffalo dung, finely ground leaf and weed debris, and (b) high-quality organic fertilizer after 15 and 30 days of fermentation compared to commercial organic fertilizer samples. Note: Sample A1 is cow and buffalo manure 1, A2 is cow and buffalo manure 2, A3 is cow and buffalo manure 3, A4 is cow and buffalo manure 4, A5 is finely ground fermented leaf scraps, and A6 is weed debris from the Nong Harn wetlands, B1 is high-quality organic fertilizer after 15 days of fermentation, B2 is high-quality organic fertilizer after 30 days of fermentation, B3 is commercial organic fertilizer samples 1, and B4 is commercial organic fertilizer samples 2.

EC in fertilizers measures the concentration of dissolved salts, indicating the availability of nutrients for plants. High EC levels can signal excessive salinity, which may harm plant growth by negatively affecting water and nutrient uptake. Conversely, low EC indicates insufficient nutrient levels, leading to deficiencies and poor plant growth. According to the 2005 announcement from the Department of Agriculture regarding organic fertilizer standards, the EC of standard organic fertilizers must not exceed 6 mS/cm, while high-quality organic fertilizers should not exceed 15 mS/cm [15,20,34]. The results of the experiment indicated that all the starting materials in **Table 1**, exhibited relatively low EC values. This suggests that the concentration of salt compounds, primarily nutrients such as nitrate, K, and ammonium, available for plant absorption and utilization in the growth process is quite low. Consequently, if these starting materials are used to directly nourish the soil, it may take a considerable amount of time for them to release the essential nutrients.

The results of the OM and OC content analysis in the starting material samples indicated that weed debris from the Nong Harn wetlands had the highest OM and OC content, likely due to the long-term accumulation of weed debris and sediment in the area. Cow and buffalo manure had the next highest OM and OC content, with values being similar across all 4 sources. In contrast, finely ground, fermented leaf scraps exhibited low OM and OC content. This may be attributed to the daily collection of fallen leaves, which were piled up to initiate the decomposition process, resulting in the earlier collected leaves decomposing fully while the later collected leaves may not have fully decomposed. OM and OC in organic fertilizers are vital for several reasons: They improve soil structure, enhance aeration, and increase water retention, leading to healthier plants. They serve as reservoirs for essential nutrients, which are released during decomposition for plant uptake. High levels of OM and OC support diverse microbial communities that facilitate nutrient cycling and OM breakdown. Additionally, OM buffers soil pH and enhances moisture retention, reducing irrigation needs and improving drought resistance. Therefore, OM and OC are crucial for soil health, nutrient availability, and sustainable agriculture [6,12,14,35].

The analysis results of total N, P, and K—the primary nutrients required for plants—revealed relatively low levels across most starting material samples, failing to meet the established criteria, particularly for P and K. However, the weed debris from the Nong Harn wetlands exhibited the highest total N content among the samples. This elevated total N level may be attributed to the accumulation of sediment and the thorough decomposition of weed debris in the water source. Ca and Mg, essential nutrient minerals for plant growth, were present in all samples of the starting materials, albeit in relatively low amounts. Each source of starting material used to produce these high-quality organic fertilizers showed varying levels of Ca and Mg. While there are no minimum requirements for Ca and Mg in organic fertilizers, these minerals are crucial for plant growth and play a significant role in regulating the acid-base conditions of the soil [6,8,11,18]. The analysis of cow and buffalo manure, finely ground fermented leaf scraps, and weed debris from the Nong Harn wetlands indicates that each type of starting material has certain properties that make it unsuitable for direct application as fertilizer for plants. Using these materials in their current state may negatively impact plant growth rather than support it. Therefore, it is crucial to enhance these starting materials through a process of improvement, which includes the addition of other ingredients and fermentation. This process will increase the efficiency and quality of the organic fertilizer, enabling it to effectively nourish plants and achieve the higher yields desired by farmers.

Analysis of biochar and crushed shells as precursors for high-quality organic fertilizer production

The results of the analysis for BET surface area, pore volume, average pore diameter, and iodine adsorption efficiency of the biochar powder compared to regular charcoal are presented in **Table 2**. The analysis shows that the biochar powder exhibits significantly higher BET surface area, pore volume, average pore diameter, and iodine adsorption efficiency compared to regular charcoal. The explanation for this experimental result is that the biochar powder sample was prepared from dry tree branches and processed using a biomass incinerator developed by the Appropriate Technology Center, Faculty of Science and

Technology, Sakon Nakhon Rajabhat University [21]. The incinerator operates at a temperature range of 600 - 800 °C and can maintain this temperature for approximately 1 - 2 h. As a result, the high-temperature treatment facilitates the transformation of the tree branches into biochar with high porosity. In contrast, regular charcoal is produced from logs burned in a traditional kiln based on local wisdom. This type of kiln reaches a maximum temperature of around 400 °C, and the heat distribution is inconsistent. Consequently, the resulting charcoal has low porosity, making it unsuitable for use as an adsorbent but more appropriate for use as fuel for cooking. This experimental result aligns with the findings of Sbizzaro *et al*. [36] and Tomczyk *et al*. [37], who reported that higher pyrolysis temperatures improve biochar properties, such as surface area, pore volume, and adsorption capacity, making it more effective for environmental applications.

The surface area and porosity of both biochar powder and regular charcoal samples were corroborated by morphological characterization using the SEM technique. **Figures 4(a)** and **4(b)** display the biochar powder samples, which exhibit high porosity and a uniform distribution. In contrast, **Figures 4(c)** and **4(d)** illustrate the surface characteristics of the regular charcoal samples, which have a smooth surface with minimal porosity, where some particles exhibit small, shallow, and irregular pores. The experimental results indicate that incorporating biochar powder with high porosity into the production of high-quality organic fertilizer is crucial for mineral absorption, enabling gradual release for plant uptake. Additionally, biochar powder enhances moisture retention, provides a habitat for microorganisms, and improves soil aeration by creating a looser structure (**Figures 4(e)** and **4(f)**). These properties significantly contribute to soil fertility, supporting healthy plant growth and allowing roots to expand and access nutrients effectively. This discussion aligns with the findings of Ding *et al*. [38] and Nepal *et al*. [39], who highlight advancements in biochar technology and its significant contributions to enhancing soil fertility, biochemical quality, and environmental applications. Their insights underscore the broader implications of biochar in sustainable agriculture.

Table 2 Comparison of the BET surface area, pore volume, average pore diameter, and iodine adsorption efficiency of the biochar powder and regular charcoal.

Parameters	**Biochar powder**	**Regular charcoal**
BET surface area (m^2/g)	433.06	50.99
Total pore volume (cm^3/g)	0.5397	0.0071
Average pore diameter (nm)	3.6318	2.7336
Iodine adsorption efficiency (mg I_2/g of sample)	468.23	87.24

Note: All of the results in **Table 2** were averaged from the repeats analytical 3 times and the standard deviation was within 3 %.

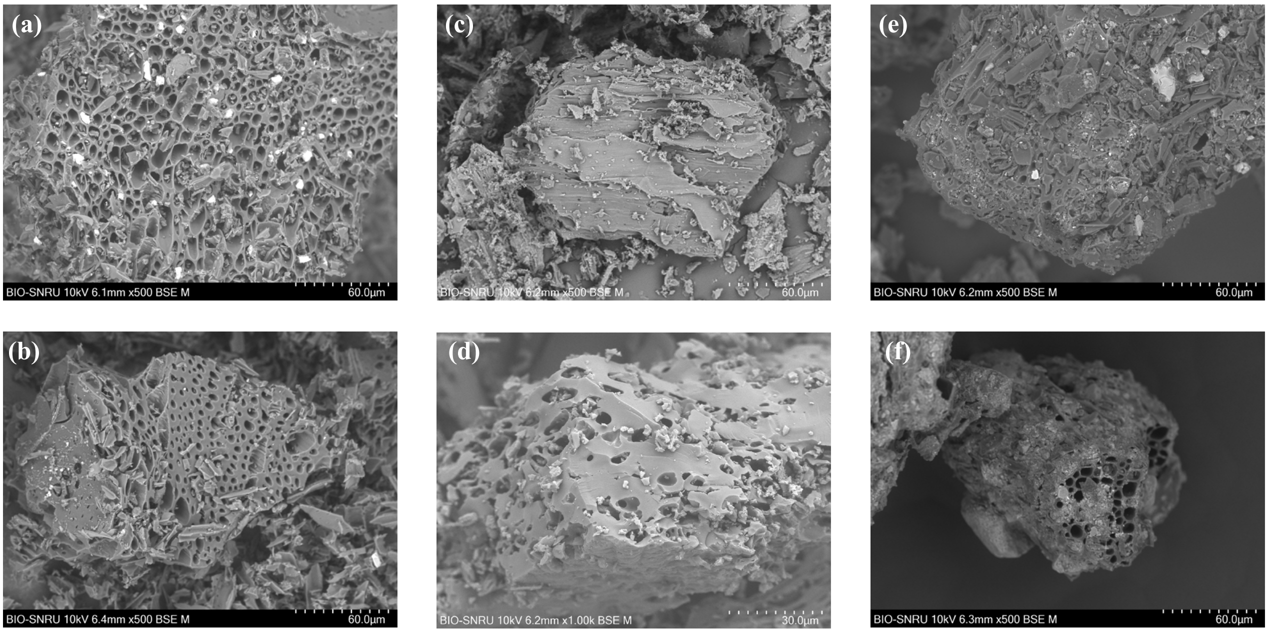

Figure 4 SEM images of biochar samples (a) and (b), regular charcoal (c) and (d), and biochar mixed with high-quality organic fertilizer (e) and (f).

This study also analyzed the composition of finely ground shells and eggshell samples, which are crucial ingredients for developing high-quality organic fertilizers. The results from the EDX analysis indicated that calcium (Ca) was the primary component, comprising 95.42 % of the samples. Additionally, Mg was present at 2.86 %, while other minerals—including sodium (Na), strontium (Sr), aluminum (Al), potassium (K), silicon (Si), zinc (Zn), iron (Fe), and manganese (Mn)—accounted for approximately 1.72 %. These findings underscore the potential of using shells and eggshells in organic fertilizer formulations, given their high Ca content and the presence of other beneficial minerals [40,41]. Therefore, the incorporation of crushed shells and eggshells into organic fertilizers significantly enhances soil quality and promotes sustainable plant growth. These materials are rich in Ca, which strengthens plant structures and aids root development, while also improving soil moisture retention and aeration. Additionally, they help immobilize heavy metals and toxins in the soil, supporting beneficial microorganisms essential for OM decomposition and soil restoration, making this approach an effective and environmentally friendly practice in agriculture [38-41].

Quality analysis results of produced organic fertilizers

The analysis results of high-quality organic fertilizer after 15 and 30 days of fermentation, in comparison to commercial organic fertilizer samples, are presented in **Table 3**. The pH analysis results indicated that the high-quality organic fertilizer sample fermented for 15 days had a pH value of 8.04, while the sample fermented for 30 days showed a slight decrease to 7.94, both of which fall within the acceptable range of the high-quality organic fertilizer standard (5.5 - 10.0). In comparison, the 2 brands of commercial organic fertilizers had pH values of 8.13 and 7.17. Thus, the high-quality organic fertilizer sample after 30 days of fermentation is slightly basic, making it suitable for agricultural use in the Ban Wa Yai community, where soil pH values were found to be acidic (ranging from 4.67 to 5.38). The slightly basic nature of the fertilizer can help adjust the soil pH to a more favorable level for plant growth [11-13]. Additionally, the slight alkalinity observed in the high-quality organic fertilizer after 30 days of fermentation poses no harm to plants, as confirmed by the GI analysis of both the organic fertilizer samples and the commercial alternatives, as depicted in **Figure 3(b)**. The study results revealed that the high-quality organic fertilizer, after 30 days of fermentation, exhibited a high GI value of 129 ± 1.86, the highest among all samples tested. Conversely, the high-quality organic fertilizer sample after 15 days of fermentation had a GI value of 80 ± 1.48, which met the standard criteria for use. This discrepancy may be attributed to incomplete fermentation, which can leave certain components in a state that may be toxic to plants if applied prematurely. Notably, the commercial organic fertilizers also demonstrated relatively high GI values, indicating their potential effectiveness as well [11,14,15].

The analysis of EC in organic fertilizers shows that high-quality organic fertilizer after 30 days of fermentation exhibits values comparable to commercial organic fertilizer sample 1 (EC value above 7 mS/cm), indicating readiness for nutrient release, particularly nitrate, K, and ammonium. These nutrients are vital for plant growth. In contrast, the high-quality organic fertilizer after 15 days of fermentation had a lower EC value of 2.78 mS/cm, while commercial organic fertilizer sample 2 recorded an even lower value of 0.86 mS/cm. These lower EC values suggest that these samples contain insufficient mineral nutrients, likely due to incomplete fermentation in the high-quality organic fertilizer or limited mineral content in Commercial Organic Fertilizer Sample 2 [11,12,14,15].

Table 3 The results of high-quality organic fertilizer analysis after 15 and 30 days of fermentation compared to commercial organic fertilizer samples.

Sample	pH (1:10)	EC (mS/cm)	OM (%)	OC (%)	Total N (%)	P (%)	K (%)	Ca (%)	Mg (%)
High-quality organic fertilizer after 15 days of fermentation	8.04	2.78	20.51	11.90	1.06	0.90	0.89	9.37	1.17
High-quality organic fertilizer after 30 days of fermentation	7.94	7.04	20.38	11.82	1.11	0.73	1.28	7.23	1.13
Commercial organic fertilizer samples 1	8.13	0.86	7.64	4.43	0.19	0.51	0.42	17.33	0.43
Commercial organic fertilizer samples 2	7.17	7.39	14.52	8.42	1.43	0.63	1.29	4.57	0.87

Note: All of the results in **Table 3** were averaged from the repeats analytical 3 times and the standard deviation was within 3 %.

The results of the OM and OC tests indicated that high-quality organic fertilizer samples, after both 15 and 30 days of fermentation, contained OM and OC values approximately 40 - 60 % higher than those of the 2 commercial organic fertilizer brands. This high-quality organic fertilizer was produced by mixing finely ground fermented leaf scraps and weed debris from the Nong Harn wetlands in a proportion of up to 20 % along with cow and buffalo manure. In contrast, the lower OM content in both commercial brands suggests they may lack the same beneficial properties. The elevated OM and OC values in the high-quality samples enhance soil structure, improve aeration, and increase water retention, contributing to healthier plant growth. Furthermore, the OM functions as a reservoir for vital nutrients, gradually releasing them as it decomposes, making them available for plant absorption. Elevated levels of OM and OC foster a rich microbial ecosystem that enhances nutrient cycling and the degradation of organic materials. Additionally, OM is instrumental in regulating soil pH and enhancing water retention capabilities which can help minimize the frequency of irrigation while also improving resilience to drought conditions. The findings presented are consistent with the research conducted by Loss *et al*. [13], Ding *et al*. [38], Nepal *et al*. [39], and Ok *et al*. [40]. These studies provide valuable insights into the advantages of utilizing high-quality organic fertilizers, emphasizing the critical contributions of OM and carbon to soil health and the enhancement of plant growth.

The analysis of Total N showed that high-quality organic fertilizer samples met the 1 % N standard after 15 and 30 days of fermentation, comparable to commercial organic fertilizer sample 2. In contrast, commercial organic fertilizer sample 1 fell below this criterion. N and P are essential macronutrients that significantly enhance plant growth; N supports protein, enzyme, and chlorophyll synthesis, crucial for photosynthesis and development, while P aids energy transfer, root development, and flowering. Regional standards for available P in organic fertilizers vary: Thailand requires a minimum of 0.5 % P_2O_5, the USDA recommends 0.4 - 3.0 %, and EU regulations set a range of 0.3 - 2.0 % P_2O_5 based on type and use. The test results confirmed that P levels in all samples met these standards, ensuring their effectiveness for plant growth and soil health. Similarly, the required levels of available K vary: Thailand mandates 0.5 % K_2O, while USDA and EU guidelines recommend 0.4 - 3.0 % and 0.3 - 2.0 %, respectively. The K test results also confirmed compliance with the specified standards, affirming the fertilizers' contributions to balanced plant growth and productivity [20,36,42]. It is noteworthy that the high-quality organic fertilizer samples, after 30 days of fermentation, exhibit total N, P, and K values that are quite high, comparable to those of commercial organic fertilizer samples 2, and exceeding both high-quality organic fertilizer samples produced after 15 days of fermentation and commercial organic fertilizer samples 1. Furthermore, when compared to the starting materials studied earlier, the high-quality organic fertilizer produced after 30 days of fermentation shows significantly higher values. This indicates that mixing the ingredients and fermenting them for 30 days results in high-quality organic fertilizers with mineral nutrients readily available for plants to absorb and utilize effectively.

In terms of secondary minerals like Ca and Mg, it was found that the Ca content in both high-quality organic fertilizer samples, after 15 and 30 days of fermentation, exceeded the standard limit of 5 %. However, this excess was not significantly high and is considered advantageous for improving the soil conditions in the Ban Wa Yai community, which has been reported to have acidic soil. For future production of organic fertilizers, it may be beneficial to reduce the amount of crushed shells and eggshells to lower the Ca content. Regarding Mg, although there are no specified standards for its concentration in organic fertilizers, the analysis of the high-quality organic fertilizer samples indicated a Mg content of 1 % after both 15 and 30 days of fermentation. This value is higher than that found in samples from both commercial organic fertilizer brands, making it suitable for providing secondary nutrients essential for plant growth [14,30,38].

Experimental use of high-quality organic fertilizers produced in rice farming

One of the key findings of this research is the practical application of high-quality organic fertilizers in rice farming within the Ban Wa Yai community, involving 15 experimental households. This study initially surveyed and collected data on rice farming practices utilizing chemical fertilizers in 2021 and 2022. In the 2023 rice farming cycle, participants transitioned to using high-quality organic fertilizers produced from local resources. The project also received ongoing support in 2024, ensuring continued development and monitoring of the fertilizer's effectiveness. The data indicates that the average rice yield per rai in Ban Wa Yai, Akat Amnuay District, Sakon Nakhon Province, is approximately 400 - 450 kg per rai for regular rice, while glutinous rice yields about 350 - 400 kg per rai. In the 2021 - 2022 farming seasons, rice cultivation relied on chemical fertilizers, which averaged around 800 baht per rai. However, in 2023, farmers transitioned to using high-quality organic fertilizers produced locally. This switch did not result in significant differences in the yields of both regular and glutinous rice compared to the previous 2 years. Notably, the fertilizer costs decreased to 480 baht per rai, achieving a remarkable reduction of approximately 40 % from earlier expenses. The use of these self-produced organic fertilizers highlights a sustainable approach that benefits both the environment and the farmers' economic situation. This trend aligns with findings that highlight the effectiveness of organic fertilizers in maintaining crop yields while reducing costs. As shown in **Figure 5**, the diagram illustrates the experimental use and development of high-quality organic fertilizer in rice farming by the Ban Wa Yai Community Organic Farming Enterprise. The experiment involves producing high-quality organic fertilizer from local materials and further developing it into pellet form for distribution to community members. The figure also includes an image demonstrating the rice yield obtained from using the high-quality organic fertilizer produced.

Although this information serves as preliminary data for this research study, the results clearly indicate notable differences. However, to obtain more definitive conclusions, it is essential to collect data over a period of at least 3 - 5 years. This extended period will allow for a comprehensive summary that can serve as a guideline or prototype for developing sustainable organic farming practices applicable to other communities. In addition to monitoring rice yields, it's crucial to consider other factors, including environmental impacts, community health, changes in soil quality, and the overall quality of organic rice produced. Expanding community capabilities to produce and distribute high-quality organic fertilizers that meet established standards is vital, as is ensuring the production and distribution of safe organic rice that commands higher prices than typical market offerings. This research marks a significant starting point for applying scientific and technological knowledge to address community challenges, ultimately improving the quality of life. It aligns with the philosophy of a sufficiency economy, emphasizing self-reliance, reducing expenses, and increasing income while maintaining responsibility towards the community and the environment. This holistic approach to sustainable agriculture not only fosters economic growth but also promotes environmental stewardship and community well-being.

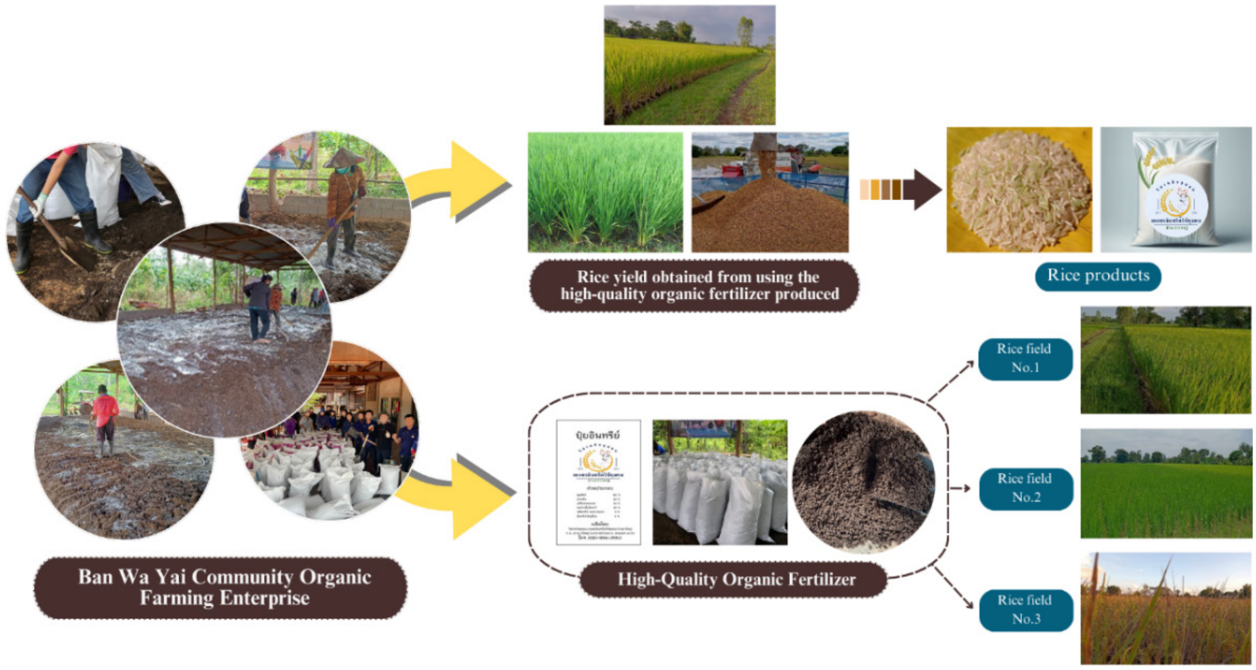

Figure 5 Diagram of the experimental use and development of high-quality organic fertilizer in rice farming by the Ban Wa Yai Community Organic Farming Enterprise.

Conclusions

The research on the development of high-quality organic fertilizers from biomass waste and the application of biochar in Sakon Nakhon Province, Northeastern Thailand, highlights significant advancements in sustainable agricultural practices. The fertilizers produced demonstrate a well-balanced nutrient profile essential for enhancing plant growth and soil health. Analysis revealed pH levels of 8.04 and 7.94 for fertilizers fermented for 15 and 30 days, respectively, indicating slight alkalinity that benefits the acidic soils of the Ban Wa Yai community. The GI results supported this, with a high value of 129 ± 1.86 after 30 days, the highest among the samples tested, confirming the effectiveness of these organic fertilizers in promoting plant vitality. The N, P, and K concentrations in the organic fertilizers not only meet but often exceed established organic product standards. This nutrient balance fosters increased microbial activity in the soil, crucial for nutrient cycling and overall soil vitality. Additionally, the incorporation of biochar significantly enhances the effectiveness of the fertilizers. Biochar's porous structure increases surface area for microbial colonization, improves water and nutrient retention, and reduces nutrient leaching, contributing to better soil structure and resilience against drought conditions. The research also indicated that OM and OC contents were approximately 40 - 60 % higher than those found in commercial fertilizers, promoting improved soil aeration and water retention. Furthermore, the Ca and Mg levels were found to be beneficial for ameliorating soil acidity. Overall, this research underscores the potential of high-quality organic fertilizers to enhance soil fertility and crop productivity while promoting a sustainable and economically viable agricultural model for local farmers, reducing fertilizer costs by an estimated 40 %. This research underscores the potential of utilizing local resources to create a circular economy, fostering self-reliance within the community while minimizing environmental impacts and promoting a sustainable approach to agriculture.

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References

[1] W Suphannachart. A review of agricultural research system in Thailand: The development, policies, institutions, investment patterns, and impact assessment. *Review of Integrative Business and Economics Research* 2015; **4(4)**, 63-89.

[2] A Tawatsin. Pesticides used in Thailand and toxic effects to human health. *Medical Research Archives* 2015; **3**, 176.

[3] W Laohaudomchok, N Nankongnaba, S Siriruttanapruk, P Klaimala, W Lianchamroon, P Ousape, M Jatiket, P Kajitvichyanukul, N Kitanah, W Siriwong, T Hemachudha, J Satayavivad, M Robson, L Jaacks, DB Barr, P Kongtip and S Woskie. Pesticide use in Thailand: Current situation, health risks, and gaps in research and policy. *Human and Ecological Risk Assessment* 2021; **27(5)**, 1147-1169.

[4] S Chaigarun, S Somboon and S Wanchana. Insecticide residues in Isan vegetable and local foods (*in Thai*). *KKU Journal for Public Health Research* 2013; **6(3)**, 122-129.

[5] TP Coulibaly, J Du and D Diakité. Sustainable agricultural practices adoption. *Agriculture* 2021; **67(4)**, 166-176.

[6] R Sapbamrer and A Thammachai. A systematic review of factors influencing farmers' adoption of organic farming. *Sustainability* 2021; **13(7)**, 3842.

[7] G Király, G Rizzo and J Tóth. Transition to organic farming: A case from Hungary. *Agronomy* 2022; **12(10)**, 2435.

[8] Y Suzuki, S Kamma, P Sookgul, N Chaichana and T Pakoktom. Effects of alternate wetting and drying water management and rice straw incorporation for sustainable rice production under dry season conditions in central Thailand. *Agriculture and Natural Resources* 2023; **57**, 437-446.

[9] J Kaweewong, T Kongkeawa, S Tawornprek, S Yampracha and R Yost. Nitrogen requirements of cassava in selected soils of Thailand. *Journal of Agriculture and Rural Development in the Tropics and Subtropics* 2013; **114(1)**, 13-19.

[10] Industry Outlook 2023 - 2025: Chemical fertilizer, Available at: https://www.krungsri.com/en/research/industry/industry-outlook/chemicals/chemical-fertilizers/io/io-chemical-fertilizers-2023-2025, accessed September 2024.

[11] PM Carr, MA Cavigelli, H Darby, K Delate, JO Eberly, HK Fryer, GG Gramig, JR Heckman, EB Mallory, JR Reeve, EM Silva, DH Suchoff and AL Woodley. Green and animal manure use in organic

field crop systems. *Agronomy Journal* 2020; **112**, 648-674.

[12] B Ali, GA Shah, B Traore, SAA Shah, SUS Shah, SGM Al-Solaimani, Q Hussain, N Ali, K Shahzad, T Shahzad, A Ahmad, S Muhammadi, GM Shah, M Arshad, RA Hussain, JA Shah, A Anwar, MW Amjid and MI Rashid. Manure storage operations mitigate nutrient losses and their products can sustain soil fertility and enhance wheat productivity. *Journal of Environmental Management* 2019; **241**, 468-478.

[13] A Loss, RDR Couto, G Brunetto, MD Veiga, M Toselli and E Baldi. Animal manure as fertilizer: Changes in soil attributes, productivity and food composition. *International Journal of Research - Granthaalayah* 2019; **7(9)**, 307-331.

[14] N Rayne and L Aula. Livestock manure and the impacts on soil health: A review. *Soil Systems* 2020; **4(4)**, 64.

[15] A Kaufman and S Watanasak. Farmers and fertilizers: A socio-ecological exploration of the alternative agriculture movement in Northeastern Thailand. *Environment and Natural Resources Journal* 2011; **9(3)**, 1-11.

[16] C Virochsaengaroon, C Piratanatsakul, P Lawongsa and TS Sukitprapanon. Rice farmers' perceptions and behaviors on nitrogen fertilizer applications for RD6 glutinous rice cultivation in Northeast Thailand. *In*: Proceedings of the 7th National Soil and Fertilizer Conference 2022, Chiang Mai, Thailand. 2022, p. 340-351.

[17] A Inthasin, P Klanarong and C Chaiprasert. The impact of rising fertilizer costs on smallholder oil palm farmers in Thailand. *Agricultural Systems* 2023; **92(2)**, 458-470.

[18] M Yothong, L Phimphan and T Laoprapa. A study of household agricultural expenses and the role of fertilizers in crop yield improvements in Sakon Nakhon Province. *Northeastern Agricultural Review* 2024; **48(1)**, 97-108.

[19] I Finore, A Feola, L Russo, A Cattaneo, PD Donato, B Nicolaus, A Poli and I Romano. Thermophilic bacteria and their thermozymes in composting processes: A review. *Chemical and Biological Technologies in Agriculture* 2023; **10**, 7.

[20] EE Ammar, HA Rady, AM Khattab, MH Amer, SA Mohamed, NI Elodamy, A AL-Farga and AAA Aioub. A comprehensive overview of eco-friendly bio-fertilizers extracted from living organisms. *Environmental Science and Pollution Research* 2023; **30**, 113119-113137.

[21] W Roschat, S Donrussamee, P Smanmit, S Jikjak, T Leelatam, S Phewphong, K Namwongsa, P Moonsin and V Promarak. Quality improvement of crude glycerol from biodiesel production using activated carbon derived from Krabok (Irvingia malayana) seed shells. *Korean Journal of Materials Research* 2024; **34(1)**, 1.

[22] W Roschat, P Butthichak, N Daengdet, S Phewphong, T Kaewpuang, P Moonsin, B Yoosuk and V Promarak. Kinetics study of biodiesel production at room temperature based on eggshell-derived CaO as basic heterogeneous catalyst. *Engineering and Applied Science Research* 2020; **47(4)**, 361-373.

[23] NN Gurusamy, N Puffer, CD Jongh, CR Gil and TJ Aspray. Effect of initial moisture content and sample storage duration on compost stability using the ORG0020 dynamic respiration test. *Waste Management* 2021; **125**, 215-219.

[24] A Makan, O Assobhei and M Mountadar. Effect of initial moisture content on the in-vessel composting under air pressure of organic fraction of municipal solid waste in Morocco. *Iranian Journal of Environmental Health Science & Engineering* 2013; **10(1)**, 3.

[25] A Singh, P Kumar and S Raj. Microbial dynamics and compost quality: Evaluating the effect of fermentation time. *International Journal of Agricultural Science* 2023; **54(2)**, 312-325.

[26] C Lee, J Park and K Kim. The impact of fermentation duration on nutrient release in organic fertilizers. *Journal of Environmental Science and Technology* 2022; **71(4)**, 98-107.

[27] M Patel, D Sharma and R Nair. Standardized methods for analyzing compost quality during different stages of fermentation. *Agricultural Research* 2023; **62(1)**, 145-155.

[28] Y Xie, C Li, H Chen, Y Gao, T Vancov, B Keen, LV Zwieten, Y Fang, X Sun, Y He, X Li, N Bolan, X Yang and H Wang. Methods for quantification

of biochar in soils: A critical review. *CATENA* 2024; **241**, 108082.

[29] DLD Carmo, LBD Lima and CA Silva. Soil fertility and electrical conductivity affected by organic waste rates and nutrient inputs. *Revista Brasileira de Ciência do Solo* 2016; **40**, e0150152.

[30] B Ernest, A Eltigani, PZ Yanda, A Hansson and M Fridahl. Evaluation of selected organic fertilizers on conditioning soil health of smallholder households in Karagwe, Northwestern Tanzania. *Heliyon* 2024; **10**, e26059.

[31] AOAC International. *AOAC 955.04, Nitrogen (total) in fertilizers*. Official Methods of Analysis of AOAC International, 2019.

[32] G Bekele, N Dechassa and T Tana. Effect of inorganic and organic fertilizers on productivity of groundnut (*Arachis hypogaea* L.) varieties in East Hararghe, Eastern Ethiopia. *Oil Crop Science* 2022; **7(3)**, 112-121.

[33] CK Tangga, H Mohidin and S Abdullah. The effect of empty fruit bunch (EFB) compost and *Trichoderma* biofertilizer on growth and yield performance of chili (*Capsicum annuum* L. var. Kulai). *IOP Conference Series Earth and Environmental Science* 2022; **1114**, 12070.

[34] GAP Standards for Organic Agriculture, Available at: https://www.acfs.go.th/standard/download/eng/ GAP_ organic_1.pdf, accessed September 2024.

[35] WGO Solomon, RW Ndana and Y Abdulrahim. The comparative study of the effect of organic manure cow dung and inorganic fertilizer N.P.K on the growth rate of maize (*Zea Mays* L). *International Research Journal of Agricultural Science and Soil Science* 2012; **2(12)**, 516-519.

[36] M Sbizzaro, SC Sampaio, RRD Reis, FDA Beraldi, DM Rosa, CMBDF Maia, CSDCMDS Cordovil, CTD Nascimento, EAD Silva and CE Borba. Effect of production temperature in biochar properties from bamboo culm and its influences on atrazine adsorption from aqueous systems. *Journal of Molecular Liquids* 2021; **343**, 117667.

[37] A Tomczyk, Z Sokołowska and P Boguta. Biochar physicochemical properties: Pyrolysis temperature and feedstock kind effects. *Review of Environmental Science and Bio/Technology* 2020; **19**, 191-215.

[38] Y Ding, Y Liu, S Liu, Z Li, X Tan, X Huang, G Zeng, L Zhou and B Zheng. Biochar to improve soil fertility: A review. *Agronomy for Sustainable Development* 2016; **36**, 36.

[39] J Nepal, W Ahmad, F Munsif, A Khan and Z Zou. Advances and prospects of biochar in improving soil fertility, biochemical quality, and environmental applications. *Frontiers in Environmental Science* 2023; **11**, 1114752.

[40] YS Ok, SS Lee, WT Jeon, SE Oh, ARA Usman and DH Moon. Application of eggshell waste for the immobilization of cadmium and lead in contaminated soil. *Environmental Geochemistry and Health* 2011; **33(S1)**, 31-39.

[41] JSDO Spelta and AGDS Galdino. Bioceramic composite: Hen's eggshell characterization and main applications. *Revista Ifes Ciência* 2018; **4(1)**, 9-20.

[42] X Wei, B Xie, C Wan, R Song, W Zhong, S Xin and K Song. Enhancing soil health and plant growth through microbial fertilizers: Mechanisms, benefits, and sustainable agricultural practices. *Agronomy* 2024; **14(3)**, 609.