

## Optimizing a Biowaste Treatment Design for Energy and Environmental Efficiency of an Integrated Farming System in Tien Giang Province

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### ABSTRACT

Agricultural wastes can be converted into biofuels. To meet the requirements of biofuels, the conditions of their manufacturing process for these products must be considered. The purpose of this research is to optimize experimental designs for converting biomass into energy products like pyrolysis and pelleting process. The products were optimized in terms of their energy performance while lowering CO<sub>2</sub> emissions. In Tien Giang province, we experimented with pyrolysis and pelleting biowastes derived from an integrated farming system in acid sulfate soil. The experimental factors influencing the energy content of products were determined using statistical analysis and optimization methods, and the potential CO<sub>2</sub> emissions from the products were calculated. The optimization results revealed that the ideal pyrolysis parameters were 120 minutes of combustion time at 400°C and 30% moisture content of orchard pruning residues. The best pellets were obtained by combining biogas sludge and biochar from mango pruning residues. These products will store approximately 900 kilograms of CO<sub>2</sub> emissions a year. The optimized processes would benefit the environment and bring profits to the system.

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## 1. Introduction

Biofuels were defined as combustible materials derived from plant and animal biomass waste [1], [2]. Using the right technologies, biowastes were converted into a form of clean and useful energy [3], a renewable and promising source of fuels through a specific processing [4]. These secondary fuel products were produced from various biomass sources using various treatment processes [5]. Pyrolysis is said to be the most advanced thermochemical process for biomass under non-oxidizing conditions, producing high-energy products such as biochars [2], [4], [6] – [11] while pelleting is a way to enhance the energy content of biomass. These techniques are feasible to be applied at a small-scale integrated farming household.

Biochars and biomass pellets bring environmental benefits [2], [12] – [14]. Thus, we considered producing biochars and fuel pellets from biosolid wastes of the integrated farming system (IFS). This system is popular for farmers in the Mekong Delta which is composed of production components mainly of livestock, orchard/or crop field, fishpond which generates a plentiful supply of biosolid wastes [15] – [19]. Most research on pyrolysis took place in pilot experiments and/or laboratories. In the pyrolysis literature, branches and leaves of cherry trees, chestnut trees, oak trees, almond trees, apple trees [20], apple, pear, and plum [21], and mango leaves [11] were studied. Mango trees, jackfruit trees, and banana trees can thrive in acidic soil. They require additional research on their energy products.

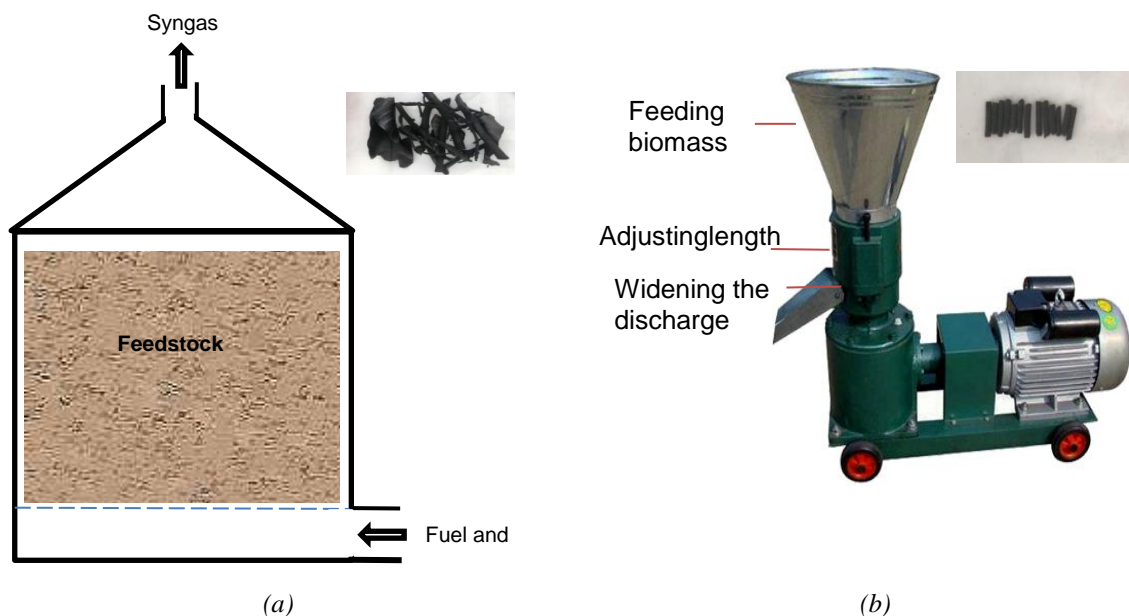
Therefore, we conducted on-field experiments on pyrolysis and pelleting some types of biowaste from productive components of an integrated farming household in acid sulfate soil in Tien Giang province. The process focuses on producing energy products with the highest energy content of energy

products and lowest CO<sub>2</sub> emissions. Factors that influence the pyrolysis and pelleting processes would be used as variables of experimental optimization for the energy content of biochar and pellet products. The optimization functions' goals are to maximize energy and minimize emissions in output products of the two processes.

## 2. Materials and Methods

### 2.1. Materials

The experiments were carried out in an acidic soil area of Tien Giang province (10°34'45" N, 106°12'12" E) of the Mekong Delta at a farming household using a system of Orchard-Pig shed-Biogas tank (V-A-B in Vietnamese). The total land area was 2,000 m<sup>2</sup>, which included a pig shed and a 1,000 m<sup>2</sup> orchard with various fruit trees such as mango trees, jackfruit trees, and banana trees. The average annual income of a household was less than 2 million VND per month. Figure 1 depicts the designs for biomass pyrolysis and pelleting, as well as their products. They are a charcoal oven and pelleting machine that have been chosen to supplement the current farming system. They should be compatible with the income levels of farming households. Orchard pruning residues were used as feedstocks for the pyrolysis process, while animal manure, compost from manure, and biogas sludge were used for the pelleting process. Compost was also used as a pelleting feedstock to supplement the other pellets in the system. However, while pelleting, manure and compost would emit a foul odour. Because only their blends could reduce odour [22] – [24], we used these mixtures as pellet feedstock in our research. The pyrolysis technology was a forty-liter charcoal oven for 4-6 kg of biomass per operation, which corresponded to an orchard scale of less than 5,000 m<sup>2</sup>. The oven's combustion temperature ranged between 300°C and 400°C. Pelleting machines produced cylindrical pellets with diameters of 3 mm, 5.5 mm, and 8 mm and lengths of 20 mm. In this study, the biomass-biochar mixtures mentioned above were used as pellet feedstock. The mixtures were dried to a moisture content of 10% to 15% to improve pellet adhesion.



**Figure 1.** (a) Pyrolysis and (b) pelleting design and products

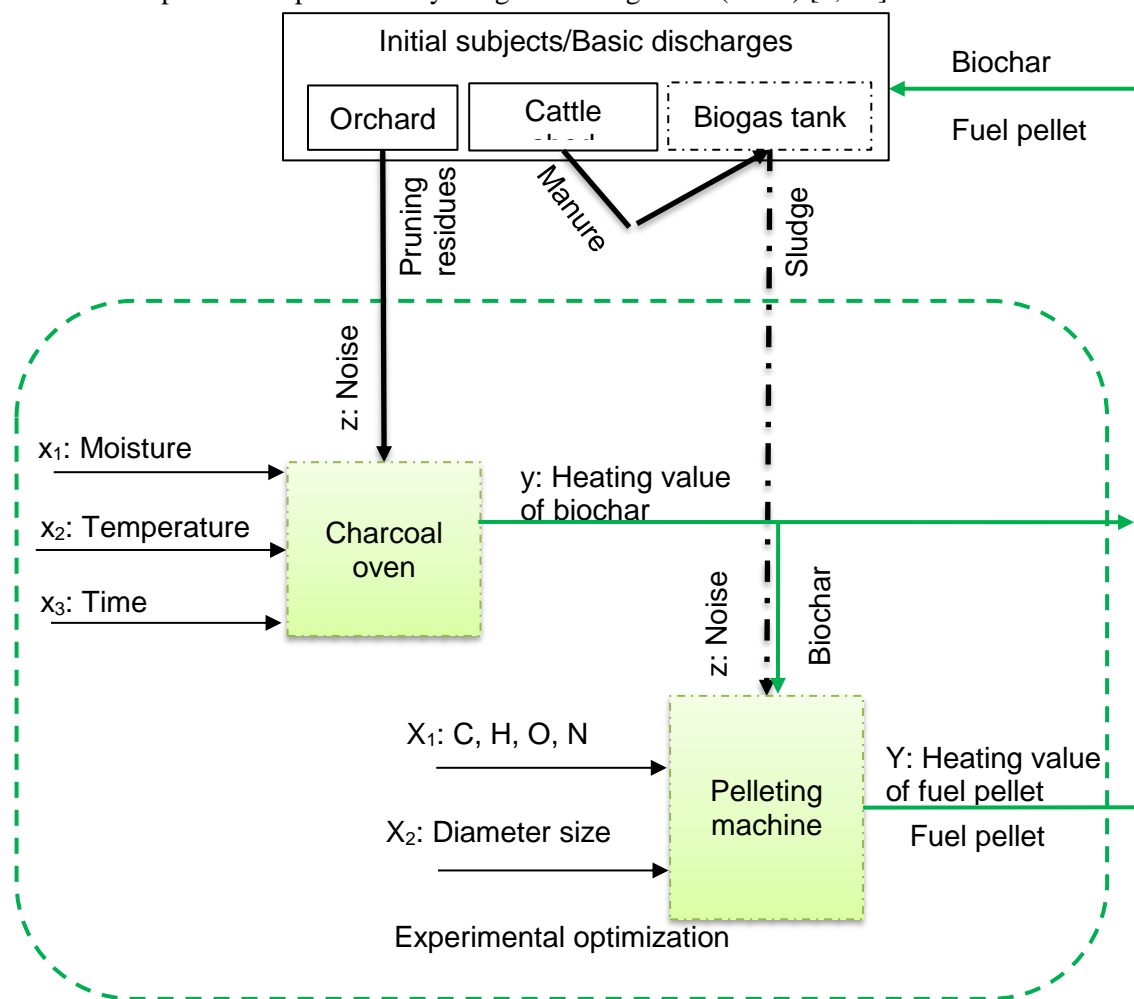
### 2.2. Methods

Figure 2 depicts the research framework for optimizing biomass treatment processes to generate energy products for the IFS. To calculate objective functions, an empirical model was built based on the

input parameters (or variables  $x_j$ ). The regression equation was used to express this model after preliminary analysis of experimental parameters. It was predicted as objective function  $y$  as:

$$y = f(x_1, x_2, \dots, x_k) + z \quad (1)$$

Where  $z$  (noise) was an undefined and uncontrolled random variable [20] as described in Figure 2. Combustion temperature, heating rate, pellet diameter size, and moisture content of biomass feedstock are all parameters that must be optimized in the pyrolysis and pelleting processes. The moisture content of orchard pruning residues was typically 30% after open-air drying. The moisture content of the feedstock for pelleting was 10-15%. These parameters were optimized using statistical analysis software such as Excel and Minitab. Experimental optimization must achieve functional objectives such as maximizing the energy content of output products while minimizing  $\text{CO}_2$  emissions. The energy content of biochars and pellets is represented by a higher heating value (HHV) [4, 25].



**Figure 2.** Research framework on optimization of solid waste flows within an integrated agricultural system

Another method is to use Dulong's formula to calculate HHV based on the content of carbon (C), hydrogen (H), nitrogen (N) [26], and oxygen (O) [25] in the biomass. The formula is as follows [25, 27]:

$$HHV = 0.3383C + 1.442(H - O/8) \quad (2)$$

Thus, our research would derive a formula for HHV using analytical results on these elements of output products produced by experiments. To consider its application, this formula will be compared to Dulong's formula.

In addition, the carbon content of biochars and pelleting products corresponds to the content of CO<sub>2</sub> emissions, implying that carbon-containing biomass pellets sequester CO<sub>2</sub>. The calculation of CO<sub>2</sub> in biomass is shown by the equation as [27, 28]:

$$\text{Carbon dioxide emission } \left(\frac{\text{kg}}{\text{MJ.yr}}\right) = \frac{\text{Biochar or pellet yield } \left(\frac{\text{kg}}{\text{yr}}\right) \times \text{Carbon in biochar or pellet } \left(\frac{\%}{\text{w}}\right) \times \frac{44}{12}}{\text{HHV of biochar or pellet (MJ)}} \quad (3)$$

The natural conditions of the area, as well as household income, were constraints to the IFS's efficiency. By utilizing the majority of biowastes to produce potential energy products, the optimized processes would benefit the environment and household livelihoods. Biochars and pellets would be circulated through this system as inputs/feedstock for the farming components.

### 3. Results and Discussion

The number of experiments on pyrolysis based on influencing parameters was estimated by the statistical analysis software Minitab 16. Experimental optimization was performed at the lowest and highest levels of three variables: moisture content (30%; 50%), combustion time (120 minutes; 160 minutes), and combustion temperature (300°C; 400°C), all of which were coded by (0; 1). The allocation of these levels resulted in the eight biochar samples shown in Table 1.

**Table 1.** Experimental designs of parameters for HHV of biochar

Sample	Moisture	Combustion time	Temperature
C1	0	0	0
C2	0	0	1
C3	0	1	0
C4	0	1	1
C5	1	0	0
C6	1	0	1
C7	1	1	0
C8	1	1	1

These designs were applied for pyrolyzing the orchard pruning residues of the system. When compared to other tree pruning residues, biochars from mango tree pruning residues have the highest energy content. Their HHVs matched those found in the studies of [29, 30]. All parameters were statistically significant at  $p < 0.05$ , according to the ANOVA analysis for these experiments (as expressed in Table 2). The experimental results were consistent with a regression coefficient  $R^2$  of 0.94. The objective (y or HHV) for the pyrolysis process was expressed as a regression equation as follows:

$$y = 18.8 - 0.0495x_1 + 0.0271x_2 + 0.00660x_3 \quad (4)$$

Where y denotes HHV;  $x_1$ ,  $x_2$ , and  $x_3$  denote the moisture content of mango tree pruning residues, combustion time; and combustion temperature, respectively.

**Table 2.** Results for experiments of pyrolysis mango tree pruning residues

Source	Seq SS	Adj SS	Adj MS	F	P
Moisture	1.9602	1.9602	1.9602	24.93	0.008
Combustion time	2.3544	2.3544	2.3544	29.95	0.005
Combustion temperature	0.8712	0.8712	0.8712	11.08	0.029
Error	0.3145	0.3145	0.0786		

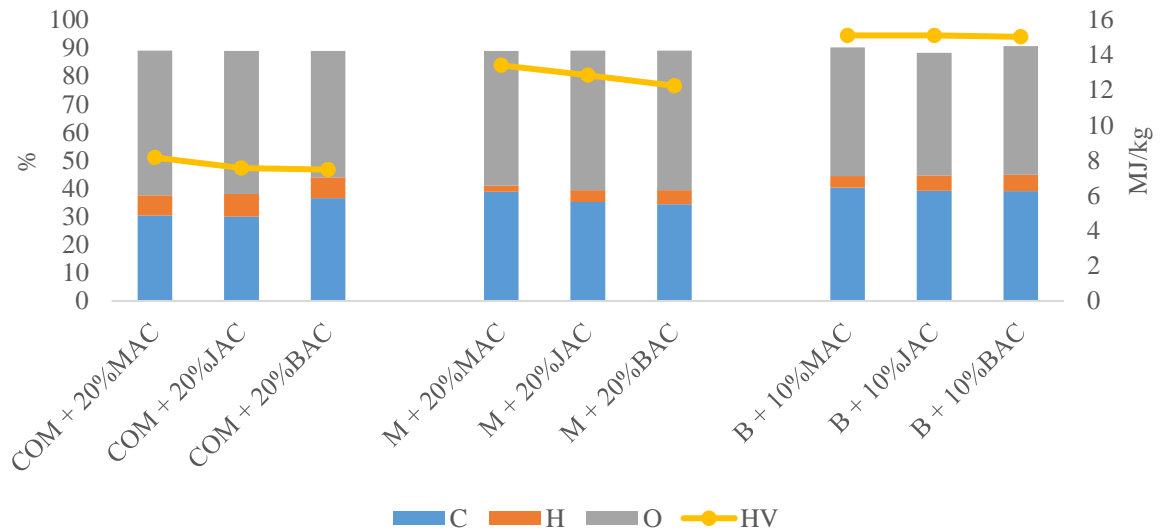
Using Minitab’s Taguchi analysis to determine the ideal factors for the highest HHV of biochars, the results show that the combustion time ranked first, followed by moisture, and then by the temperature at levels of 160 minutes, 30%, and 400°C, respectively. They proposed C4 parameters that would result in the best HHV performance. Biochars from this allocation also produced the least amount of CO<sub>2</sub> based on the C content of biochars from the designs in Table 3. This amount is comparable to C2, C3, and C8.

**Table 3.** Estimated CO<sub>2</sub> emissions of biochars of mango tree pruning residues in pyrolysis experiments

Sample	HHV (MJ/kg)	C (%)	CO <sub>2</sub> (g/MJ)
C1	22.29	59.6	98
C2	23.46	60.96	95
C3	23.76	61.03	94
C4	23.98	61.25	94
C5	21.35	57.81	99
C6	22.24	59.54	98
C7	22.79	59.72	96
C8	23.15	60.5	96

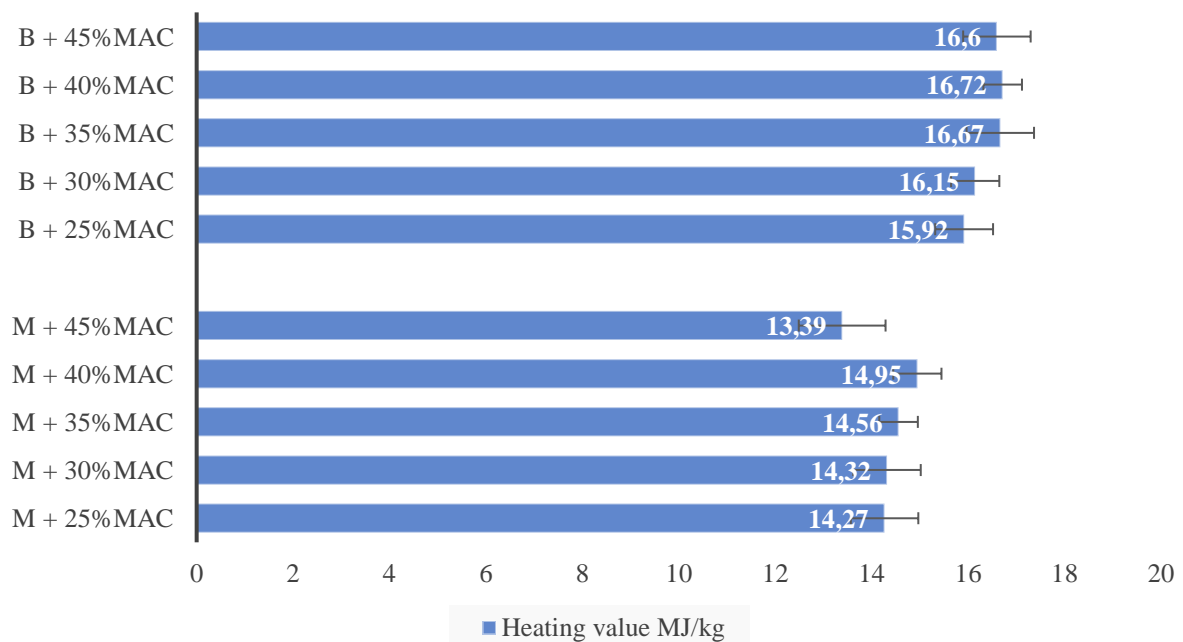
As feedstock, manure, compost, biogas sludge, and biochar were used as materials for pelleting. As previously stated, manure and compost emit foul odors; combining them with biochar would reduce odor release. The proportions and diameter sizes of the mixtures influence their HHV and CO<sub>2</sub> emissions potential. As a result, their contribution to the biomass mixture would be reduced. Biochars acted as binders in the mixtures, so their impact was minimal. These deployments yielded an optimal fraction of biogas sludge, manure (or compost), and biochar ranging from 50 to 90 percent, 10 to 50%, and 10 to 50%, respectively.

Figure 3 depicts the HHVs of feedstock for pelleting. Manure, compost, or biogas sludge alone had low HHV, ranging from 10 to 15 MJ/kg, with compost having the lowest HHV. The highest HHV was found in biomass-biochar mixture pellets. When the biochar fractions in the pellet ranged from 10% to 20%, the HHV was low. HHV levels increased between 30 and 50 percent, then met the standard HHV for biofuels (above 16 MJ/kg), which is consistent with the literature [2] – [31]. By combining biochar from mango pruning residues (MAC) and other biomass, they were able to achieve the highest energy content in their pellets.



**Figure 3.** HHV graph of combining pellets with 10% to 20% biochar in mixtures. COM: Compost; M: Manure, B: Biogas sludge; MAC: Biochar of mango pruning residues; BAC: Biochar of banana pruning residues; JAC: Biochar of jackfruit pruning residues

The graph in Figure 4 shows that mixing MAC pellets with biogas sludge yielded the highest energy content.



**Figure 4.** HHV graph of mixing pellets with over 20% of additives in mixtures

According to Figures 3 and 4, the sludge-MAC mixtures produced the pellets with the highest HHV, with a sludge fraction ranging from 60% to 90% and a MAC ratio ranging from 10% to 40% in the mixtures. The proportion of N in the mixtures was lower than the proportions of C, H, and O (as shown in Table 4). As a result, the elements of C, H, and O in these mixtures revealed a linear equation with a p-value of 0.05 and a high correlation  $R^2 > 0.80$  as equation (4).

$$HHV = 11.7 + 0.147C + 0.310H - 0.0702O \quad (4)$$

When Dulong's formula is applied to the elements of these pellets, the results show that it has a low correlation with them ( $R^2 < 0.75$ ). As a result, equation (4) was appropriate for pellets from the experiments in this study. These pellets produced the least CO<sub>2</sub> according to the CO<sub>2</sub> emission calculation from equation (4).

**Table 4.** Energy content and estimated CO<sub>2</sub> emissions of biomass pellets

Mixture	Average HHV (MJ/kg)	CO <sub>2</sub> (g/MJ)
Manure and biochar	14.19	102
Biogas sludge and biochar	16.40	96
Manure and biogas sludge	13.98	94

Aside from the components, the diameters of the pellets affect their HHVs as well as the amount of CO<sub>2</sub>. The ratios of sludge-MAC mixture with diameter were assigned using Minitab's Taguchi design; the ratios were 1.5, 2.1, and 3, and the diameters were 3 mm, 5 mm, and 8 mm, respectively. These variables have been encoded (-1; 0; 1). Table 5 shows the optimization results for these assignments. These mixtures had a high level of significance ( $p < 0.05$ ,  $R^2 > 0.9$ , and R-predicted  $> 0.8$ ). However, neither the mixing ratio nor the diameter size had any effect on the HHV of the pellet.

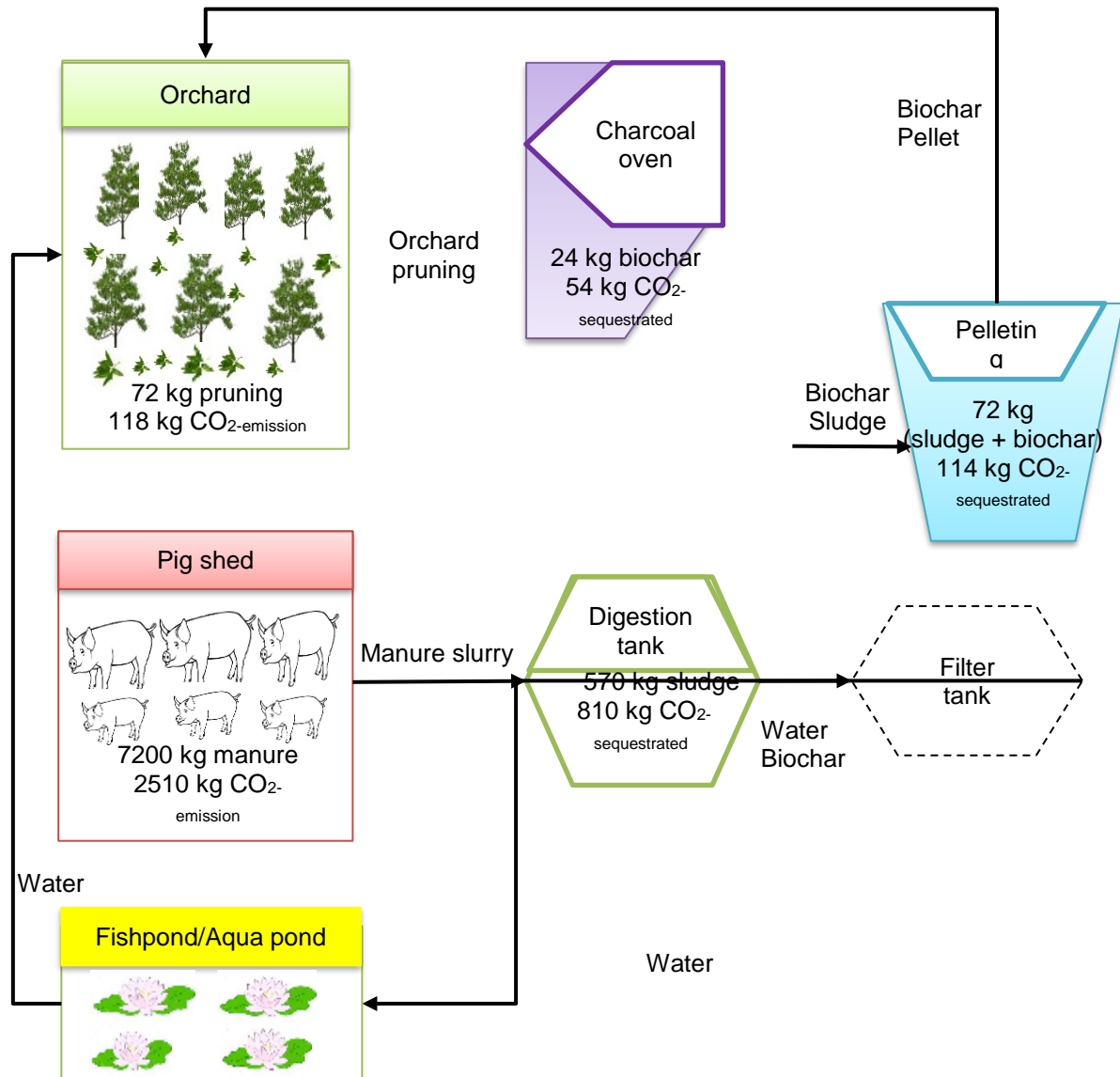
Based on the results in Table 3-5, we can conclude that the MAC biochar was the best product. It was designed with the optimizing parameters of a 30% moisture input feedstock, a 400°C oven heating temperature, and a 160-minute combustion rate. Furthermore, with biogas sludge and MAC blend feedstock, the best pellets had the largest diameter (8 mm). When used, these biochars and pellets gained the most HHV and potentially released the least CO<sub>2</sub>.

**Table 5.** Results of biomass pellets with diameter sizes and mixing ratios

No.	Mix Ratio (%/%)	Diameter (mm)	HHV (MJ/kg)	C (% w/w)	CO <sub>2</sub> (g/MJ)
1	-1	-1	16.95	46.32	100
2	-1	0	16.76	45.79	100
3	-1	1	16.32	43.2	97
4	0	-1	16.67	45.6	100
5	0	0	16.54	44.61	99
6	0	1	16.44	43.01	96
7	1	-1	15.56	41.14	97
8	1	0	15.34	40.56	97
9	1	1	15.15	39.85	96

Biochars and pellets have the potential to improve the acidic soil quality [32-36]. They also supplied secondary biofuels in the integrated V-C-B system (Figure 5), and have the potential to reduce waste load and CO<sub>2</sub> emissions. Pyrolysis produced an average biochar yield of 35%, producing approximately 24 kg of biochar per year and storing 54 kg of CO<sub>2</sub> emissions. This amount of CO<sub>2</sub> would be two times

lower than that of naturally decomposed orchard residues. Furthermore, the pig shed produced 7200 kg of manure volume per year (20% volatile matter in dry matter), resulting in an 811 kg reduction in CO<sub>2</sub> emissions [37]. Their market value is more than five times that of compost. Then they could bring in a steady stream of profits to supplement the family's income.



**Figure 5.** Optimal circulation of waste flows in an integrated system

Converting agricultural wastes into useful products such as fertilizers and/or biofuels would benefit household farming systems in general. Because of their high market price, biofuels are the better option for recycling. However, the households in this area faced difficulties due to the inefficiency of modern facilities' operation and the high cost of modern facilities. Furthermore, substances that can be used as additives or binders to increase the energy content of pellets require further investigation.

#### 4. Conclusions

Agricultural wastes were used in an integrated V-C-B household system within acidic soil in this study. Pig manure, orchard residues, and biogas sludge were used as feedstock for pyrolysis and pelleting processes to produce biofuels. The experimental designs were optimized for both pyrolysis

orchard pruning residues into biochars and pelleting biomass from biochars and other wastes. The experimental optimization sought to maximize the energy content (HHV) of biochars and pellets while emitting the fewest CO<sub>2</sub> emissions when these biofuels were burned. The ideal parameters influencing the optimal goals for the pyrolysis and pelleting processes were determined using statistical analysis. The ideal pyrolysis parameters were a moisture content of 30% in orchard pruning residues, and a combustion time of 120 minutes in the oven at a temperature of 400°C. The best pellets were obtained by combining biogas sludge and MAC. Biofuel products could also be used as fertilizers in agriculture to improve acidic soil.

### Abbreviation

B: Biogas sludge; BAC: Biochar of banana pruning residues; C: Carbon; CO<sub>2</sub>: Carbon dioxide; COM: compost; H: Hydrogen; HHV: Higher heating value; JAC: Biochar of jackfruit pruning residues; M: Manure; MAC: Biochar of mango tree pruning residues; N: Nitrogen; O: Oxygen; V-C-B: Orchard-Pig shed-Biogas tank.

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