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Article

# Biochar Utilization to Sustain Rice Cultivation in Taiwan: A Review

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**Abstract:** The responses of rice production and pyrolysis-based biochar in Taiwan are reviewed as biochar is an available soil amendment alternative. We examine how biochar addition to the rice field would influence rice planted areas in Taiwan due to crop yield increase. The result provides insights into biochar utilization and changes in current rice cultivation activities with a modified Taiwanese agricultural model. The area of higher rice yields increases while the lower output area decreases. Plant location also influences the change in area. With a change in plant location, rice plantations change considerably. While most biochar is used in southern and central Taiwan, the results vary depending on where the pyrolysis plant is built and the transportation cost. Climate change might have substantial influences on Taiwan's rice production.

**Keywords:** Biochar, Rice Cultivation, Taiwan

## 1. Introduction

Bioenergy, specifically biofuel and biopower, is widely promoted and produced in many countries including Brazil, the USA, and European Union. Several forms of biomass such as energy crops, agricultural residuals, municipal solid wastes, and animal manure are treated as renewable energy resources (TMOEA, 2018). However, biofuel is criticized because it sometimes emits more greenhouse gases (GHG) than it offsets. Under the circumstance, pyrolysis which grabs carbon from the air is considered an attractive alternative. Specifically, pyrolysis is to heat biomass without the existence of oxygen and results in the decomposition of biomass into different byproducts to generate biopower and sequester carbon. Therefore, there are multiple approaches to utilizing biomass to mitigate climate change and sustain energy supply. Biochar is a typical byproduct of pyrolysis to increase the productivity of land and protect the environment. It is stabilized in soil (Lehman et al., 2003) and enhances crop yields owing to its properties of retaining nutrients (Chan et al., 2007). Moreover, it reduces environmental $CO_2$ concentration (Lehmann, 2007).

Since Taiwan imports more than 97% of its energy (Chen et al., 2011) and the nuclear power plants play an important role in electricity production, reliable renewable energy sources reduce the dependency on foreign fossil energy and alleviate the disequilibrium of the world energy market. Thus, based on the urgent need of Taiwan's situation, this study is carried out to seek for approaches to improve renewable energy production. Since pyrolysis is considered an effective way to stabilize biopower production, and biochar is useful to sustain agricultural practice under climate impacts, it is useful for future agricultural and renewable energy policies.

We review the response of Taiwan's rice cultivation when pyrolysis-based biochar becomes an available soil amendment alternative. In this study, with biochar as a soil additive, the change in rice planted areas of Taiwan is investigated in terms of crop yield increase. The results provide useful information on how biochar utilization affects the current rice cultivation activities to redesign and promote existing agricultural policies and how climate influence makes difference in current agricultural practices and provides the stability of feedstock supply that can be transferred to future renewable uses.

## 2. Materials and Methods

Fast pyrolysis is one of the decomposition processes of biomass which involves treating the feedstocks with moderate temperatures. In this stage, the particle of biomass experiences high heat transfer and a relatively short hot vapor heating time in the reactor turbine. According to Bridgwater et al. (1999), Huang et al. (2017), Liu et al. (2017), and USDOE (2005), parameters such as environmental temperatures, a heating rate of biomass, environmental pressure are likely to change the rate of decomposition and the output yields during this process. Wright et al. (2008) and Ringer et al. (2006) further pointed out that configurations of reactors have impacts because their conditions may make the fuel production up to seventy-five percent based on the weight of dried biomass (Bridgwater et al., 1999; Khan and Bakar, 2020).

Based on the USDOE's 2005 report, a few fast thermal decomposition modules have become a near-commercial stage before 2000, in which a plant treats more than fifty tons of biomaterials. These plants are generally located in the U.S.A., north Canada, and western Europe. There are also several small-scale plants employing thermal pyrolysis. Slow pyrolysis is much different from the characteristics of fast pyrolysis and is popular due to much substantial amount of biochar production. Wright, Brown, and Boateng (2008) showed approximately 15% of black char, 70% of raw oil, and about 30% of syngas can be produced by fast pyrolysis. However, Ringer, Putsche, and Scahill (2006) argued that about 35% of the biomass would end up in charcoal, one-third in low-class oil, and the rest would be ended up in flammable gases.

Nevertheless, the USDOE's report in 2005 showed that the factors including the types of characteristics of biomass, the working conditions of reactors, and the efficiency associated with material collection and transportation are likely to affect the output ratios of the modules. For example, Bridgwater and Peacocke (2000) proved that two-thirds, one-eighth, and one-eighth of synoil, syngas, and black char, respectively, would be produced under the uses of Aspen. Additionally, Radlein (2007) illustrated the production of black charcoal can be greatly increased if the bark biomass is used to replace the choices of bagasse and straw of wheat. However, with raw oil production, it is better to use bagasse than the other two possibilities.

The operation produces synoil, syngas, and black char. Conventionally, the synoil and black charcoal are used in energy production, and the char has alternative usages such as additives to soil for enhancing land productivity, which is studied widely in recent years. This application is not a new concept because the simple application was conducted several thousand years ago. For example, the existence of black charcoal was observed by Sombroek et al. (2003) and Erickson et al. (2003) indicating the applications of the charcoal were much longer before the arrivals of native populations and were applied for habitation activities and soil. In addition, the use of biochar is useful in the improvement of retaining soil nutrients. As presented by Deluca et al. (2009), there might exist a potentially unclear mechanism that makes a nutrient transformation between the charcoal and soil. For example, they showed that the carbon available for bioresources attaches to the surfaces of biochar and consequently decreases the nitrates formed from the immobilization process in the face of charcoal stimulation of nitrification. Under such circumstances, applying black charcoal with conventional nitrate fertilizers to soil benefits in terms of fertilizer linkage and crop growth. Moreover, the availability of short-term impacts on nitrogen by biochar application may last from hundreds to thousands of years.

Chan et al. (2007) showed that biochar implementation may not enhance the increase in the yield of crops like radishes when fertilizer with nitrogen was not employed. They showed that the fertilizer interaction between charcoal and nitrogen component may be substantial, and the growth of the plant may be more efficient from this dual application. In their experiments, the yield of radishes might be improved from 95 to up to 266%, in terms of the weight of dry material with different rates of charcoal uses (i.e., under ten, fifty, and one hundred tons per hectare). Applications of black char and similar products like the ash from a volcanic explosion in the production of crops were intensively investigated since 2000 (Liu et al., 2019; Glaser et al., 2002; Steiner et al., 2007). Many crops such as corn, green bean, soybean, and certain types of trees have been analyzed by scholars for using black char. The results indicate no general agreement among the experiments about the application rates of black charcoal. This may be due to either the difference in geographical condition or other unobservable factors.

In this study, we utilize the agricultural sectoral model that has been modified to fit the condition of Taiwan (TASM) that was proposed by Chen and Chang (2005). The model contains more than sixty crops that are conventionally planted, five crops related to floral species, seven to livestock, three trees, and twenty-seven secondary commodities. In general, these products consist of more than 85% of the total value of Taiwanese agricultural production. Additionally, each of the commodities is specified for subregional activities. The model is applied to the mixtures of crops and animal species, but other constraints such as markets associated uses are separately denoted under the regional level.

$$Max \ \ \sum_i \int \psi(Q_i)\, dQ_i - \sum_i \sum_k C_{ik} X_{ik} - \sum_k \int \alpha_k(L_k) dL_k - \sum_k \int \beta_k(R_k) dR_k + \sum_i P_i^G * Q_i^G + \sum_k P^L * AL_k + \sum_j \sum_k SUB_j * EC_{jk} + \sum_i \int ED(Q_i^M) dQ_i^M - \sum_i \int ES(Q_i^X) dQ_i^X - \sum_i \sum_k C_{ik}^R * Q_{ik}^R + \sum_i \int EXED(TRQ_i) dTRQ_i + \sum_i [tax_i * Q_i^M + outtax_i * TRQ_i] - P_{GHG} * \sum_g GWP_g * GHG_g \tag{1}$$

$$Q_i + Q_i^X + Q_i^G - \sum_k Y_{ik} X_{ik} - \sum_j EC_{jk} X_{jk} - (Q_i^M + TRQ_i) \leq 0 \quad for\ all\ i \tag{2}$$

$$\sum_i X_{ik} + AL_k + \sum_j EC_{jk} - L_k \leq 0 \quad for\ all\ k \tag{3}$$

$$\sum_i f_{ik} X_{ik} - \sum_j f_{jk} X_{jk} - R_k \leq 0\ for\ all\ k \tag{4}$$

$$\sum_{i,k} E_{gik}\, X_{ik} - GHG_g \quad \le \; 0 \quad for\ all\ g \tag{5}$$

| | |
|---|---|
| $Q_i$ | Demand of the $i^{th}$ product in domestic |
| $Q_i^G$ | Quantity related to the government purchases of $i^{th}$ supported product |
| $Q_i^M$ | Quantity of the $i^{th}$ product to be imported |
| $Q_i^X$ | Quantity for the $i^{th}$ product that is exported |
| $Q_i^R$ | Quantity of the collected $i^{th}$ agricultural wastes |
| $\psi(Q_i)$ | Inversely expressed function for demand of the $i^{th}$ product |
| $P_i^G$ | Price used by government purchase on the $i^{th}$ product |
| $C_{ik}$ | Cost related to input purchase in $k^{th}$ region for $i^{th}$ product |
| $C_{ik}^R$ | Cost of collection and transportation of the $i^{th}$ wastes in $k^{th}$ region |
| $X_{ik}$ | Cropland to be used for $i^{th}$ commodities in $k^{th}$ region |
| $L_k$ | Land supply observed and available in $k^{th}$ region |
| $\alpha_k(L_k)$ | Land function expressed by the inverse supply in $k^{th}$ region |
| $R_k$ | Labor supply function found in $k^{th}$ region |
| $\beta_k(R_k)$ | Labor inverse supply estimated in $k^{th}$ region |
| $P^L$ | Set-aside subsidy proposed by the government |
| $AL_k$ | Set-aside acreage available in $k^{th}$ region |
| $SUB_j$ | Subsidy on planting $j^{th}$energycrop |
| $EC_{jk}$ | Planted acreage of $j^{th}$ energy crop in$k^{th}$ region |
| $ED(Q_i^M)$ | Inverse curve of excess import demand for $i^{th}$ product |
| $ES(Q_i^X)$ | Inverse curve of excess export supply for $i^{th}$ product |
| $TRQ_i$ | Import quantity more than the quota for $i^{th}$ product |
| $EXED(TRQ_i)$ | Inverse curve of excess demand for $i^{th}$ product with import quantity greater than quota. |
| $tax_i$ | Tariff of the imported good of $i^{th}$ product |
| $outtax_i$ | Tariff of out-of-quota for $i^{th}$ product |
| $Y_{ik}$ | Per hectare yield of $i^{th}$commodity produced in$k^{th}$ region |
| $E_{gik}$ | $g^{th}$ greenhouse gas emission from $i^{th}$ product in $k^{th}$ region |
| $P_{GHG}$ | Price of GHG gases |
| $GWP_g$ | Global warming potential of $g^{th}$ greenhouse gas |
| $GHG_g$ | Net greenhouse gas emissions of $g^{th}\ gas$ |
| Baselineg | Baseline emission of greenhouse gas of the $g^{th}\ gas$ |
| fik | Labor required per hectare of commodity iin region k |

## 3. Results

### *3.1. Product yield under pyrolysis*

Table 1 presents the product yields of sweet potatoes and poplar under different pyrolysis modules (McCarl et al., 2009). In general, more charcoal would be produced under the slow pyrolysis for biomasses, and bio-oil for the fast pyrolysis mode.

**Table 1.** Outputs from fast and slow pyrolysis

| | Output | Poplar | Sweet potato |
|---|---|---|---|
| Fast Pyrolysis | Biooil | 66% | 70% |
| | Biogas | 13% | 15% |
| | Biochar | 14% | 13% |

| | | | |
|---|---|---|---|
| Slow Pyrolysis | Biooil | 56% | 30% |
| | Biogas | 7% | 35% |
| | Biochar | 31% | 35% |

*3.2 Biopower production*

Table 2 shows the energy conversion rate under a per ton biomass basis. The power generation in Table 2 came from the use of bio-oil and bio-gas, and charcoal is not included because charcoal is used in soil for climate change mitigation. For this reason, we do not compute the electricity generated from the use of biochar but illustrate the potential energy content of charcoal to know its energy potential. The lower heating value of biochar is taken as 11.4 MJ $kg^{-1}$ (McCarl et al., 2009) and the electricity from burning biochar is 0.31–1.25 $MWh^{-1}$ for sweet potato and 2.82–3.4 $MWh^{-1}$ for poplar under different pyrolysis methods.

**Table 2.** Electricity from fast and slow pyrolysis (without burning biochar)

| Unit ($MWh^{-1}$) | Sweet Potato | Poplar |
|---|---|---|
| Fast Elec | 1.25 | 3.4 |
| Slow Elec | 0.31 | 2.82 |

Altogether the power potential is expressed in Table 3 where the biopower produced by the charcoal is included. However, if biochar is used in soil for agricultural benefits, the energy conversion rate is based on the results displayed in Table 2.

**Table 3.** Electricity from fast and slow pyrolysis (with burning biochar)

| Unit (MWh-) | Sweet Potato | Poplar |
|---|---|---|
| Fast Pyrolysis | 1.391 | 3.843 |
| Slow Pyrolysis | 1.420 | 3.801 |

*3.3 Site selection of operating plant*

It is necessary to decide where the plants are put before estimating transportation costs. The site selection greatly affects the transportation distances and costs. It is assumed that the charcoal used by the farmers is directly bought from the plant, and because the data show a cheaper cost of labor and construction in southern Taiwan, we further assume the plants are grown in this region. Specifically, the plant is located in Chiayi County and the producer later distributes the charcoal to the market across the country. Because biochar is flammable and considered a dangerous product, we increase the fixed cost associated with transportation by 50% and use this assumption to estimate the total cost.

In Chiayi County, the average distance of hauling black char is less than 10 km, and we estimate a distance of 25 km for the transportation to the next county. For instance, if we just send the char within the Chiayi, then the distance is 10 km, but it increases to 35 km if we send the char to counties like Yunlin, and 25 km longer to Changhua County. Therefore, the assumed longest distance from Chiayi to Ilan County is estimated as 210 km. Along with the information provided by McCarl et al. (2009), we create a crop budget. Taking all components into account, there are at least two cost components such as (1) the cost to farmers for buying the biochar and (2) the cost associated with the char transportation if we transport the char from the plant to the cropland. In recent years, the price of thermal char is about NT$1.7 per kg. As the energy content of black char is 60% less than that of thermal char, the price of the black char was set to NT$1.0 per kg.

*3.4 Influence of black char on agriculture*

Biochar would benefit agriculture if it is applied as a fertilizer. The benefits are categorized as follows. First, in terms of water holding capacity, Tryon (1948) pointed out that the moisture of the soil is greatly improved, especially for sandy soil. Moreover, scholars further demonstrated that 18% of soil water retention is enhanced if biochar is properly applied (Glaser et al., 2002). Therefore, we assume a 10% saving for irrigation. Second, in terms of crop yield enhancement, Lehmann (2007) indicated that available nutrients for the plants increase with black char. Thus, we assume the increases in crop yield with biochar (Glaser et al., 2002; Steiner et al., 2007).

Nehls (2002) showed that rice output increased by 115 to 320% of the paddy with 7.9 tons of biochar per year. Since this figure is too good to be real, we use a more conservative measure of 5% for the crop yield increase in the study region. Third, for the benefits associated with savings from seed and nutrients, we use the measures from Steiner et al. (2007).

Lehmann (2003) stated other environmental benefits of the use of biochar. For example, up to 60% of leaching from fertilizer application was reduced, thereby reducing the water quality problem in the nearby watershed (Zwieten et al., 2010; Goodall, 2010; Free et al., 2010).

## 4. Discussion

Areas with biochar that is made by fast and slow pyrolysis in different counties differ (Tables 4 and 5) according to scenarios to improve agronomic benefits under various energy and emission prices.

**Table 4.** Rice hectares (1000 ha) with biochar application from fast pyrolysis

| Pyrolysis | Fast | Fast | Fast | Fast |
|---|---|---|---|---|
| GHG Price | NT$300 | NT$300 | NT$500 | NT$500 |
| Electricity Price | NT$1.7 | NT$3.45 | NT$1.7 | NT$3.45 |
| Changhua | 7.25 | 7.25 | 7.4 | 7.67 |
| Pingtung | 7.49 | 7.49 | 7.49 | 7.49 |
| Ilan | 10.58 | 10.57 | 10.83 | 10.81 |
| Total | 25.32 | 25.31 | 25.72 | 25.98 |

Table 4 shows that fast pyrolysis would produce less amount of biochar than slow pyrolysis. The results show that approximately 25,500 ha of paddy would use the black char to improve the soil quality. Chiayi, the county where all pyrolysis plants are located and operated, does not use black char at all and simply transfers the char to other counties and cities. This result implicitly points out that other counties would have higher benefits if black char is applied, even after the deduction of expensive transportation costs. Therefore, to improve the overall agronomic benefits such as the increase in crop yield, improvement of soil quality, and enhancement of watershed quality, the optimal strategy is needed to utilize biochar in the southern counties.

As shown in Table 5, slow pyrolysis produces more biochar, and thus counties can improve the quality of more cropland. Additionally, the results show that most of the land receiving biochar is located in southern and central Taiwan, where rice yields are higher, input costs are lower and transportation costs are lower. This implies that the crop producers and farmers estimate the lowest cost for their production.

**Table 5.** Rice hectares (1000 ha) with biochar application from slow pyrolysis

| Pyrolysis | Slow | Slow | | Slow | Slow |
|---|---|---|---|---|---|
| GHG Price | NT$300 | NT$300 | GHG Price | NT$500 | NT$500 |
| Electricity Price | NT$1.7 | NT$3.45 | Electricity Price | NT$1.7 | NT$3.45 |
| Hsinchu | 6.31 | 6.31 | Hsinchu | 6.31 | 6.31 |
| Miaoli | 10.13 | 10.13 | Miaoli | 12.02 | 10.21 |
| Changhua | 23.66 | 23.98 | Nantu | 3.48 | 3.48 |
| Yunlin | 60.92 | 60.92 | Changhua | 15.03 | 15.03 |
| Chiayi | 28.22 | 28.22 | Yunlin | 35.98 | 35.98 |
| Kaohsiung | 6.91 | 6.91 | Chiayi | 52.5 | 52.5 |
| Pingtung | 7.49 | 7.49 | Pingtung | 7.49 | 7.49 |
| Ilan | 12.69 | 12.69 | Ilan | 12.47 | 12.47 |
| Total | 156.33 | 156.65 | Total | 145.29 | 145.55 |

## 5. Conclusions

While all outputs from pyrolysis are used to generate biopower and mitigate climate change, black char is an alternative to benefit the entire agriculture by increasing the yield of crops and reducing costs associated with irrigation and fertilizer applications. For this reason, it is necessary to investigate the possibility of using biochar. In this study, most of the biochar is applied in the southern and central counties of Taiwan.

We investigated the influences of site determination and found that operating the plants in Chaiyi would be most efficient as the labor and construction costs can be greatly reduced. While this may not be appropriate for all crops because of unequal pyrolysis output yields, it provides a basis for site selection. It is also important to notice that such applications may not suit large countries in which agricultural production has a substantial influence on the global market. If this is the case, the commodity price needs to be taken as endogenous rather than exogenous variables so that the equilibrium can reflect reality. However, for small countries and regions such as Taiwan, Singapore, and Hong Kong, this analytical framework could be useful.

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