GREENHOUSE GAS MITIGATION COST OF BIOCHAR APPLICATION TO SOIL

MS. KANOKRAT KHEMANUWONG
ID: 55300700401

A THESIS SUBMITTED AS A PART OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF SCIENCE
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Thesis Committee

………………………………………………
(Assoc. Prof. Dr. Amnat Chidthaisong) Advisor

………………………………………………
(Assoc. Prof. Dr. Sirintornthep Towprayoon) Member

………………………………………………
(Asst. Prof. Dr. Sudarut Tripetchkul) Member

………………………………………………
(Assoc. Prof. Dr. Niramon Sutummakit) External Examiner

Thesis Title: Greenhouse Gas mitigation cost of biochar application to soil

Student's name, organization and telephone/fax numbers/email

Ms. Kanokrat Khemanuwong,

The Joint Graduate School of Energy and Environment,

King Mongkut's University of Technology Thonburi,

Telephone: 0-8158-76855

E-mail: kkhemanuwong@yahoo.com

Supervisor's name, organization and telephone/fax numbers/email

Assoc. Prof. Dr. Amnat Chidthaisong,

The Joint Graduate School of Energy and Environment,

King Mongkut's University of Technology Thonburi,

Telephone: 02-4708309 ext. 4119 Fax. 02-8729805

E-mail: amnat_c@jgsee.kmutt.ac.th

Topic: Greenhouse gas mitigation cost of biochar application to soil
Name of student: Ms. Kanokrat Khemanuwong **Student ID:** 55300700401
Name Supervisor: Assoc. Prof. Dr. Amnat Chidthaisong

ABSTRACT

The application of biochar to soil is one of the potential greenhouse gas mitigation technologies. However, little information is available about the costs associated with the implementation of this technology in Thailand. Accordingly, this study investigates the costs of carbon sequestration in soil through the use of biochar produced from different feedstocks, such a mangrove, rice husk, bamboo, corn cob and mixed softwood. This cost estimate includes the steps from crop production to application to soil. Several field surveys and farmer interviews were made to collect the information necessary for cost estimates. The results reveal that greenhouse gas mitigation costs for mangrove, rice husk, bamboo, corn cob and mixed softwood biochar were approximately 381, 9,845, 1,677, 28,413, and 3,489 THB/tonCO_2e, respectively. These costs varied on the costs associated with biomass feedstock production and pyrolysis technology being applied by different farmers. In addition, the mitigation costs also depend on the carbon sequestration potential, of which is related to the carbon content of the each feedstock and biochar produced. The result of greenhouse gas mitigation cost is important in selecting an appropriate feedstock for biochar production and biochar application to soil in Thailand.

Keywords: Biochar, Global warming, Greenhouse gas, Mitigation cost, and Agricultural soil

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CONTENTS

CONTENTS (Cont')

CONTENTS (Cont')

LIST OF TABLES

LIST OF TABLES (Cont')

LIST OF FIGURES

LIST OF FIGURES (Cont')

LIST OF FIGURES (Cont')

LIST OF FIGURES (Cont')

LIST OF FIGURES (Cont')

LIST OF SYMBOLS AND ABBREVIATIONS

C: Carbon

CH_4: Methane

CO_2: Carbon dioxide

CO_2-eq: Carbon dioxide Equivalent

N_2O: Nitrous Oxide

EF: Emission factors

GHG: Greenhouse gases

GWP: Global warming potential

ha: hectare

IPCC: Intergovernmental Panel on Climate Change

IRRI: International Rice Research Institute

LDD: Land Development Department

N_2O: Nitrous oxide

OC: Organic Carbon

SOC: Soil Organic Carbon

TGO: Thailand Greenhouse Gas Management Organization (Public Organization)

THB: Thai Baht rates

CHAPTER 1
INTRODUCTION

1.1 Rationales

Global warming is caused by greenhouse gas emissions, such as carbon dioxide (CO_2) and methane (CH_4) and is a great concern for the world. The release of these greenhouse gases is resulted in mounting global air temperatures that leads to climatic change. Specifically, global warming will cause a rise in sea level, changes in the rain-fall pattern, and other problems. If Thailand has also affected by climate change as well as other countries, a question arises whether Thailand should change its way of production and consumption in order to mitigate GHG and reduce the climate change impacts on vulnerable communities and people in Thailand.

Climate change is a trans-boundary environmental problem that requires cooperation from every country to solve [1]. Although the contribution is small as compared with the world data, but the trend has increased. In order to secure the route to climate change solutions, it requires new response and breakthroughs in innovative technologies in ways that are compatible with economic growth.

The market mechanism can be used as a tool for combating climate change and persuading developing countries to participate in the mechanism. The concept of a market mechanism is to apply a price mechanism with greenhouse gases (GHG) or carbon dioxide, considering them as goods and making them marketable. This mechanism is based on an economic concept of “tradable emission permits” and is called a “Carbon Market.” [2].

Establishing a carbon market is one of the mitigation options that may generate mutual benefits among the private firms, public, and global levels. The following section provides some theoretically arguments on economic tools in reducing greenhouse gases [2].

Since the carbon market is a widely used tool for managing GHGs in developed countries, the impacts of such a market on economic circumstances needs to be inevitably determined. Moreover, to be well-prepared for the post-Kyoto regime and other international measures for combating climate change, Thailand needs to be familiar with tools for lessening domestic greenhouse gas emissions such as the carbon market [2].

Currently, carbon markets provide a financial opportunity to adopt conservation and mitigation technologies and practices to reduce GHGs, and also offer some agricultural businesses the potential to generate revenue, and to help compensate for additional on-farm costs associated with voluntary and/or future mandatory air quality improvements and energy management.

The agricultural sector is a net source of greenhouse gases emissions and thus is warranted for various mitigation measures. To be able to successfully assess mitigation potential technologies, various aspects such potential reduction potential, economic cost and factors effecting mitigation must be known.

An added challenge for the design of a carbon reduction policy will be finding ways to recognise the sequestration of carbon in soils and vegetation, or the incorporation of carbon into the soil through processes such as biochar [3]. This process provides opportunities to both lower emission reduction costs and increase farm productivity, but will require careful development of the carbon reduction policy rules to ensure that appropriate incentives are created.

Using biochar in the agricultural sector is one of the options of such technologies for carbon sequestration. Soil sequestration of carbon through biochar offers a means of mitigating climate change while delivering other economic and environmental benefits. These benefits can include the issues such as the restoration of degraded soils and increase in crop productivity.

Currently, the global potential production of biochar is 0.6 ± 0.1 gigatonnes (Gt) per year (10^9 tone or PgC per year) as estimated by Lehmann *et al.* [4]. By 2100, production of biochar could reach between 5.5 and 9.5 Gt per year. There are large uncertainties attached to these numbers, however, arising from competition for land-use, competition for use of biofuel and agricultural wastes and huge divergence (of nearly 1000%) in different expert estimates of the potential future global supply of biomass for bioenergy purposes. The breakdown of calculation of the potential is shown in Table 1.1 below.

Table 1.1 Global biochar production potential [4]

Source of biomass	Current potential for biochar production/PgC per year
1. Substituting slash-and-char for slash-and-burn in tropical shifting cultivation	0.190–0.213
2. Charcoal production waste	0.008
3. Forestry residues	0.021
4. Rice husks	0.038
5. Peanut shells	0.002
6. Municipal waste	0.03
7. if the current rate of production of biomass energy (6 EJ in 2001) were by pyrolysis	0.18

If all existing agricultural crop residues were used to produce biochar, this would constitute 1 gigatonne of carbon storage [5]. A reasonably conservative assumption would be that biochar has the potential to offset global atmospheric carbon emissions at the gigatonnes per year scale by 2050 (and probably by 2030 if concerted effort were made).

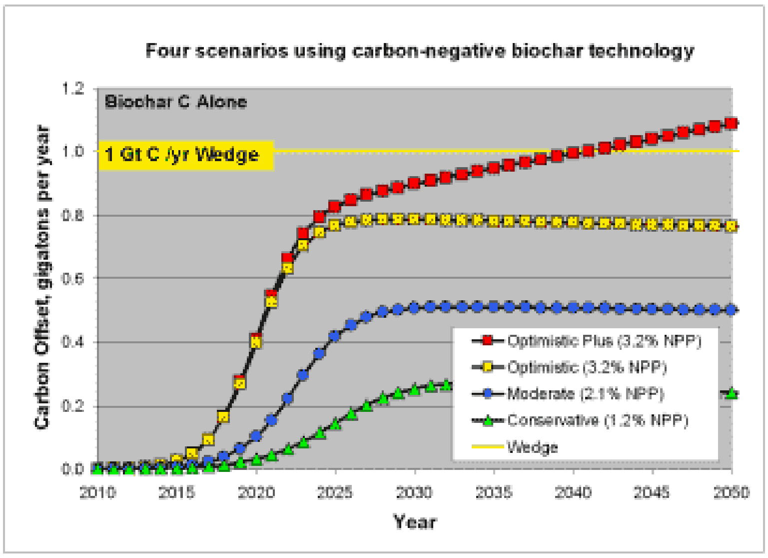


Figure 1.1 Mitigation potential of carbon dioxide emissions using biochar as predicted by the biological activated carbon (Biochar) to the year 2050 [5].

The amount of biochar that can be added to soils before it ceases to function as a beneficial soil amendment and becomes detrimental will be the limiting factor in the use of biochar as a soil additive. The strongest evidence that high concentrations of carbon in soil may be beneficial under some conditions comes from the Amazonian Dark Earths (ADEs), such as terra preta and terra mulata– charcoal rich soils, which contain approximately three times more soil organic matter, nitrogen and phosphorus, than do adjacent soils, and have twice the productivity [6]. A hectare of terra preta can contain up to 250 Mg of soil organic carbon (SOC) in the top 30cm (compared to 100 Mg in unimproved soils from similar parent material), and up to 500 Mg ha^{-1} in the top 1m [7]. Of this total SOC, as much as 40% may be black carbon [5], though the mean value in the most charcoal rich layer - the top 40cm – is around 20% [8]. It is estimated that the mean total amounts of black carbon found in terra preta soils were25±10 Mg ha^{-1} and 25±9 Mg ha^{-1} at 0–30 cm and 30–100 cm soil depths, respectively [8]. These values do not necessarily represent a ceiling on how much black carbon may be beneficially added to soils. Indeed, cation exchange capacity (CEC) of ADEs increased linearly within creasing SOC – a trend that continued up to the highest SOC values studied [9].

Thailand is an agricultural country. A large amount of agricultural residues, known as biomass, such as rice husks, corn cob residues, mixed softwood residues, etc., is produced. These residues can be converted into energy through various technologies, such as combustion, gasification and pyrolysis. On the other hand, these materials could be also considered as feedstock for biochar production that help enhance soil carbon sequestration and crop productivity. However, costs associated with biochar application and soil carbon sequestration have not been sufficiently studied. To make biochar application viable so that we could benefit from enhancing soil carbon sequestration and improving crop productivity, consideration of cost associated with its application is necessary. This study aims to evaluate the greenhouse gas mitigation cost of biochar application to agricultural soils.

1.2 Literature reviews

The agricultural sector is relevant to climate change due to emissions of greenhouse gases and other radiative forcing agents in food production and emissions through land-use change. Collectively, these account for carbon-equivalent emissions equal, globally, to that of transport. However, the fact that agricultural land is actively managed means that the emissions can potentially be mitigated or reversed. Agricultural soils contain a relatively small proportion of the global soil carbon pool, but this quantity is significant relative to the annual atmospheric flux.

1.2.1 Production of biochar and its properties

Biochar is a type of charcoal (black carbon material) produced from the decomposition of plant-derived organic matter (biomass) in a low or zero – oxygen environment (i.e. pyrolysis or gasification) to release energy [10]. Biochar comprises biomass in a deliberately stabilized carbon form, for which the soil may provide storage on a very large scale. With requisite physical and chemical properties, these forms of carbon could still offer potential value to crop productivity through dynamic or reversible interactions with nutrients and soil mineral particles. Any improvement to the productivity of existing agricultural land has the potential to ease pressure on biodiversity and often carbon rich natural ecosystems. Biochar has emerged as a potential win–win strategy for climate change mitigation and food production at the global scale [11].

Basically, the potential of biochar carbon sequestration depends on the types and properties of feedstock (i.e. feedstock property, moisture and size), pyrolysis conditions (i.e. pressure, temperature and residence time), or even type of pyrolysis. Many researchers have studied these effects. These are described below.

Kwapinski and his colleagues [12] reported that biochar has received much attention recently as a means of sequestering carbon due to its high chemical stability, high carbon content and its potential to reside in soils over long periods. These physico-chemical properties mean that biochar application to soils may provide a greater sequestration potential, with a lower risk profile than would be the case with increasing organic matter through conventional management practices such as no-tillage farming. Specifically, conversion of biomass carbon to biochar carbon leads to sequestration of approximately 50 per cent of the initial carbon [13], but this is highly dependent on the feedstock used and the pyrolysis conditions. Soil carbon residence times are also greatly increased when biochar is added to soils compared with direct biomass application to soils.

The Availability of large quantities of biomass feedstock and the transportation distance to a pyrolysis plants are essential considerations for an efficient and economically viable biochar production system [13]. Lehmann et al. [4] indicated that nut shells, bagasse and olive and tobacco waste are all highly suitable feedstocks due to the location of farms, and their existing processing facilities, and because of the large biomass quantities produced. For example, bagasse production in Queensland produces approximately 12 million tonnes annually [14]. It is possible to co-locate pyrolysis plants with biomass processing operations (for example, in the sugar cane industry) to minimize handling costs and to provide a waste management solution. The production of biochar has the potential to be scaled to any level of production based on location and feedstock quantities and quality. As such, pyrolysis systems can be developed for on-farm production or at a regional or state level [15].

Lehmann reported that biochar can be produced at almost any pH between 4 and 12 by appropriate selection of feedstock and operating conditions [16]. Typically, low pyrolysis temperatures (up to approximately 400 °C) yield acidic biochar (pH < 7), with pH increasing with pyrolysis temperature above this point to produce alkaline biochar (pH > 7). At very high temperatures (~800 °C) biochar can reach pH12.

Maiti and his colleagues reported that changes in pH occur in the temperature range of 300–550°C, the cause of which could be due to a separation of organic (carbon) and inorganic components (alkali metal salts) in the husk. After this temperature range, the pH remained almost constant, as the ash content remained relatively same [17].

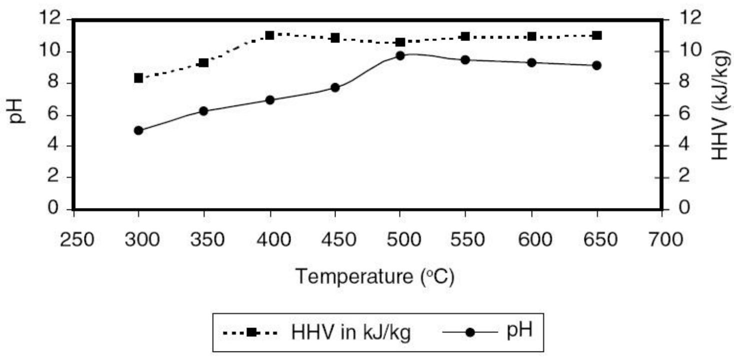


Figure 1.2 Variation of high heating value and pH of the resulting char with temperature [17].

Stoyle reported that having a high surface area is important to the placement of the biochar underground. With larger surface area per gram of a sample, there is less erosion and more ability to capture any particulates that may pass through the sink or into the biochar-fertilized soil [18]. Therefore, the longevity is increased and carbon capturing can take place over a longer period of time. Table 1.2 below includes the data from the BET detection. From the table, the higher temperatures have the larger surface area and rice has the larger square meter per gram. Similar to previous characterization, this can be connection to the initial sample of biomass that was used and also the grinding method that was used for preparation prior to the testing.

Table 1.2 Surface area of biochar produced from different feedstocks [18]

Biochar	Surface Area (m^2 / g)
Corn 200	1.91
Corn 350	2.44
Corn 500	31.7
Rice 200	1.92
Rice 350	27.8
Rice 500	198
Manure 200	2.09
Manure 350	5.82
Manure 500	24

Novak and his colleagues reported that the total surface charge of the biochars was influenced by feedstock selection and pyrolysis temperature. The relationship between pyrolysis temperature (°C) and surface area (m^2g^{-1}) of biochar produced from different feedstocks are shown in Table 1.3 [19].

Table 1.3 Surface area of biochar from different feedstocks produced at low and high temperatures [19]

Feedstock	Pyrolysis T (ºC)	Surface Area $m^2\ g^{-1}$
Peanut hull	400	0.52
	500	1.22
Pecan shell	350	1.01
	700	222.00
Poultry litter	350	1.10
	700	9.00
Switchgrass	250	0.40
	500	62.20

Among the eight biochars, pecan shell biochar produced at 700 ºC had the highest surface area (222 m^2g^{-1}), which is explained by its intrinsic higher density and through structural modifications that occurred at higher pyrolysis temperature. Figure 1.4 shows the relationship between surface area and carbonization temperature [20]. The high results of surface area is explained by the structural modification that happened at higher pyrolysis temperature. Surface area was the most well developed in sugarcane bagasse at carbonization temperatures above 500 °C. From the surface area results, some materials, for example bagasse, can provide relatively large surface areas as compared to wood charcoal.

Novak and his colleagues reported that although poultry litter, rice husk and cow biosolids were produced at higher pyrolysis temperatures at 700, 800 and 800 °C respectively, the surface area index was much lower than expected because the pores had been plugged by ash [19].

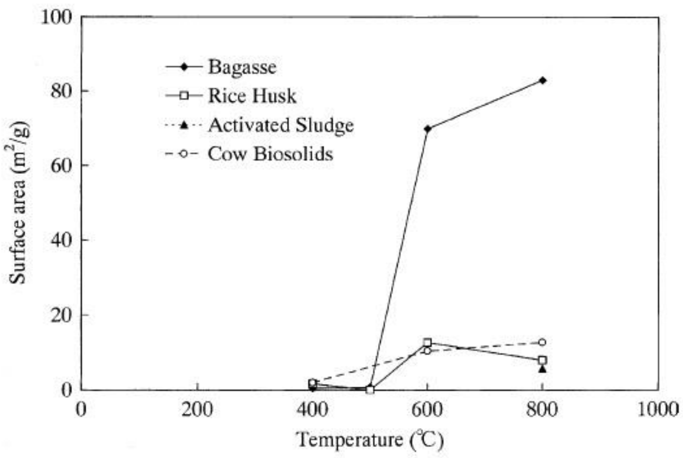


Figure 1.3 Surface area and temperature [20].

Downei and her colleagues showed the ideal biochar structure development with highest treatment temperature (HTT): (A) increased proportion of aromatic C, highly disordered in amorphous mass; (B) growing sheets of conjugated aromatic carbon, turbostratically arranged; (C) structure becomes graphitic with order in the third dimension (Figure 1.5) [21].

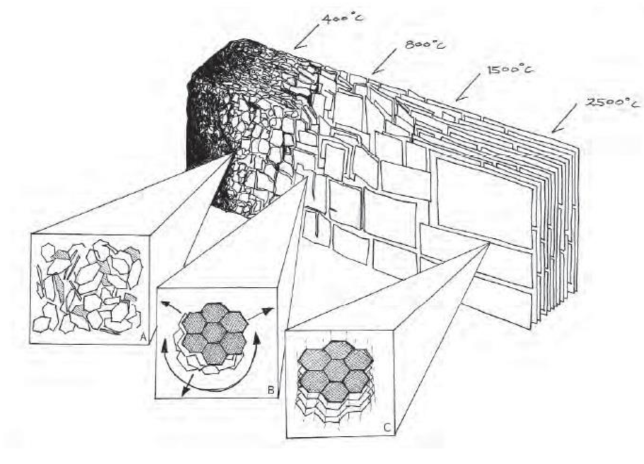


Figure 1.4 The Ideal biochar structure development with highest treatment temperature [19].

During thermal decomposition of feedstock, mass loss occurs in the form of volatile matter leaving an extensive pore network. Biochar pores are classified into three categories, according to their internal diameters (ID): Micropores (ID <2 nm), Mesopores (2 nm< ID <50 nm) and Macropores (ID >50 nm). Verheijen and his colleagues reported that the relationship between micropore volume and total surface area of biochar can explain that pore size distributed in the micropore rang effectively account for the large surface area characteristic. The development of microporsity has been shown to be favoured by higher temperature and retention time [22].

Hu and his colleagues reported that many micropores are produced during rapid pyrolysis. Under some conditions, the high temperature causes the micropores to broaden because it destroys the walls that connect the pores, resulting in the expansion of the pores. However, the relative influence of each parameter on the microporsity is determined by the type of feedstock [23]. Increasing pyrolysis temperature is affected to progressively increase in micropore while a maximum of larger pores occurred at 600 °C. At the higher temperature (850 °C), micropore development becomes strongly predominant [24]. Mesopores are important for use to be adsorbent by mixture with micropores. However, macropores had role in soil functions for instance aeration and hydrology. Furthermore, macropores are also significant to the movement of roots through the soil.

In the past, when biochars and activated carbons were evaluated mainly for their role as adsorbents, macropores were thought to be only important as feeder pores for the transport of adsorbate molecules to the meso-pores and micro-pores [25]. Nevertheless, macro-pores are extremely relevant to vital soil functions, such as aeration and hydrology. Macropores are also relevant to the movement of roots through soil and as habitats for a vast variety of soil microbes. Although micropore surface areas are significantly larger than macropore surface areas in biochars, macropore volumes can be larger than micropore volumes. It is possible that these broader volumes could cause greater functionality in soils than narrow surface areas.

As anticipated from the regular size and arrangement of plant cells in most biomass from which the biochars are derived, the macropore size distribution is composed of discrete groups of pore sizes rather than a continuum [25] [26]. To put this in perspective with typical soil particles, these discrete groups of pore diameters observed in this sample of ~5μm to 10μm, and ~100μm compare to incredibly fine sand or silt particle sizes, and fine sand particle sizes, respectively.

Table 1.4 Comparison of surface area and volume associated with pore characteristics [26]

	Surface area (m^2 / g)	Volume (cm^2 / g)
Micropores	750 – 1,360	0.2 – 0.5
Macropores	51 - 138	0.6 – 1.0

Ghani and his colleagues reported that the rate of CO_2 adsorption on sawdust-derived biochar samples generally increase with increasing temperature from 450 to 650 °C, but then decrease with increases in production temperature [27]. Derived biochar represents a potential alternative material for capture CO_2. CO_2 adsorption/desorption profiles of the rubber-wood sawdust- derived biochar at various temperatures are illustrated in Figure 1.6.

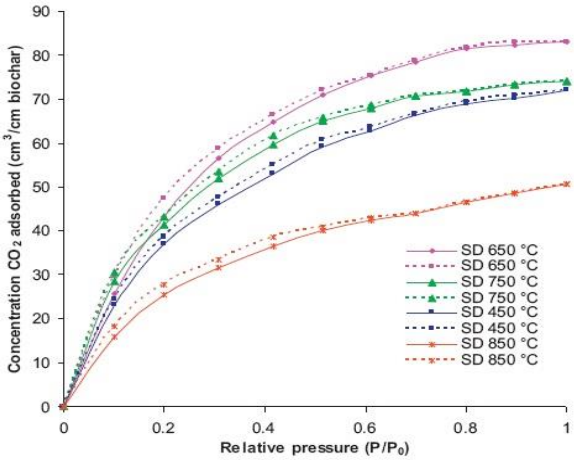


Figure 1.5 Adsorption and desorption isotherms of CO_2 at different production temperatures of rubber-wood-sawdust biochar [27].

Furthermore, the rates of adsorption of CO_2 on biochar samples generally increase with increasing temperature from 450 to 650 ◦C but decreases as the production temperature increases from 750 to 850 ◦C.

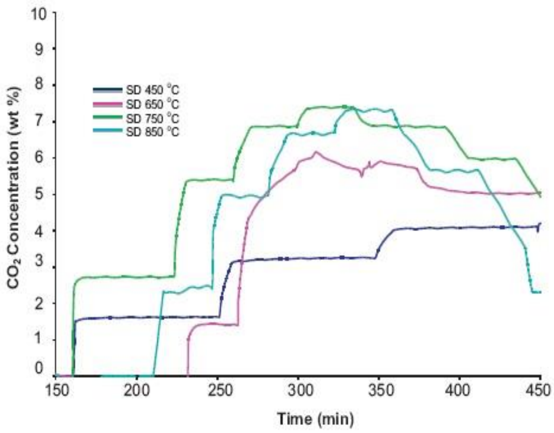


Figure 1.6 Adsorption and desorption profile of the biochar samples produced at different temperatures [27].

Sparkes and Stoutjesdijk showed that the nutrient content of biochar reflects the nutrient content of the feedstock. Biochar derived from manure or bone is relatively high in nutrients, especially phosphorous [16]. Biochars produced from plant material, those produced from wood generally have low nutrient levels and those produced from leaves and food processing waste have higher nutrient levels. Pyrolysis conditions also affect nutrient content and availability. High pyrolysis temperatures may decrease nitrogen content and availability. Total nitrogen content was found to decrease from 3.8 to 1.6 per cent when the pyrolysis temperature was increased from 400 to 800^{o}C, respectively.

Another study reported a similar effect on the nitrogen content in both woody and herbaceous char: nitrogen was gradually released from the char samples, beginning at 400^{o}C and continuing through to 750^{o}C, at which time slightly more than half the initial nitrogen remained [28]. In addition to partial loss of nitrogen, a reduction in the availability of the remaining nitrogen to plants was also found. An explanation for this proposes that the remaining nitrogen becomes incorporated into the carbon matrix, limiting the availability of nitrogen in the biochar produced.

1.2.2 Effects of biochar application on soil

Granatstein and his colleagues found varying pH effects when different types of biochar were added to the soil. This study noted that soil pH increased from 7.1 to 8.1 when 39 tonnes per hectare of herbaceous feedstock derived biochar was added to a sandy soil. The increase in pH was less pronounced for biochars from woody feedstocks. A smaller overall pH increment was observed when all types of biochar were applied to silt loam soils at rates up to 39 tonnes per hectare [29]. Sparkes and Stoutjesdijk suggested that the smaller pH increases in loam soils are due to the high initial cation exchange capacity (and hence, a high buffering capacity) of the loams [15].

Lal reported that another consideration is the type of microbial communities that utilize soil pores as a preferred habitat [30]. Microbial cells typically range in size from 0.5μm to 5μm, and consist predominantly of bacteria, fungi, actinomycetes and lichens. Algae are 2μm to 20μm. The macropores present in biochars therefore provide suitable dimensions for clusters of microorganisms to inhabit. The application of biochar in soil can increase the micropores. There, biochar can improve soil water retention especially biochar derived from high pyrolysis temperature. Novak and his colleagues reported that increasing water retention by sandy, Coastal Plain soils after biochar application is an important achievement; more water retained in soil implies less crop moisture stress and potentially higher yields [19]. Among the two switchgrass biochars, more water was retained by the Norfolk loamy sand after mixing in the biochar produced at the higher temperature. Peanut hull biochar produced at the lower pyrolysis temperature also significantly increased water retained (Table 1.5). While an exact mechanism for more soil water retention is unknown, it is speculated that these results may be a combination of these three biochar types being more polar or having more micropores for physically retaining water, or improved aggregation that created pore space for water storage.

Biochar is a stable source of carbon because microbes find it very difficult to break down. This means that the carbon contained in biochar is not likely to degrade to CO_2 to the same extent as untreated organic materials. The researchers have spent several years investigating biochar's suitability for storing carbon in soil. They put biochar into the soil and then test the stability of the carbon in the soil, by measuring how much CO_2 the soil releases.

The trick, of course, is distinguishing between the CO_2 that is emitted by the biochar, and the CO_2 that is emitted from other carbon sources in the soil. The researchers are able to do this with a technique that capitalizes on the fact that different kinds of plants are characterized by different carbon isotope compositions. The researchers have found that the biochar degraded by less than one percent during the past two years. In comparison, the same amount of untreated straw degraded by ten percent over the course of two years. This means that biochar is approximately twenty times more stable for storing carbon than using untreated straw or other organic materials during the first two years that is it put into the soil [31]. The mean residence time of biochars under controlled conditions (25 °C, 40% field capacity) was estimated from 244 to 1700 years, generally increasing with charring temperature and duration [32].

Table 1.5 Percentage deionized water retained by Norfolk soila after incubation for 28 days with 2% (w/w) and without biochars pyrolyzed from different feedstocks and at different temperatures [19]

Norfolk Soil + Biochar Type	Pyrolysis Temp. (°C)	Percentage by Weight of Water Retained Mean[b]	Standard Deviation
Control (0% biochar)	---	35.1a	0.95
Peanut Hull	400	39.7b	1.17
	500	37.9a	2.22
Pecan shell	350	36.9a	0.79
	700	38.3a	1.92
Poultry litter	350	34.1a	1.18
	700	34.8a	1.14
Switchgrass	250	41.8b	2.05
	500	51.0b	2.41

[a]Treatments (n = 4) leached with 1.2 pore volumes of deionized H_2O; water collected after 30 h of free drainage
[b]Means followed by a different letter are significantly different than control using a Holm-Sidek multiple comparison test at *P* = 0.05

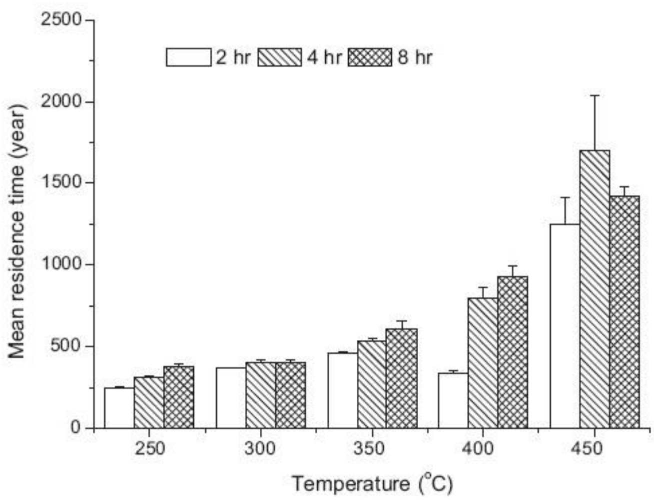


Figure 1.7 Mean residence time (MRT) of rice straw-derived biochar as affected by charring temperature and duration [32].

Ameloot and his colleagues suggest that N_2O emissions from biochar amended soils were suppressed due to the addition of biochar by an increase in (i) soil pH, (ii) soil aeration and (iii) short term retention of nitrate onto the internal biochar surface [33]. In the 350 °C biochars, these denitrification suppressing mechanisms were counteracted by the provision of easily available substrate through volatile biochar compounds (Fig. 1.9).

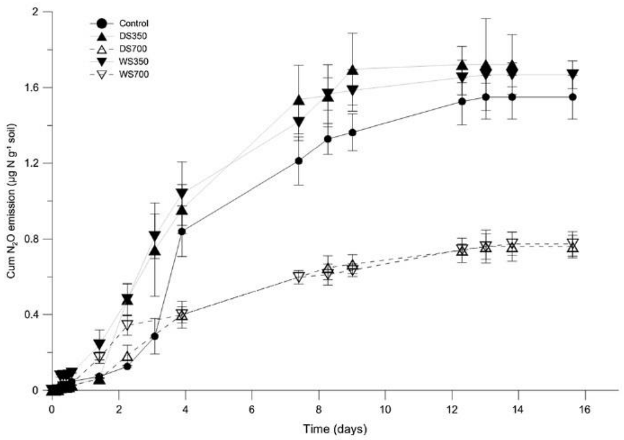


Figure 1.8 Cumulative N_2O emissions (μg N g^{-1} soil) from the different treatments after 15 days (N_2O emission experiment) [33].

Glaser and his colleagues reported that large amounts of carbon may be sequestered in the soil for long time periods (hundreds to thousands of years at an estimate), but precise estimates of carbon amounts sequestered as a result of biochar application are scarce [34]. Marris suggests that a 250-hectare farm could sequester approximately 1,900 tons of CO_2 a year [35]. Carbon input to soil with biochar will remain sequestered in soil, controlled by its stability. The ability of biochar to store carbon and improve soil fertility will not only depend on its physical and chemical properties, which can be varied in the pyrolysis process or through the choice of feedstock, but also on the technical and economic limitations of handling biochar in quantity in an agronomic setting [36]. From the definition, stability of biochar in the soil is the most important factor for sequestered C. In addition, application of biochar in soil can reduce the emission of other greenhouse gas. Nitrous oxide emission were reduce by up to 50% when biochar was applied to soybean and by 80% in grass stands [4].

Khare and Goyal [37] reported that the carbon sequestration experiment was done in three sets: (Co); II charcoal (CH) and III bio-char (BC) (Fig. 1.9). The control soil with bio-char and charcoal amended soil for an incubation period of 7 and 15 days. The CO_2 production showed sharp increase after 15 days when compared with 7 days. In 7 days, soil with bio-char showed lowest CO_2 released as compared to soil with charcoal and control soil. However, in 15 days order of release of CO_2 was control soil > soil with bio-char > soil with charcoal. The release of CO_2 in control soil was highest suggested that soil amended with charcoal and bio-char is capable of sequester the CO_2. It can be evident from the figure that in seven days incubation period release of CO_2 from soil amended with bio-char and charcoal was approximately similar. It is probably due to initial microbial decomposition of oxygenated groups of charcoal and biochar. However, soil treated with charcoal showed higher CO_2sequestration after 15 days of incubation. It might be due to presence of condensed ring in charcoal, which was less susceptible of microbial degradation. However, other properties of soil like SOM, available potassium and urease activity were higher in soil treated with bio-char. It is reported that black carbon produced above 600 ◦C is dominated by napthelene, benzofuran, dephenyl. These char tend to give lower CO_2 due to their increased resistance to surface oxidant and microbial mineralization. However, weakly charred biopolymer present in the biochar is more susceptible for CO_2 production. It suggests that biochar used for soil amendment and carbon sequestration may have rational proportion of condensed ring and oxygenated functional groups.

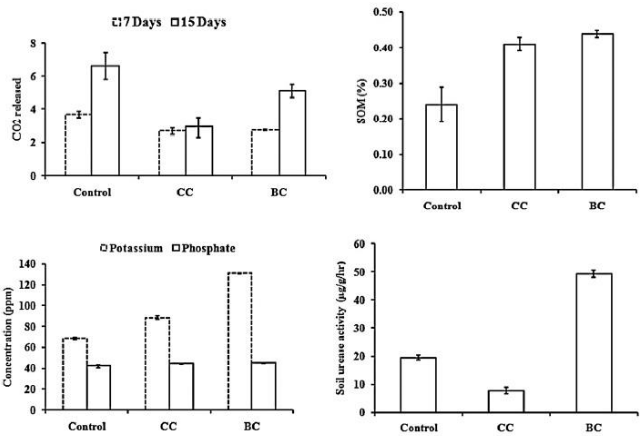


Figure 1.9 CO_2 sequestration and properties of soil. Control: control soil, CC: soil with charcoal; and BC: soil with biochar [37].

There are some research studies in Thailand investigating biochar application in soil. Quaillitter biochar (QLB) application can significantly decrease the bioavailability of Cd to physic nut plants, increase plant growth potential and yield, and has potential to remediate Cd contaminated soil. However, QLB levels higher than 15 g kg^{-1} soil mixture were not advisable because QLB is alkaline in nature, and this can affect soil pH [38].

Mixing biochar into paddy soil before rice transplantation significantly increased the tiller number, and as a result, the panicle number increased more than those without adding bio-char and biochar application was significantly able to maintain the ammonium ions more than other rates. Therefore, it should evenly collaborated chemical fertilizers with improving bio-char for improving paddy soil abundance [39].

1.2.3 Cost and benefit of biochar application to soil

Galinato and his colleagues studied the carbon sequestration potential and cost [40]. They reported that the carbon content of biochar in winter wheat cultivation varies depending on the feed stock [40]. Approximately 0.61 – 0.80 MT of carbon (or 2.2 – 2.93 MT of CO_2) is sequestered for every ton of biochar applied to the soil. The approximate value of biochar C sequestration is $2.93 – $90.83/MT biochar (Table 1.6). A soil application of 76.53 tons of biochar for wheat cultivation resulted in a 58% of the wheat crop yield increase. That is, the crop yield goes from 3.92 tons/ha to 6.22 tons/ha. With the cost of biochar sequestration $2.93 to $90.83 per ton, the total cost of biochar sequestration was $224.23 to $6,951.22 /tons.

Table 1.6 Potential and cost of soil C sequestration with biochar [40]

Rate tons/ha	Potential of soil C sequestration from biochar tons of CO2/ha	Total farm Potential of soil C sequestration with biochar tons of CO2/ha	Crop yield tons/ha	Carbon price $/tons	Carbon offsets $/tons
76.53	2.2 to 2.93	168.37 to 224.23	3.92 to 6.22	2.93 to 90.83	224.23 to 6,951.22

Thomas and his colleagues reported that the average carbon sequestration with biochar application in Australia was 28.6 tons/ha, equal to the fraction that about 1% of carbon in biochar is accumulated within the soil (Table 1.7) [41]. Considering the carbon price at $27.5/tons and the tradable amount resulted from biochar application of 1.90 tons of carbon each year, the cost for one ton of carbon offset was $52.4. At a rate of 20 tons per hectare (an average of 28.6 tons per hectare) of biochar, soil carbon will increase by 1%.

Table 1.7 Potential and cost of soil C sequestration with biochar applications in Australia [41]

Rate tons/ha	Potential of soil C sequestration from biochar tons of CO_2/ha	Total farm Potential of soil C sequestration with biochar tons of CO_2/6.66ha	Cost of biochar $/tons	Total cost of biochar $/tons	Expected carbon price $/tons	Carbon offsets $/tons
28.6	0.286	1.9047	50 to 200	1,430 to 5,720	27.5	52.38

Williams and Arnott in Colorado, U.S.A., examined the costs of two methods of biochar applications to soil [36]. The first method was broadcast-and-disk, in which biochar was applied by using conventional agricultural application equipment along with a disking pass to enable the shallow incorporation of the biochar into the soil. The second method was trench-and-fill, in which biochar was applied by using implements, such as a skid steer with a trenching attachment to cut trenches and then using a lime spreader or similar device to fill trenches with biochar. Investigating the cost of biochar application in soil, the broadcast method was generally cheaper than the trenching methods (Table 1.8). The costs per ton for applying biochar at rates of 6, 12, 25, 62, and 124 tons ha^{-1} were $12, $9, $7, $6, and $6, respectively. The total cost increased as the rate of application increased for both methods. Among these, labor cost made up the majority. The cost of the trench and fill process depended on several variables (labor, fuel and maintenance), trenching (labor, fuel and maintenance), and operator efficiency. The rates were between 12 to 186 tons ha^{-1} and total cost $ton^{-1}$was $14 (Table 1.8). Results from this study clearly indicate that costs of biochar application are dependent of application methods. However**,** they did not present the effect of biochar application on soil carbon sequestration with both two methods**.**

Table 1.8 Cost evaluation of broadcast-and-disk application results and trench-and-fill application results [36]

Method	Rate ton/ha	Cost Application ($) (Labor+Fuel+Maint.)	Disking	Total cost ($)	Total cost per ton($/ton)
broadcast and disk application	6	34	37	71	12
	12	69	37	106	9
	25	141	37	178	7
	62	351	37	388	6
	124	706	37	743	6
trench and fill application	12	83	85	168	14
	31	210	214	423	14
	62	418	426	844	14
	124	837	854	1691	14
	186	1257	1281	2537	14

Zwieten and his colleagues presented the value of several biochars produced by BEST Energies slow pyrolysis [42]. Two approaches were used: the first based on the fertiliser and C trading value of the biochar, and the second on a gross margin analysis using biochar in a sweet corn (*Zeamays*) crop.

This trial has shown that the benefits of biochar are long-lasting and this should be factored into economic models. Fertiliser and carbon trading value of biochar is $73 - $300/t. The gross margin analysis of crop yields values it at around $1000/t. This shows that biochar has potentially great economic value for agriculture. Table 1.9 shows an economic valuation of the fertiliser value and carbon trading value of three biochars. This method for valuation does not include attributes that are site-specific. For example, water holding capacity, tensile strength, CEC and soil health depend on soil type and climate. Maize: PL biochar at 10 t ha^{-1} 51% yield increase, at 50 t ha^{-1} 109% increase over nil. Beans: highest yields were observed where biochars were added with fertiliser. PL biochar alone out performed luxury fertiliser treatment, lime amendment and compost. If biochar increases crop yield, farmers ‘willingness to pay’increases. Table 1.10 is an analysis of crop yields and profits obtained from the sweet corn trial at Wollongbar.

Table 1.9 Economic valuations of the fertiliser value and carbon trading value of biochars [42]

Components	Poultry litter ($)	Greenwaste ($)	Papermill ($)
N	52	6	11
P	177	4	8.12
K	39	0.13	0.88
$CaCO_3$	23	1.50	12
C trading value	38	73	40
Estimate value $AU/ton biochar	329	85	72

Table 1.10 Analysis results of crop yields and profits obtained from the sweet corn applied with biochar [42]

Biochar Rate (tones/ha)	Crop yield	Number of fruit boxes (filled/ha)	Sale of packages	Fixed non capital (cost/ha)	Profit/ha	Difference in profit	Benefit/ ton biochar added
0	16t	1777 packs	$19,550	$12,000	$7,550	-	-
10	25t	2777 packs	$30,555	$12,000	$18,555	$11,005	$1,100
50	35t	3888 packs	$42,777	$12,000	$30,777	$23,227	$465

In Thailand, Norsuwan and his colleagues compared the application rate of biochar and the effects on paddy rice yield and soil nutrients [39]. They compared the effects of biochar at 4 rates (0, 4, 8 and 16 ton/ha). Biochar was mixed into paddy soil before rice transplantation. They studied the costs and economic returns in the first year of production area 1 rai (0.16 hectare) for supporting the decision to use biochar to increase the rice yields. The net incomes for these application rates were $235.62, $53.12, -$51.73 and -$157.66, respectively. The cost mainly comes from the production of biochar. However, the cost related to the amount of greenhouse gas emission was not evaluated in this study. This indicates that biochar application was resulted in increase in operation cost and drove down the net income. However, it was also found that the addition of 8 and 16 ton of biochar per ha were significantly able to maintain the ammonium ion more than other rates at 0 and 4 ton/ha.

Table 1.11 Production cost and economic return rates of biochar [39]

Item	Without biochar	Biochar rate (ton per ha)		
		4	8	16
1) Biochar production cost -production cost of biochar kiln -labor cost of preparing and loading wood chips	0	$210	$293.75	$413.75
2) Management cost	0	$0.63	$0.63	$0.63
3) Total cost = (1) + (2)	0	$210.63	$294.38	$414.38
4) Yield (ton)	0.67	0.75	0.69	0.73
5) Sale price of rice (per ton)	$351.67	$351.67	$351.67	$351.67
6) Total income = (4) × (5)	$235.62	$263.75	$242.65	$256.72
7) Net profit = (6) – (3)	$235.62	$53.12	-$51.73	-$157.66

Working hour (US$10 per day)

While there are many research studies trying to evaluate the carbon sequestration potential and investigate the effects of biochar application to soil on soil property and crop productivity, the cost associated with biochar applications have not been sufficiently studied especially in Thailand. To make biochar application viable so that we could benefit from enhancing soil carbon sequestration and improving crop productivity, consideration of cost associated with its application is necessary.

This study proposes to evaluate the cost of biochar applications to agricultural soils. The scope of this thesis is based on a literature review, field data collection, and analysis of the direct cost and the carbon sequestration potential of biochar production and applications in agricultural soil in Thailand. The results are expected to assist in prioritizing and selecting biochar technology for global warming mitigation, crop production, and other environmental benefits.

Table 1.12 The summary of studies on biochar used as a soil amendment

Crop	Biochar application rate	Soil type	Type of biochar feedstock	Crop response	Location	Reference
Soybean	0, 0.2, 2.0 and 6.1 t/acre	Volcanic ash soil, loam	Unknown wood	At 0.2 t/acre, increased yield by 51%. At 2 t/acre and 6.1/acre, reduced yield by 37% and 71%, respectively. Reductions were attributed to micronutrient deficiency induced by an increase in pH.	Japan	Kishimoto and Sugiura (1985)[a,b]
Vegetation in hearth and non-hearth areas compared after 110 years	Unknown	Forest area on relic charcoal hearths	Wood for charcoal production	Tree density and basal area were reduced by 40%.	United States (Pennsyl-vania)	Mikan and Abrams (1995)[b]
Trees	Unknown	Forest area on relic charcoal hearths	Wood for charcoal production	Lower overstory tree cover and density on relic charcoal hearths than on adjacent, non-hearth areas. The richness and diversity of overstory and understory tree cover as well as ground vegetation were consistently lower on hearths**.**	United States (Appala-chian mountains)	Young *et al*. (1996)
Rice, Cowpea	0, 27.2 and 54.7 t/acre	XanthicFerralsol	Secondary forest wood	At application rate of 27.2 t/acre, biomass increased by: 20%, rice; 50%, cowpea compared to control treatment where no biochar was applied. At application rate of 54.7 t/acre, biomass of cowpea increased by 100%.	Brazil	Glaser *et al*. (2002)
Banana	4.5 t/acre	XanthicFerralsol	Wood	Reduced soil acidity and increased K uptake	Brazil	Steiner (2006)c

Table 1.12 The summary of studies on biochar used as a soil amendment (con't)

Crop	Biochar application rate	Soil type	Type of biochar feedstock	Crop response	Location	Reference
Maize	6.1 t/acre	Acid soil	Bark	Higher yields with biochar and fertilizer, than fertilizer alone	Indonesia	Yamamoto *et al*. (2006)c
Rice, Sorghum	4.5 t/acre	XanthicFerralsol	Secondary forest wood	Charcoal plus mineral fertilizer improved yield by a factor of 1.5-2 and improved stover by a factor of 1.3-1.4. Using charcoal plus compost and/or fertilizer, yields are consistently greater (i.e., 4 to 12 times greater) compared to using fertilizer alone.	Brazil	Steiner *et al*. (2007)
Wheat, soybeans	4 t/acre	Semi-tropical soil	Unknown	Wheat: biomass tripled. Soybeans: biomass more than doubled. Percentage increase in biomass is the same when nitrogen fertilizer is applied together with biochar. Biochar raised soil pH at about 1/3 the rate of lime.	Australia	Van Zwieten (2007)
Wheat	4 t/acre	Ferrosol	Paper mill sludge	30-40% increase in wheat height in acidic soil but not in alkaline soil. Response was attributed mainly to the liming value of biochar.	Australia	Van Zwietenet *et al*. (2007)b

Table 1.12 The summary of studies on biochar used as a soil amendment (con't)

Crop	Biochar application rate	Soil type	Type of biochar feedstock	Crop response	Location	Reference
Wheat	0, 5, 10 and 20 t/acre	Quincy sand, Hale silt loam	Peanut hull (PH), fir bark (SB)	Quincy: Root-shoot ratio of wheat decreased in all application rates of biochar. Hale: Using PH, decline in root-shoot ratio of wheat at 10 t/acre of biochar compared to nil; no change at 5 t/acre and 20 t/acre. Hale: Using SB, root-shoot ratio of wheat increased in all treatments. 0.5 to 1 unit increase in soil pH due to biochar addition.	Washington	Collins (2008)
Radish	0, 4, 10.1 and 20.2 t/acre	Alfisol	Poultry litter	With biochar, without N fertilizer: yield increased from 42% at 4 t/acre of biochar to 96% at 20.2 t/acre of biochar, relative to the yield from unamended control.	Australia	Chan et al. (2008)
Lime Maize, Faba beans	Maize: 0.2-20.2 t/acre PL. Beans: 4 t/acre PL and PM versus 1.2 t/acre	Ferrosol	Poultry litter (PL), Paper mill waste (PM)	Maize: 51% yield increase at 4 t/acre; and 109% yield increase at 20.2 t/acre compared to nil. Beans: Yields are highest with biochar plus fertilizer, compared to biochar alone. PL biochar outperformed lime amendment.	Australia	Van Zwietenet al. (2008)c

1.3 Research Objective

The objective of this study is to estimate the total costs of the applications of biochars to mitigate greenhouse gas emissions in agricultural soil, comparing among five feedstock type: rice husk, mangrove, corn cob, bamboo and mixed softwood.

1.4 Scope of Research Work

This thesis study covers the financial cost estimation of greenhouse gas mitigation. The data and information were based on a literature reviews, field data collection, and analysis of the direct cost and the carbon sequestration potential of biochar production and application in agricultural soil in Thailand. The results are expected to assist in prioritizing and selecting biochar technology for global warming mitigation, crop production, and other environmental benefits.

CHAPTER 2

THEORIES

2.1 Backgrounds on biochar application to soils

In the Amazon Basin, South America, charcoal has been used by the Amazonian people as a soil amendment for over 2,500 years ago. It is unclear whether they intentionally created the so-called terra preta soil ("black earth") (Figure 2.1), or if it was simply the byproduct of their slash and burn practice. These soils continue to exhibit enhanced fertility via higher carbon and nutrient content even thousands of years after their implementation. Most notably, crops cultivated in the black soil are reported to grow three times faster than those in surrounding land. Furthermore, the largest impact demonstrated by biochar addition occurs in highly acidic or nutrient depleted soils.

Figure 2.1 Comparison of usual soil and Terra Preta-charcoal containing soil [43].

The high fertility of terra preta soils has been attributed to high levels of organic matter from the addition of materials such as charcoal, residues from human and animal waste, food scraps and other nutritious waste material that were not charred [44]. These soils have a carbon content of up to 150 g/kg soil, compared with 20 to 30 g/kg soil in adjacent un-amended soils [45]. Further, the carbon is mainly in the form of black carbon, which is up to six times more stable than that in adjacent, un-amended soils [45].

In addition to increased carbon content, terra preta soils are characterized by higher pH, calcium, magnesium and phosphorous levels, higher cation exchange capacities and higher base saturation levels, compared with adjacent un-amended soils [45]. Due to these characteristics, terra preta soils are now used to produce crops such as mangoes and papaya, which are reportedly more productive than in the surrounding unimproved soils [11].

It has now become a general consensus that biochar enhances soil fertility, increases crop productivity and sequesters carbon [46]. The carbon in biochar does not directly provide nutrients to plants [47]. Biochar helps soil retain nutrients and water, and hence can reduce costs for irrigation and fertilizers and improve depleted soils in the long run. Due to greater nutrient retention, biochar limits the necessity for fertilizer and also decreases soil erosion. Zhang *et al.* [48] show that biochar significantly increased rice yields and decreased N_2O emission. Biochar also stabilizes the pH in the favorable range of 5 - 6.4 pH [49].

Figure 2.2 shows the inputs, processes, outputs, applications and impacts on global climate according to biochar applications [50]**.** Within each of these categories, the relative proportions of the components are approximated by the height/width of the colored fields. CO_2 is removed from the atmosphere by photosynthesis to yield biomass. A sustainable fraction of the total biomass produced each year, such as agricultural residues, biomass crops and agroforestry products, is converted by pyrolysis to yield bio-oil, syngas and process heat, together with a solid product, biochar, which is a recalcitrant form of carbon and suitable as a soil amendment. The bio-oil and syngas are subsequently combusted to yield energy and CO_2.This energy and the process heat are used to offset fossil carbon emissions, whereas the biochar stores carbon for a significantly longer period than would have occurred if the original biomass had been left to decay. In addition to fossil energy offsets and carbon storage, some emissions of methane and nitrous oxide are avoided by preventing biomass decay and by amending soils with biochar. Additionally, the removal of CO_2 by photosynthesis is enhanced by biochar amendments to previously infertile soils, thereby providing a positive feedback.CO_2 is returned to the atmosphere directly through combustion of bio-oil and syngas, through the slow decay of biochar in soils, and through the use of machinery to transport biomass to the pyrolysis facility, to transport biochar from the same facility to its disposal site and to incorporate biochar into the soil. In contrast to bioenergy, in which all CO_2 that is fixed in the biomass by photosynthesis is returned to the atmosphere quickly as fossil carbon emissions are offset, biochar has the potential for even greater impact on climate through its enhancement of the productivity of infertile soils and its effects on soil GHG fluxes.

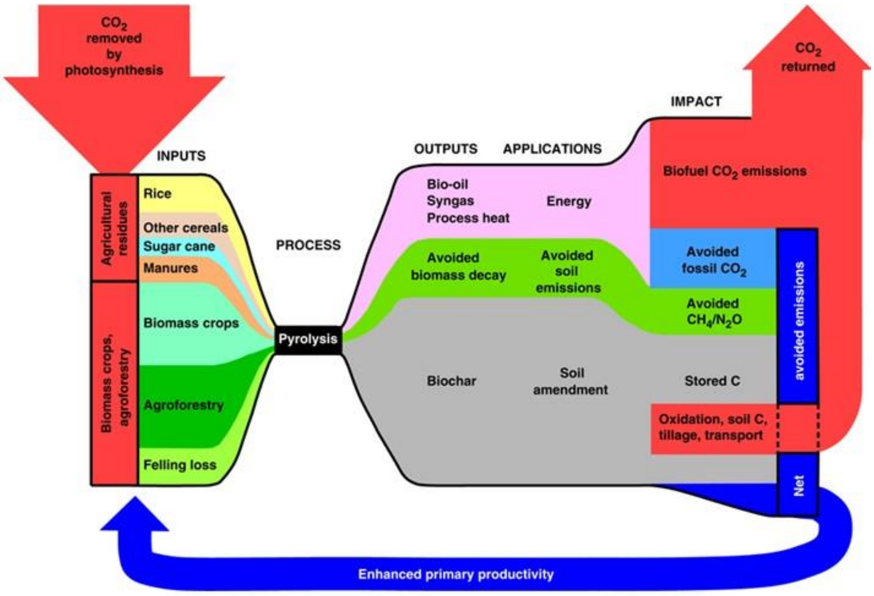


Figure 2.2 Overview of the sustainable biochar concept [50].

2.2 Properties of biochar

2.2.1 Physical property

2.2.1.1 Surface area

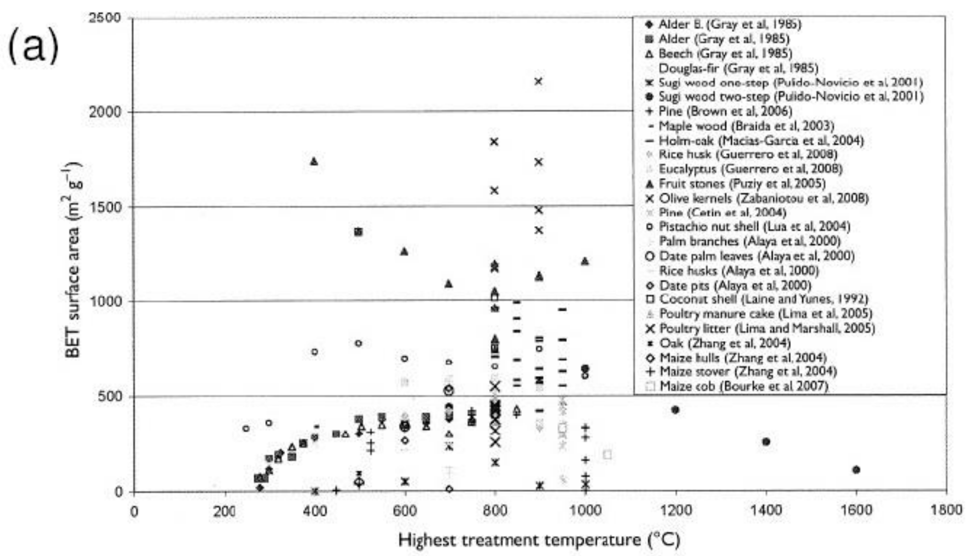
Extensive literature review has shown that biochar with a broad range of specific surface areas (SSA) can be produced (Figure 2.3). The main parameters influencing SSA are pyrolysis temperature, heating rate, residence time and presence of active reagents (e.g., steam, CO_2, O_2, etc.). Figure 2.3a shows that the total surface area of biochar from most feedstock tends to increase with increasing pyrolysis temperature. This is mainly due to the development of micropores that are responsible for most of the surface area (Figure 2.3b). At present it is not clear whether the additional surface area, presented by micropores, plays as important a role in soils as macropores, and therefore whether it is beneficial to produce a biochar with extremely high SSA. It may be possible to produce biochar with high SSA in the macropore range. However, Kurosaki *et al.* [51] reported that biochar physical structure tends to be defined by the starting material, so fine milling or compaction of the feedstock before pyrolysis is necessary to achieve a well defined macroporous product [52].

2.2.1.2 Porosity

Biochar pores are classified in this review into three categories [21] according to their internal diameters (ID): macropores (ID > 50 nm), mesopores (2 nm < ID < 50 nm) and micropores (ID < 2 nm). These categories are orders of magnitude different to the standard categories for pore sizes in soil science. The elementary porosity and structure of the biomass feedstock is retained in the biochar product formed [21]. The vascular structure of the original plant material, for example, is likely to contribute for the occurrence of macropores in biochar, as demonstrated for activated carbon from coal and wood precursors. In contrast, micropores are mainly formed during processing of the parent material. While macropores have been were identified as a 'feeder' to smaller pores [52], micropores effectively account for the characteristically large surface area in charcoals [53].

2.2.1.3 Water holding capacity

Applications of biochar in soil can increase the micropores. There, biochar can improve soil water retention especially biochar derived from high pyrolysis temperature. Novak et al. [19] reported that increasing water retention by sandy, Coastal Plain soils after biochar application is an important achievement; more water retained in soil implies less crop moisture stress and potentially higher yields.



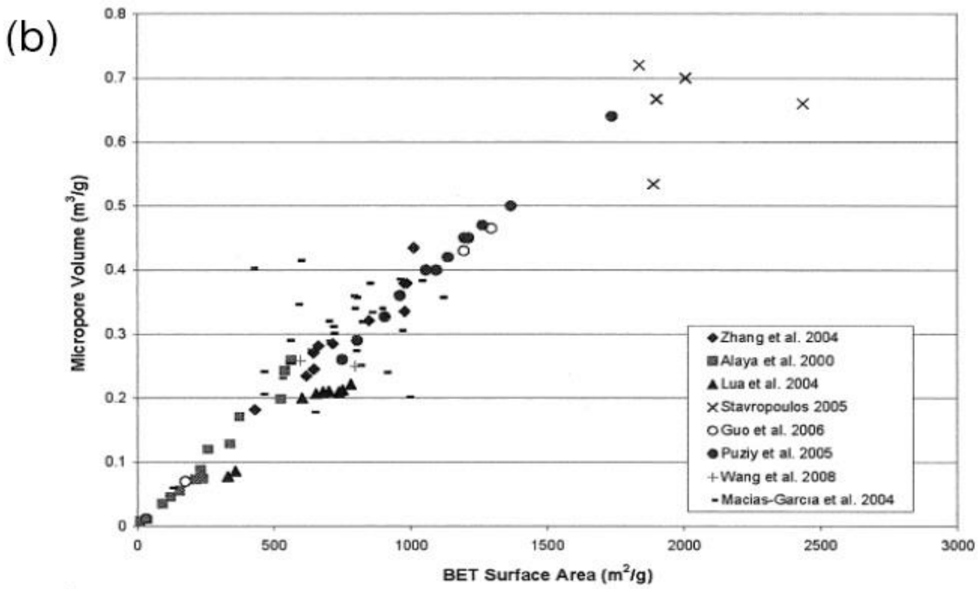


Figure 2.3 Biochar surface area (a) plotted against treatment temperature and (b) its apparent relationship with micropore volume [21].

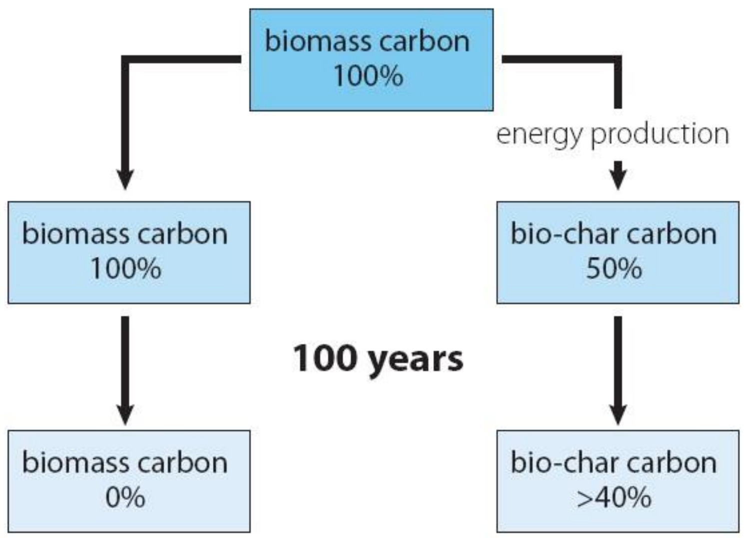
Mc Elligott *et al.* [54] reported that increased surface area and porosity, and lower bulk density in mineral soil treated with biochar can alter water retention and aggregation, and can decrease soil erosion. Soil water retention is determined by the distribution and connectivity of pores in the soil matrix, which are largely affected by soil texture, aggregation, and organic matter content. Biochar has a higher surface area and greater porosity relative to other types of soil organic matter and can therefore improve soil texture and aggregation, which improves water retention.

2.2.1.4 Adsorptivity

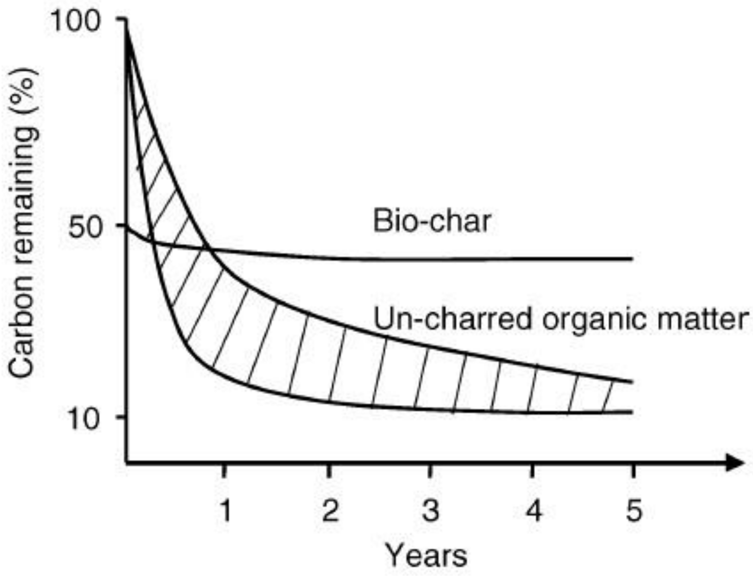
Biochar has a greater ability to adsorb and retain cations in an exchangeable form than other forms of soil organic matter due to its greater surface area and negative surface charge [55]. Studies have shown significant increases in the availability of all major cations [34] [56] [57]. Tryon [58] found increasing amounts of exchangeable bases in sandy and loamy soils after adding 45% hardwood and conifer charcoals. Additionally, freshly produced biochar is reported to have an anion exchange capacity. Cheng *et al*. [59] found biochar to exhibit an anion exchange capacity at pH 3.5, which decreased to zero over time as the biochar aged in soil. Biochar’s pores, high internal surface area, and increased ability to adsorb organic matter provide a suitable habitat to support soil microbiota, which catalyze processes that reduce N loss and increase nutrient availability for plants [47]. It has been suggested that pores serve as a refuge to microbes by protecting them from predation and desiccation, while the organic matter adsorbed to biochar provides carbon energy and mineral nutrient requirements [54].

2.2.1.5 Decomposability

Biochar is a stable form of charcoal that has the potential to sequester soil organic carbon due to its claimed 'recalcitrant' form. The carbon atoms in biochar molecules are strongly bound to one another, and makes biochar resistant to attack and decomposition by micro-organisms [10]. For instance, research by Skjemstad *et al*. [60] identified biochar as one of the major sources of long time storage of soil carbon (Figure 2.4) owing to its capacity to resist microbial decomposition [61]. Verheijen *et al*. [62] reported that a good proportion of the carbon can remain in soils for hundreds, and possibly, thousands of years. A number of studies have demonstrated that the Mean Residence Time (MRT) of biochar is frequently reported to be from 100s to 1000s of years.



(A)



(B)

Figure 2.4 Schematics for biomass or bio-char remaining after charring and decomposition in soil. **(A)** Comparison of traditional biomass and biochar applications to soils on soil carbon retention over 100 years. **(B)** Range of biomass C remaining after decomposition of crop residues from Jenkinson and Ayanaba (1977); estimation of bio-char decomposition [4].

2.2.2 Chemical property

2.2.2.1 pH

It has been reported that biochar can be produced at almost any pH between 4 and 12 by appropriate selection of feedstock and operating conditions [16]. Typically, low pyrolysis temperatures (up to approximately 400 °C) yield acidic biochar (pH < 7), with pH increasing with pyrolysis temperature above this point to produce alkaline biochar (pH > 7). At very high temperatures (~800 °C) biochar can reach pH12.

2.2.2.2 Molecular composition

Thermal degradation of cellulose between 250 and in 350ºC results in considerable mass loss in the form of volatiles, leaving behind a rigid amorphous C matrix. As the pyrolysis temperature increases, so thus the proportion of aromatic carbon in the biochar, due to the relative increase in the loss of volatile matter (initially water, followed by hydrocarbons, tarry vapours, H_2, CO and CO_2), and the conversion of alkyl and O-alkyl C to aryl C [63] [64]. Around 330ºC, polyaromatic graphene sheets begin to grow laterally, at the expense of the amorphous C phase, and eventually coalesce. Above 600ºC, carbonization becomes the dominant process. Carbonization is marked by the removal of most remaining non-C atoms and consequent relative increase of the C content, which can be up to 90% (by weight) in biochars from woody feedstocks [64] [65].

It is commonly accepted that each biochar particle is comprised of two main structural fractions: stacked crystalline graphene sheets and randomly ordered amorphous aromatic structures (Figure 2.5). Hydrogen, O, N, P and S are found predominantly incorporated within the aromatic rings as heteroatoms [66]. The presence of heteroatoms is thought to be a great contribution to the highly heterogenous surface chemistry and reactivity of biochar.

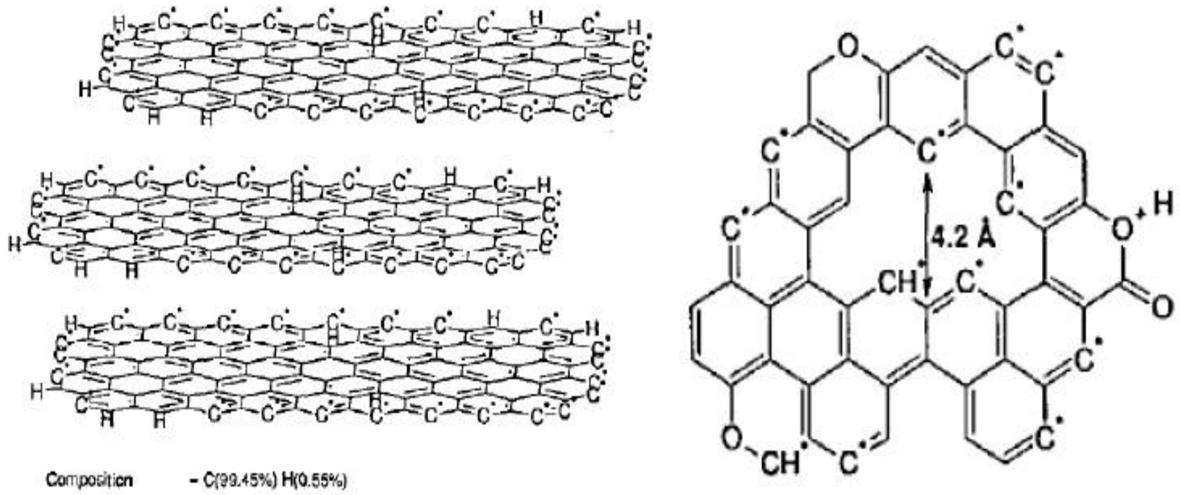


Figure 2.5 Structure of biochar. A model of a micro crystalline graphitic structure is shown on the left, and an aromatic structure containing oxygen and carbon free radicals on the right [22].

Verheijen *et al*. [22] reported on experimental results that had exhibited different functional groups with biochar molecules. Carbon atoms are incorporated to be aromatic ring including hydrogen, oxygen, nitrogen, phosphorus and sulfur atom. During pyrolysis process, breaking and rearrangement of chemical bond form the numerous functional groups occurring on the top of graphene sheet surfaces. Some groups act as electron donors (hydroxyl -OH, amino-NH_2, ketone -OR, ester -(C=O)OR) whereas the others act as electron acceptors (nitro -NO_2, aldehyde -(C=O)H, carboxyl -(C=O)OH).

Peng *et al*. [32] reported that increasing temperature had caused smaller less structured (as viewed by SEM) fragments to form with less O, H and aliphatic C functional groups, but more aromatic C, as indicated by infrared spectroscopy. Figure 2.6 shows scanning electron micrographs (SEM) images of rice straw-derived biochars produced at a range of temperature from 250 to 450 °C for duration of 4 h that with increasing temperature, the biochar particles became smaller and retained less evidence of original cell structures and figure 2.7 shows the changes of biochar spectral properties with charring temperature and duration were presented in Fig. 2.7a and 2.7b, respectively. The typical spectrum has several adsorption bands. The band around 3400 cm^{-1} was assigned to O-H stretching, 2,900 cm^{-1} to aliphatic C-H stretching, 800-1,600 cm^{-1} to C-H, C=C, C=O stretching (aromatic). Adsorption intensities at the bands 3400 cm^{-1} and 2900 cm^{-1} decreased with increasing charring temperature and duration, indicating a reduction of O, Hand aliphatic Catbonds, but the adsorption at the band 1400 cm^{-1} was intensified, which the charring temperature dependence was only evident, indicating an increase of aromatic C.

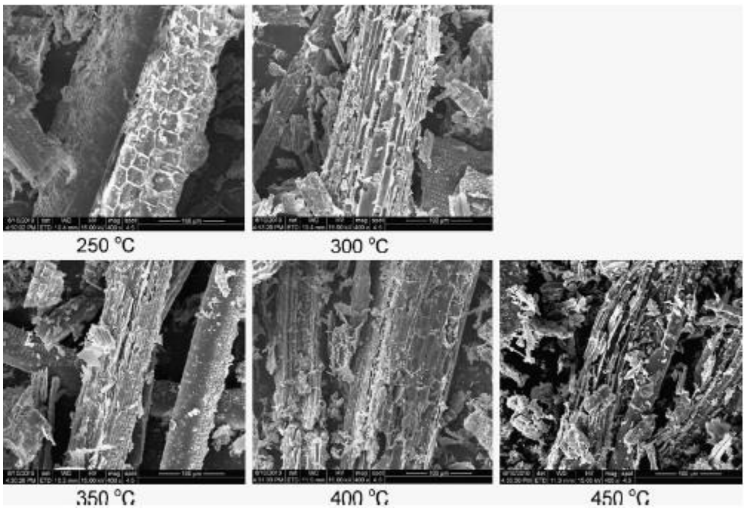


Figure 2.6 Scanning electron micrographs (SEM) images of rice straw-derived biochars produced at a range of temperature from 250 to 450 °C for duration of 4 h [32].

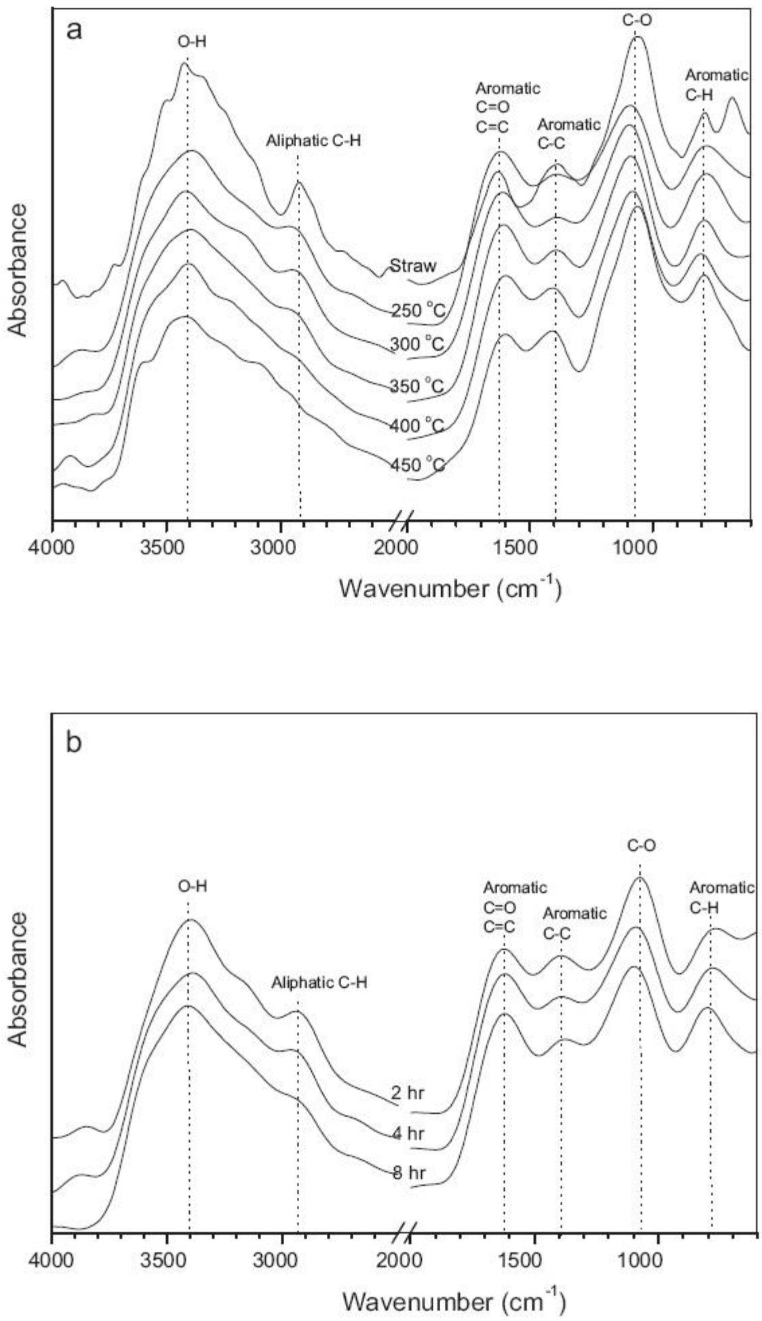


Figure 2.7 Example of infrared spectral from rice straw-derived biochar produced at (a) a range of temperatures from 250 to 450 °C for 4 h, and (b) a range of durations from 2 to 8 h at 250 °C [32].

2.2.2.3 Elemental composition

Elemental carbon and nitrogen contents increase with increasing pyrolysis temperature, while contents of hydrogen and oxygen decrease due to loss of volatile matter. These results are in accordance with others reported in the literature for different lignocellulosic materials [66].

Table 2.1 shows that increasing pyrolysis temperature with increasing percentage of P in biochar due to P is not lost pending volatilization [19].

Table 2.1 Elemental composition of biochars from different feedstocks produced at various pyrolysis temperatures

Feedstock	Pyrolysis Temp. (°C)	Elemental composition							
		Ash	C	H	O	N	S	Na	P
Peanut hull	0	3.30	50.70	6.10	38.10	1.70	0.09	---	---
	400	8.20	74.80	4.50	9.70	2.70	0.09	<0.01	0.26
	500	9.30	81.80	2.90	3.30	2.70	0.10	<0.01	0.26
Peanut shell	0	1.60	51.60	5.70	41.00	0.30	0.02	---	---
	350	35.90	46.10	3.70	8.60	4.90	0.78	1.88	2.94
	700	52.40	44.00	0.30	<0.01	2.80	1.00	2.69	4.28
Poultry litter	0	24.40	36.20	4.80	24.40	4.10	0.32	---	---
	350	35.90	46.10	3.70	8.60	4.90	0.78	1.88	2.94
	700	52.40	44.00	0.30	<0.01	2.80	1.00	2.69	4.28
Switchgrass	0	2.30	48.30	6.20	42.70	0.51	0.05	---	---
	250	2.60	55.30	6.00	35.60	0.43	0.05	<0.01	0.10
	500	7.80	84.40	2.40	4.30	1.07	0.06	0.01	0.24

The elemental composition of each feedstock was used to calculate atomic ratios as a predictor of their polarity and potential interaction with water. One would expect a biochar possessing higher H/C, O/C and (O+N)/C ratios to be more interactive with polar compounds. The atomic ratios of the biochars, because of dissimilar O and H losses, varied considerably between feedstock and pyrolysis temperatures so that the biochars were most polar (high O/C and O+N/C ratios) at the lower pyrolysis temperatures [20].

Table 2.2 shows that H/C and O/C ratios tended to be lower when increasing temperature process, partially charred plant feedstock and when using very short heating intervals.

Table 2.2 The elemental ratio and the influence of pyrolysis temperature

Feedstock	Pyrolysis Temp. (°C)	Atomic ratios		
		H/C	O/C	(O+N)/C
Peanut hull	0	1.43	0.56	0.59
	400	0.72	0.01	0.13
	500	0.42	0.03	0.06
Peanut shell	0	1.32	0.59	0.6
	350	0.98	0.32	0.32
	700	0.19	0.01	0.02
Poultry litter	0	1.58	0.51	0.6
	350	0.96	0.14	0.23
	700	0.08	<0.01	0.06
Switchgrass	0	1.53	0.66	0.67
	250	1.29	0.48	0.49
	500	0.39	0.04	0.05

2.3 Biochar production systems

Biochar is produced from technology, including gasification and pyrorysis, which yields between 2 and 35% by weight of the biomass as biochar [10]. However, there are different types of pyrolysis that could yield biochar with different physical and chemical properties, as described above. Below are summaries of the basics of the processes used to produce biochar.

2.3.1 Pyrolysis

Pyrolysis is the chemical decomposition of an organic substance by heating in the absence of oxygen. The word is derived from the Greek word, ‘pyro’, meaning fire, and “lysis”, meaning decomposition or breaking down into constituent parts. In practice it is not possible to create a completely oxygen free environment and as such a small amount of oxidation will always occur. However, the degree of oxidation of the organic matter is relatively small when compared to combustion where almost complete oxidation of organic matter occurs, and as such a substantially larger proportion of the carbon in the feedstock remains and is not given off as CO_2. However, with pyrolysis much of the C from the feedstock is still not recovered in charcoal form, but converted to either gas or oil [22].

Pyrolysis occurs spontaneously at high temperatures (generally above approximately 300°C for wood, with the specific temperature varying with the material). It occurs in nature when vegetation is exposed to wildfires or comes into contact with lava from volcanic eruptions. At its most extreme, pyrolysis leaves only carbon as the residue and is called carbonization. The high temperatures used in pyrolysis can induce polymerisation of the molecules within the feedstocks, whereby larger molecules are also produced (including both aromatic and aliphatic compounds), as well as the thermal decomposition of some components of the feedstocks into smaller molecules. Temperature itself can have a large effect on the relative proportions of end product from a feedstock (Fig. 2.8) [22].

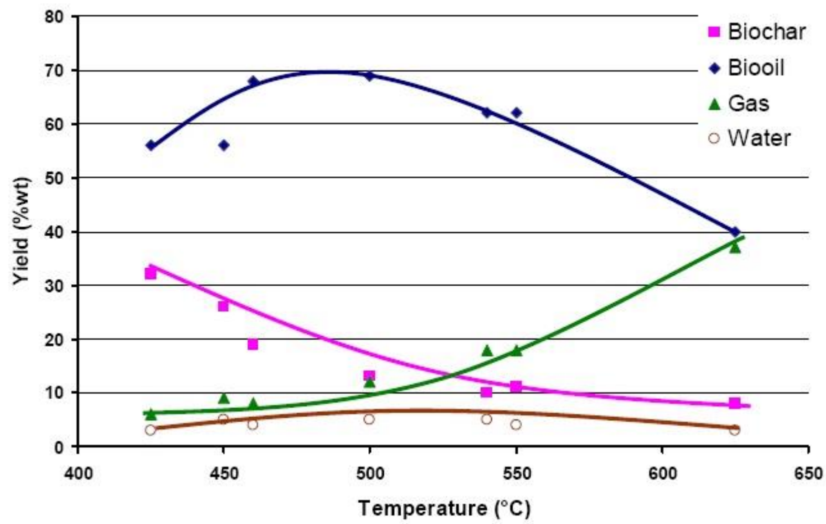


Figure 2.8 A graph showing the relative proportions of end products after fast pyrolysis of aspen poplar at a range of temperatures [22].

Pyrolysis is further divided into slow, moderate, and fast technologies, classified according to the residence time of vapor in the reactor (Table 2.3). The energy required to drive the process can be supplied (i) directly as the heat of reaction, (ii) directly by flue gases from the combustion of by-products and/or feedstock, (iii) indirectly by flue gases through the reactor wall, or (iv) indirectly by the heat carrier other than flue gases (e.g. sand, metal spheres, etc.) [67].

1) Slow pyrolysis

Slow heating in the absence of oxygen to temperatures in excess of 400°C induces the thermal decomposition of lignocellulosic biomass producing approximately equal masses of syngas, bio-oil, and biochar. In traditional charcoal kilns the syngas and the pyrolysis vapors (a multi-phase liquid formed by a decanted oil and pyrolygneous water when condensed) are vented to the atmosphere often creating serious air pollution hazards [68].

2) Intermediate pyrolysis

The term ‘intermediate pyrolysis’ has been used to describe biomass pyrolysis in a certain type of commercial screw-pyrolyser – the Haloclean reactor [69] [70]. This reactor was designed for waste disposal of electrical and electronic component residues by pyrolysis. When used for biomass, it performs similarly to slow pyrolysis techniques, although somewhat quicker [71]. Haloclean is a very flexible and rapid process that can be applied to chips, pellets, dusts, or pieces of any kind of biomass. The composition of bio-oils depends on the nature of feedstock and process conditions [72]. Other than this application the term intermediate pyrolysis has been used occasionally but not consistently in the literature.

3) Fast pyrolysis

Very rapid feedstock heating leads to a much greater proportion of bio-oil and less biochar. It was with the objective of achieving this high yield of liquid fuel that fast pyrolysis technology was developed. The time taken to reach peak temperatures of the endothermic process (the ‘resistance time’) is approximately one or two seconds, rather than minutes or hours as is the case with slow pyrolysis. The lower operating temperature also enhances the overall conversion efficiency of the process relative to slow pyrolysis. Maintaining a low feedstock moisture content of around 10% and using a fine particle size of < 2 mm permits rapid transference of energy despite relatively moderate peak temperatures of around 450°C (and in the range 350 to 500°C). The biochar product of fast pyrolysis is granular and displays a lower calorific value (23–32 MJ kg-1) than that of slow pyrolysis. However, there are currently no published studies to assess the effects of biochar from fast pyrolysis when it is applied to soil. It is highly likely that condensed volatiles will be present in the product and that this will affect its performance and desirability [73].

Table 2.3 Fate of biomass feedstock for different pyrolysis conditions [73]

Approach	Conditions	Liquid (bio-oil)	Solid (biochar)	Gas (syngas)
Slow	Moderate temperature ~500°C Long vapour residence time ~5–30 minutes	30% (70% water)	35%	35%
Moderate	Moderate temperature ~500°C Vapour residence time ~10–20 seconds	50% (50% water)	20%	30%
Fast	Moderate temperature ~500°C Short vapour residence time ~1 second	75% (25% water)	12%	13%
Gasification	High temperature >750°C Vapour residence time ~10–20 seconds	5% tar (5% water)	10%	85%

2.4 Influence of biochar application on soil fertility and crop production

Just as complex as the soil chemistry interactions, and almost certainly just as important a factor in influencing soil fertility and crop growth is the impact of biochar on bacterial and fungal populations in soils, which are intimately entwined with plant growth and nutrient access [74].

For example, the application of biochar may influence soil nutrient dynamics, which would in turn affect the soil bacterial and fungal communities present in the soil. Soil microbial communities usually exert influence on soil nutrient dynamics via the excretion of enzymes, which help to make the nutrients present in the soil or from added organic amendments more available. It is likely that the addition of biochar to the soil may have an impact on this interaction [74]. Some impacts of biochar application on soil biological aspects are described in Table 2.4.

Table 2.4 Summary of current state of knowledge regarding the influence of biochar amendments on soil biological properties [74].

Soil Parameters	Current Knowledge
Soil Microbial Population	-Microbial biomass was 43-125% higher ($p < 0.05$) overall in the Amazonian dark earth (ADE) than the adjacent soil [75]. -Microbial activity of Amazonian dark earth (ADE) is lower than neighbouring soils – lower CO_2 liberation [75]. -Biochar provides a source of chemi-sorption which affects the microbial community in soils.
Fungal Diversity	Biochar interaction with mycorrhizal fungi is the one which has been studied the most [75]. For example, Saito and Marumoto [76] also found greater levels of infection by mycorrhizal fungi associated with biochar application. Warnock *et al*. [77] suggested four possible mechanisms by which biochar might influence mycorrhizal fungi abundance. These are (in decreasing order of currently available evidence supporting them): alteration of soil physico-chemical properties; indirect effects on mycorrhizae through effects on other soil microbes; plant-fungus signalling interference and detoxification of allelochemicals on biochar; and provision of refugia from fungal grazers.

Biochar may help reduce the bioavailability of heavy metals and endocrine disruptors in some production systems and may therefore have potential in bioremediation. Several research components are working on defining the microbial-biochar-soil processes and interactions.

One study is assessing the hypothesis that biochar provides a mechanism and a habitat for microorganism, especially arbuscular mycorrhizal fungi in soil. High resolution microscopy techniques will be used to investigate the properties of biochar in relation to its suitability as habitat for survival and growth of soil microorganisms. Another research component will analyze how biochar application alters the functional stability of the microbial community. The stability of the soil microbial community influences its rate of turnover and biologically driven processes [78].

Beneficial effects of biochar application on crop yields have been reported in a number of pot and field trials [22] [79] [80] [81] [82] and other studies have reported only small or even negative crop yield responses upon biochar applications [83] [84]. Improved crop yields after biochar application have been ascribed to a number of mechanisms. A liming effect of biochar has been suggested in the literature as one of the likely reasons for improved crop yields in acidic soils [22]. Improved crop yields have also been attributed to a 'fertiliser effect' of added biochar and ash, supplying important plant nutrients such as K, N, Ca, and P. In a four year field study by Major *et al*. [85], yields of maize grain increased by 28, 30, and 140 % in year two, three and four respectively, on a Colombian savanna Oxisol. The authors attributed this to a 77-320 % greater availability of Ca and Mg in the biochar amended soils. Increased nutrient retention by biochar may be the most important factor for increased crop yields on infertile sandy soils [79] [80] [86]. For example, Chan *et al*. [80] found that additions of biochar plus nitrogen fertiliser (NH_4^+) increased radish yields more than the addition of fertiliser alone, indicating reduced N leaching and increased N use efficiency [80]. Biochar effects on the water retention and nutrient retention are expected to continue year after year, while a nutrient supply and a liming effect are short-term.

2.5 Influence of biochar on soil

Biochar has a number of specific functions in the natural environment that will be beneficial to the prevention of global warming and also to increase the functionality of soils. Decomposition of dead biomass is part of the natural carbon cycle and releases the carbon as CO_2. Fire accelerates the carbon cycle. If biochar is made from re-growing waste biomass as an alternative to burning and used as soil amendment it can enhance biomass accumulation by improving soil fertility. Therefore, biochar can be considered as a mechanism for enhancing photosynthesis (carbon capture), but decelerating the decay of the products of photosynthesis (release of CO_2). Thus, the production of biochar is a way to manipulate the carbon cycle. Photosynthesis removes CO_2 from the atmosphere and biochar stores carbon in a solid and beneficial form [87]. Also biochar can be applied to soils to enrich lands for agricultural purposes and also for reduction of contaminants [18].

2.5.1 Reduction of Contaminants in Soil

While biochar is being applied to soils for conditioning and fertilization purposes, this application can also be beneficial in the reduction of toxic components. Studies have shown that biochar is also capable of absorbing metals such as lead, and organics that contaminate soils which harm people, plants and animals [88]. This is because biochar as an additive to a soil can be expected to improve its overall absorption capacity impacting toxicity because there is a decrease in transportability and depletion of the presence of metal or organic compounds [18]. Biochar comes with the appeal of being a low cost and low-environmental-impact strategy for remediation of common and health concerning environmental pollutants. Studies have shown that biochar in combination with activated carbon sinks have comparable absorption abilities, which helps in removal of contaminants such as the herbicide atrazine [88].

Through experimental methods, the results have shown that metal ions are strongly adsorbed onto specific active sites containing acidic carboxyl groups at the surface of the charcoal [22]. According to biochar application to soil, contaminant metal intake by charcoals involves replacing already existent ions contained in the charcoal with the metal ion in the soil, suggesting a potential correlation between content of the biochar and its remediation potential for metals [22].

2.5.2 Biochar effects on greenhouse gas emissions

2.5.2.1 Non–carbon dioxide greenhouse gas reduction potential with biochar application

Methane (CH_4) and nitrous oxide (N_2O) are respectively 25 and 298 times more potent greenhouse gases (GHG) than is carbon dioxide (CO_2) [89]. It follows that reducing the emissions of these gases can have a large impact on climate change mitigation. While there are natural sources of CH_4 and N_2O emissions, the major man-made sources of CH_4 include emissions from paddy (flooded) rice fields, livestock production systems, biomass fires, fuel charcoal burning, firewood burning, and the anaerobic decomposition of organic waste [90]. Major anthropogenic sources of N_2O include agricultural soil management (including the application of N fertilizers), animal manure and human sewage management, the combustion of fossil fuels, and the industrial production of certain chemicals [91]. Evidence available to date suggests that biochar technology can potentially reduce CH_4 and N_2O emissions from field soil, and may help in avoiding CH_4 production from certain biomass wastes.

Van Zwieten *et al.* [92] proposed several mechanisms through which biochar can affect the emissions of N_2O and CH_4. Biochar affects soil physical and chemical properties, which can in turn affect the microbes responsible for producing N_2O and CH_4. For example, biochar can potentially improve soil aggregation, which would improve aeration. Due to their porous nature, biochar particles can also directly improve aeration of the soil around them. This improved aeration means that the microbial processes which produce N_2O and CH_4 will not be favored. Changes in soil structure may also favor different species of microbes with different metabolic requirements. Chemically, biochar can impact the soil's pH, the availability of inorganic N, the overall quality of available organic matter for microbes to degrade, and the redox potential of the soil. Biochar can also potentially cause a direct reduction in N_2O emissions through various mechanisms occurring on the surfaces of biochar particles and pores. The highly complex crystalline structure of biochar has areas of high potential for adsorption and reduction of N_2O to N_2. These mechanisms remain to be studied and demonstrated.

Methane is a greenhouse gas that is 25 times more effective in trapping heat in the atmosphere than a carbon dioxide over a 100-year timescale [93]. It is emitted from various natural and human sources, including wetlands, landfill and agricultural practices. Acetate, formate, carbon dioxide and hydrogen gas are all substrates for methane production by methanogenic bacteria, when organic matter is decomposed in the soil environment [92].

Aerobic, well drained soils are commonly a sink for methane due to high oxidation rates by methanotrophic organisms (Figure 2.9). However, the methane uptake capacity of a soil is dependent on a number of factors, including land use, management practices, temperature and soil conditions [92]. Conversely, methanogenesis (production of methane by methanogens) is greatest in regions with warmer climates and where anaerobic conditions prevail (including landfill, wetlands and rice fields). Both methanogens and methanotrophs are ubiquitous in soil and may occur in close proximity to one another [92].

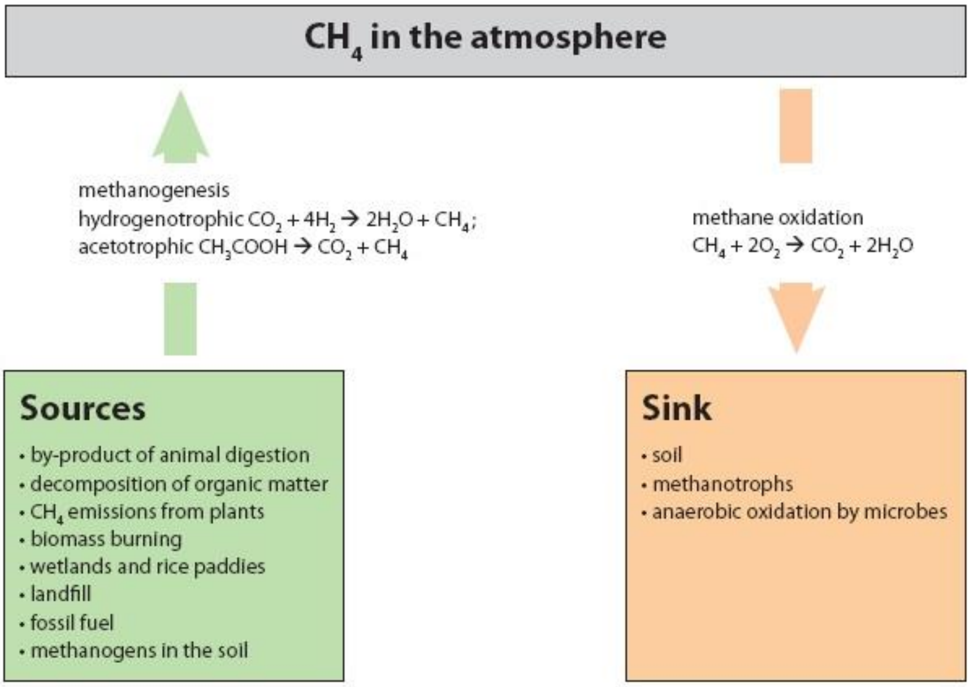


Figure 2.9 Sources and sinks for methane production (methanogenesis) and oxidation (methane uptake) relevant to the agricultural sector [15].

Oxygen concentration in the soil environment is the main limiting factor for the oxidation of methane by methanotrophs. As such, increasing oxygen concentrations in soil through decreasing soil density and increasing porosity through biochar application appears to be a viable option. Evidence that biochar increases methane oxidation in soils is extremely limited.

Major [94] reported that in landfill waste, CH_4 is also produced in piles of biomass residue remaining after biomass processing operations at a variety of scales, such as sawdust, fruit pits, nut shells and empty oil palm bunches after oil extraction. Using appropriate portions of landfilled waste and other biomass waste to make biochar would reduce the quantity of waste that would otherwise decompose, and in turn reduces the associated CH_4 emissions.

Singh *et al*. [95] reported that rice cultivation in flooded systems produces significant amounts of CH_4, at least partly due to the anaerobic decomposition of crop residue in oxygen-limited conditions. Using these crop residues to make biochar could reduce emissions of CH_4 generated from their *in situ* decomposition, apparently without reducing soil organic carbon contents in the long term.

Levine [96] reported that CH_4 emissions from biomass burning contribute about 10% of total CH_4 emissions on an annual basis. While some biomass burning is caused by wildfires, the greatest proportion of it results from deliberately set fires to clear land or to burn crop waste. Another significant source of biomass burning is fuel wood used for cooking and heating activities in developing countries. Making biochar from crop residues instead of burning them could reduce CH_4 emissions. Also, improved cooking stoves including biochar-producing stoves, could reduce such emissions if their use is widely implemented.

On the flooded rice patty fields in China it was found that applying wheat straw biochar at 0, 10 or 40 t/ha caused greater CH_4 emissions during the first growing season, while N_2O emissions were reduced [97]. Overall, the CO_2-Ce impact of the biochar amendments was significantly greater, both on a per ha and a per ton of rice produced basis, than in the unamended plots [97]. Further study is required to assess the impact of biochar amendment on flooded systems in the long term and irrigation regimes different from that studied. Also, it would be useful to carry out GHG life cycle analyses on this specific production system, to understand the net effect of combined rice crop residue management and biochar management. As indicated above making biochar from rice straw instead of allowing it to decomposed in situ could cause a reduction in CH_4 emissions.

Nitrous oxide is also a significant contributor to global warming (it contributes approximately 8 per cent to global greenhouse gas emissions), but relatively little research has been undertaken to investigate mitigation methods for this gas. Nitrous oxide is a soil-derived greenhouse gas and is produced through biological processes, such as nitrification and denitrification (Figure 2.10).

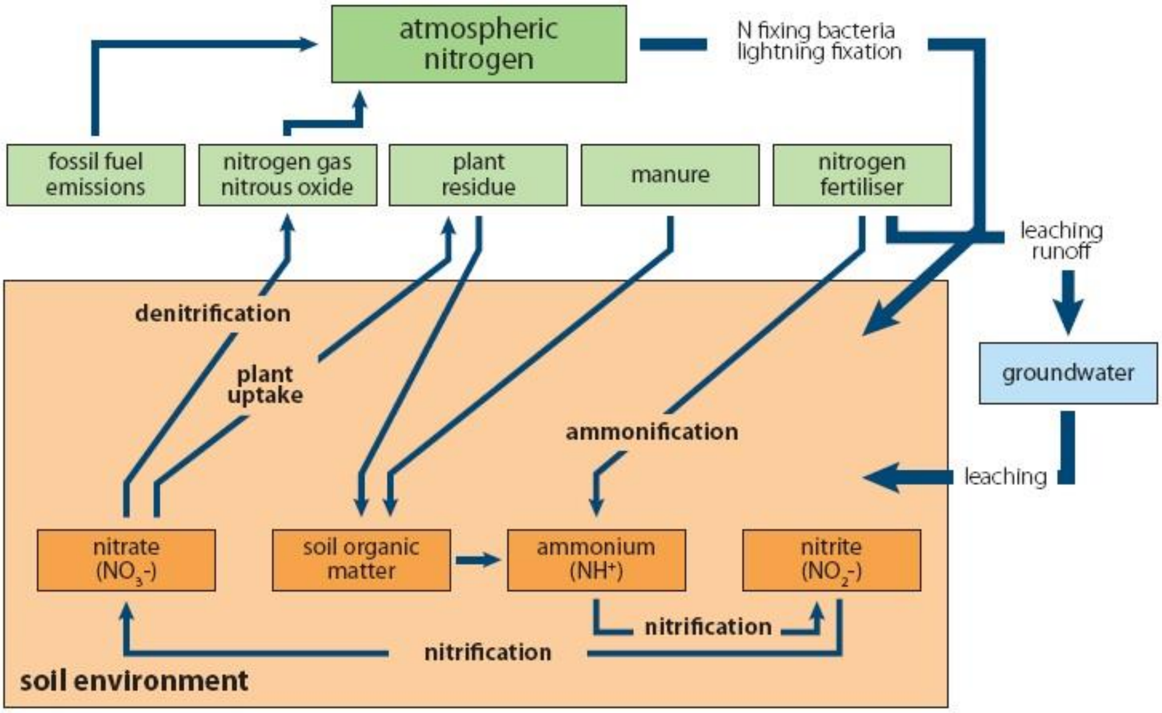


Figure 2.10 Nitrogen Cycle [15].

Note: Nitrogen applied through fertiliser application or animal manure is converted into ammonium (ammonification). Ammonium is oxidised to nitrite, which is converted to nitrate (nitrification), which is reduced to nitrous oxide or nitrogen gas (denitrification). Nitrates are also taken up by plants and are converted to proteins (both plant and animal).

A number of soil properties influence these biological processes, including available nitrogen and carbon, soil pH and water-filled pore space [98] [99]. The rate of nitrification increases as soil moisture increases, up to 0.6 water-filled pore space, but is increasingly inhibited by low oxygen concentrations beyond 0.8 water-filled pore space [99]. Further, as a result of irrigation and rainfall events, soil moisture conditions fluctuate between wet and dry periods. This fluctuation increases the availability of dissolved organic carbon and nitrogen, therefore increasing nitrous oxide emissions from the soil [99].

Nitrogen fertilisers, biological nitrogen fixation by soil biota, soil organic matter content, and animal manure and urine are all sources of nitrogen that can lead to nitrous oxide emissions from the soil [92]. Specifically, nitrogen fertiliser application rates, crop type, fertiliser type, soil organic carbon content, soil pH and soil texture are factors that significantly influence nitrous oxide emissions from the agricultural and forestry sectors.

For example, in New Zealand broadacre grazing systems, urine patches from livestock are the major source of nitrous oxide emissions, as a result of the high rate of nitrogen application to these patches surpassing the pasture's ability to use the deposited urinary nitrogen [97]. As such, it is important to understand the biological processes in the formation of nitrous oxide to ensure optimal management of biochar additions to soil, while minimising nitrate leaching.

Biochar has been found to increase nitrification rates in natural forest soils that have very low natural nitrification rates. However, in agricultural soils, which already have appreciable rates of nitrification, the effect of biochar on nitrification was found to be minimal. In some cases, biochar additions to agricultural soils also decreased apparent ammonification rates (that is, the breakdown of organic forms of nitrogen to ammonium) [100]. Similarly, Granatstein et al. [29] found that the addition of biochar to soils led to a decrease in soil nitrate production (nitrification) and a decrease in the amount of nitrogen available to plants.

Yanai *et al.* [101] also found that the addition of biochar up to 10 per cent reduced nitrous oxide emissions by 89 per cent, but only when the soil was rehydrated with 73 to 78 per cent waterfilled pore space. However, biochar added to soils rehydrated at 83 per cent water-filled pore space significantly stimulated nitrous oxide emissions compared with the control [101]. This illustrates the complex interactions between soil properties and the biochar applied.

According to Sohi *et al*. [11], no peer-reviewed studies documenting the suppression of nitrous oxide emissions in field experiments have been reported. There are, however, conference proceedings and laboratory-based peer-reviewed studies reporting reductions in nitrous oxide emissions [102]. Rondon *et al*. [103] found that adding biochar significantly reduced net methane and nitrous oxide emissions when infertile Colombian savannah soils were amended with biochar at a rate of up to 30 grams per kilogram of soil.

Researchers found that nitrous oxide and methane emissions were reduced by up to 50 and 100 percent respectively, at an optimal application rate of 20 grams of biochar per kilogram of soil [103]. Similarly, Spokas *et al*. [104] found that the suppression of both methane and nitrous oxide at levels up to 60 per cent inclusion rates in laboratory trials (corresponding to 720 tonnes biochar per hectare).

2.5.2.2 Soil organic matter and carbon dioxide emissions

Biochar has the potential to sequester carbon for decades and up to millennia, but a number of studies have found that biochar additions to soil increases soil organic matter mineralization, and consequently, carbon dioxide emission rates [85] [104]. Spokas *et al*. [104] found that adding biochar and moisture to a silt loam soil increased overall production of carbon dioxide. Sparkes and Stoutjesdijk [15] attributed this increase to reactions involving water and oxygen in the closed space above the biochar and soil. It is also possible that the carbon dioxide had been produced by labile or reactive components adsorbed to the biochar [104]. Further, Major *et al*. [85] found that cumulatively, 41 and 18 per cent more carbon dioxide was emitted when biochar was applied to soils, compared with the non-amended soil in the first and second year, respectively. However, these results appeared to be a transient increase in carbon dioxide emissions, with an expected net reduction in emissions over the longer term.

Jones *et al*. [105] has shown that instead of biochar stimulating the mineralization of soil organic matter, it represses it (at least over the short term). While short term increases in carbon dioxide emissions from soils were detected, the source of the carbon dioxide was from both the biotic (living organisms) and abiotic (non-living chemical and physical factors) release of carbon from the biochar. The amount of carbon dioxide released from the biochar only amounted to 0.1 per cent of the carbon contained in the biochar. This research may affect the potential of biochar to reduce carbon dioxide emissions, but further analyses must be undertaken to identify the effects of biochar additions on soil organic matter, carbon dioxide emissions and carbon storage potential.

2.6 Limitations and barriers to implementation of biochar application in soil

Limitations and barriers also hinder the production and adoption of biochar by the agricultural sector. Due to the heterogeneous nature of biochar, the cost of production and the limited pyrolysis facilities. Biochar application to soils remains limited. Agreed national policy and industry guidelines on biochar production, quality and use could help increase use of biochar [15]. Macias and Arbestain [106] showed that each biochar produced has a unique set of properties, based on production conditions and the feedstock used. Also, soils may respond differently based on variables such as the type of biochar used, soil type, climatic zone and land use. However, the heterogeneity of available biochar feedstocks and types provides an opportunity to purpose-produce biochars well suited for particular situations and objectives. It is possible that specific biochar types can be created for different soils and land-use applications to ensure sustained, net benefits are achieved.

However, due to an incomplete understanding of the processes that occur when biochar is added to soils, it is difficult to predict the agronomic effects in different situations [107]. Well-designed laboratory and field studies are underway at scales sufficient to enable the assessment of agricultural and environmental benefits and risks of using biochar. The experience and evidence gained from these studies will provide further information for developing an accurate predictive model for applying biochar to different soil ecosystems [15].

Due to the infancy of the biochar–bioenergy industry, the supply of biochar from commercial pyrolysis plants is limited and localized in Australia [106]. Consequently, appropriate biochars are expensive, with current biochar research activities predominantly restricted to laboratory trials. If field trials are undertaken, they may be expensive and hence restricted in size and/or scope. The cost of biochar for research and for application by farmers is likely to remain a constraint until commercial-scale pyrolysis facilities are established. Unfortunately, the uncertainty around the net greenhouse gas, agronomic and environmental benefits may be deterring the very investments that would pave the way to reducing the cost of research; and hence, the uncertainty.

The lack of regulation within the biochar–bioenergy industry also affects the quality of biochar products. For example, some farmers are producing their own biochar in uncontrolled conditions [11]. Through unregulated production of biochar, unnecessary emissions of greenhouse gases may occur; with the resultant biochar being unsuitable (unstable) for both carbon sequestration and soil amelioration. In addition, there is neither control on the feedstock source, nor an indication as to whether an accumulation of toxic substances in the final product will occur [11]. As such, production parameters and quality control standards need to be developed and implemented to ensure net benefits are realized. As well, a classification system for biochar products is essential to ensuring targeted biochar production for application to specific soil types [15].

More data is needed before firm predictions can be made about biochar's effect on soil performance across a wide range of soil types, climatic zones and land management practices [65]. Predictions about performance are needed for considering the feedstock and production characteristics employed in producing biochar. Development of a classification and governance system will be essential to maximizing the net benefits of biochar production, while limiting the potential negative environmental effects [15].

2.7 The economic cost for reducing greenhouse gas (GHG) emissions through biochar application

Many countries are now launching programs on carbon reduction and have encouraged industries to reduce carbon emissions appropriately. On many circumstances, it was observed that industries that release more carbon into the atmosphere may be assigned to engage more in carbon reduction. However, such a carbon reduction concept may turn out to be economically inefficient and expensive as carbon reduction activities may end up taking place by high cost firms in polluting industries. If high cost firms are engaged in carbon reduction the whole economy will inevitably become worse off as more resources will be mobilized towards carbon reduction unnecessary. From the economic perspective, it is necessary to establish a mechanism where carbon reduction is carried out by low cost firms hence enabling the whole economy to engage in carbon reduction in at least cost or cost efficient manner.

Economic instruments, through their encouragement of flexible selection of abatement measures, may offer the possibility of achieving environmental improvements at lower costs than regulatory instruments. They also offer the opportunity for countries to introduce limitation/reduction and adaptation measures while more detailed regulatory or other measures are being formulated and implemented [108]. However, it is unlikely that, in the final analysis, economic instruments will be applicable to all circumstances. Some combination of economic and regulatory measures will most likely be appropriate. Provision of information and technical assistance are seen as a valuable complementary instrument.

Economic instruments offer the possibility of minimizing the total social costs of achieving national goals and international commitments relating to climate change. They seek to meet limitation/reduction or adaptation objectives by adjusting or harnessing market forces to take into account environmental costs. However, the use of economic instruments raises moral concerns in the minds of some contributors relating to the fact that some of the economic instruments imply "paying for the right to pollute" and that economic instruments introduce a profit motive element into the achievement of public goals of environmental protection. Others have responded that regulations allow for the same rights to pollute, the only difference being in the transferability of the right, and that regulation does not banish the profit motive, since profit opportunities in regulatory systems are often directly dependent on securing favorable regulatory treatment. Indeed, the misuse of resources in lobbying for favorable regulatory treatment represents a considerable drawback of the regulatory approach.

Looks at measures that might be used in centrally planned economies to reduce emissions and then examines the role of regulations in market economies. Because of the differences between the social and economic structures in different countries, different combinations of instruments or at least different emphases in their use will be required. In the particular case of centrally planned economies, the central plan encompasses a comprehensive set of regulations and is the major instrument for achieving sustainable limitations or reductions in emissions. Central planning provides possibilities for the government to coordinate and direct all efforts to limit or reduce emissions. Possibilities include: planning emissions reductions/limitations by those enterprises that can achieve them best at least cost so as to minimize the financial burden to society as a whole; provision of loans on favorable terms for environmentally sound investments; and alterations in price regulations to enhance the introduction of new environmentally acceptable technologies and activities. The instruments that might be considered as alternatives or supplements to the regulations are tradable emission permits, emissions charges, subsidies and sanctions.

1) Tradable emission permits

Generally, an international programme will carry with it the same benefits and difficulties as will a national programme. The potential cost savings may be higher but the level of the administrative and enforcement complexity could be even more severe. A n international body of some kind would be required to identify whether the allowable limit of pollution was being exceeded. In addition, political concerns about the "right to pollute" and the ability of wealthy nations to procure those rights would be greater. Also, there is a lack of experience of these programmes at the international level [108].

Major concerns were expressed by contributors over the use of tradable emission permits, some believe that an international system of tradable permits was not advisable. While it was agreed that studies of tradable permits should continue, these countries asked that their major misgivings should be taken into consideration. There are a number of other issues associated with a tradable emission permit programme that need further exploration, including: the political problem created by a "right to pollute"; the criteria used to determine the initial allocation of emission entitlements; the special situation of developing countries; the potential scope and size of a trading market; and the feasibility of the administrative structure that would be required to implement such a programme, including the conditions necessary for them to be feasible, such as identifiable emission point sources, standard metering practices, availability of comprehensive and up-to-date information on options, and a market in which to trade permits [108].

The contribution from the Environmental Defense Fund discussed in some detail the practical arrangements that might be adopted in the implementation of a system of tradable emission rights, both at national and international levels. This and other such work should be consulted in the further development of proposals that might utilize this instrument. Some contributors thought that an alternative approach to a system of emission charges would be to have the polluter pay by conducting research designed to reduce emissions—e.g., through an appropriate tax credit system [108].

2) Emissions charges

Emission charges are levies imposed in relation to the level of emissions. They provide a means of encouraging the limitation or reduction of emissions to a level that is socially desirable [108]. They also provide an ongoing incentive for the parties concerned to implement efficient means of limiting or reducing emissions by, for example, implementing energy efficiency measures [108]. For governments, the major attraction of taxes may be the revenue they generate. This revenue could provide a funding base for further pollution abatement, research, and administration. It could also enable other taxes to be lowered, budget deficits to be reduced or government expenditures to be increased in other fields [108]. Recent work by the Organisation for Economic Co-operation and Development (OECD) has shown that the use of taxes to fight pollution has been growing in popularity amongst OECD countries, although the experience to date shows that the primary function of pollution taxes (which in the climate change context can be emission taxes) has been to raise the revenue required for pollution management. The taxes have not generally been set high enough to influence the behavior of polluters [108]. There are some problems associated with the use of emissions charges. These will require careful consideration in the development of response strategies that might make use of this option.

First, it is difficult to assess the optimal rate at which the tax should be applied in order to meet national goals, where these can be defined in terms of technical levels of emissions. Unlike regulations or the system of tradable emission rights, the level of emissions is not set directly but attained through the market responding to the taxes. In order for national goals to be attained, some quite detailed knowledge is required about how the market is likely to react to different taxation levels. This information could be difficult and expensive to acquire. Second, there is the difficulty of deciding on the basis for the taxes and how they would be collected. (This criticism also applies to a number of other economic and regulatory instruments.)

The implementation of a coherent emission tax regime at the international level poses further practical difficulties. In particular, factors, such as varying local price elasticities and tax structures, exchange rate fluctuations, etc., mean that it would be extremely difficult to derive with any confidence a uniform tax that would lead to the required limitation or reduction in emissions, where there is sufficient technical knowledge to enable such an emission level to be specified [108]. A reasonable and practical option would be to give each country flexibility to set its own national charge rates at a level that would achieve its national goals. However, some contributors felt that an international levy system should not be discarded from consideration in this context. It is evident that the question of emission charges raises many complex and difficult issues. Careful and substantive analysis of the short and long run environmental and economic impacts of such measures is needed [108].

3) Subsidies

The use of subsidies to limit or reduce greenhouse gas emissions by developing countries is discussed in the financial mechanisms. This section looks at the domestic use of subsidies [108]. Subsidies and government financial assistance (hereinafter referred to as "subsidies") are aimed at assisting environmentally sound goods and actions by lowering their costs [108]. Various forms of subsidies have been used, among other things, to encourage the use of energy efficient equipment and to encourage the use of non-fossil energy sources. These include direct grants, low interest rate financing, loan guarantees, tax deferrals (e.g., accelerated depreciation), tax credits, etc [108]. Because of the external public benefits of developing environmentally sound technologies, subsidies could be used to encourage the development and greater use of such technologies. A number of difficulties are associated with the use of subsidies [108].

4) Sanctions

The use of economic sanctions for the enforcement of international agreements [108] would require an international convention to establish a system of agreed trade or financial sanctions to be imposed on countries that did not adhere to agreed targets. The aim here would be to discourage non-complying countries from deriving benefits without taking action. Discussion of trade sanctions has already taken place under the Montreal Protocol in relation to products containing CFCs and halons. Sanctions might range from the imposition of import taxes on the offending products to outright bans until the exporter conforms with agreed international standards. The mechanisms for operating such a system would need to be made consistent with existing trade agreements, such as GATT [108]. However, many contributors expressed considerable reservations about applying this measure to greenhouse gases other than CFCs and halons because of the complexity of the situation [108]. In particular, it would be difficult to monitor the many diverse sources of greenhouse gases. Moreover, it was felt that sanctions could appear arbitrary, since it could be difficult to determine accurately whether particular countries exceeded internationally agreed levels or not [108]. This could create confusion and resentment as to why they were subject to the sanctions. Some contributors objected to the concept of sanctions because of the risk that they could be used as a pretext to impose new non-tariff barriers on the exports by developing countries [108].

While biochar has the potential to deliver a number of benefits to the agricultural sector, its economic viability must also be considered to ensure significant development within this emerging industry [15]. The economic viability of the pyrolysis system for producing biochar is highly dependent on a number of factors, including feedstock costs, the process itself and the value of end products [15].

When choosing a feedstock to produce biochar, it is essential to undertake a full life-cycle assessment to estimate the economic costs of a particular system. For example, when considering crop stubble as a potential feedstock, the harvest, transportation and opportunity costs of using the crop stubble for a different purpose (such as preventing soil erosion and supplying nutrients to future crops through soil organic matter) must be examined. By considering these factors it has been estimated that the potential farm-gate price of maize residue for producing biochar is US$27.59 per tonne (Table 2.5) [109].

Table 2.5 Economic analysis of fast and slow pyrolysis for biochar production using crop stubble in the United States [109]

	Fast pyrolysis (US$ per tonne of feedstock)	**Slow pyrolysis** (US$ per tonne of feedstock)
Farm-gate cost	–27.59	–27.59
Transportation cost [a]	–6.86	–6.86
Storage of seasonal crops [b]	–25.00	–25.00
Value of energy created	100.00	25
Biochar value	2.00	15.75
Biochar transportation cost	–0.39	–3.07
Fixed cost of pyrolysis facility	–34.13	–21.28
Facility operating costs	–55.95	–31.58
Greenhouse gas offset value [c]	3.29	4.55
Total value of production	–44.63	–70.08

[a] Assuming average transportation of 14.8 km.
[b] Storage of seasonal crops will ensure a continual supply of feedstock for the pyrolysis process.
[c] Includes offsets for displaced fossil fuels and potential of biochar to sequester carbon.

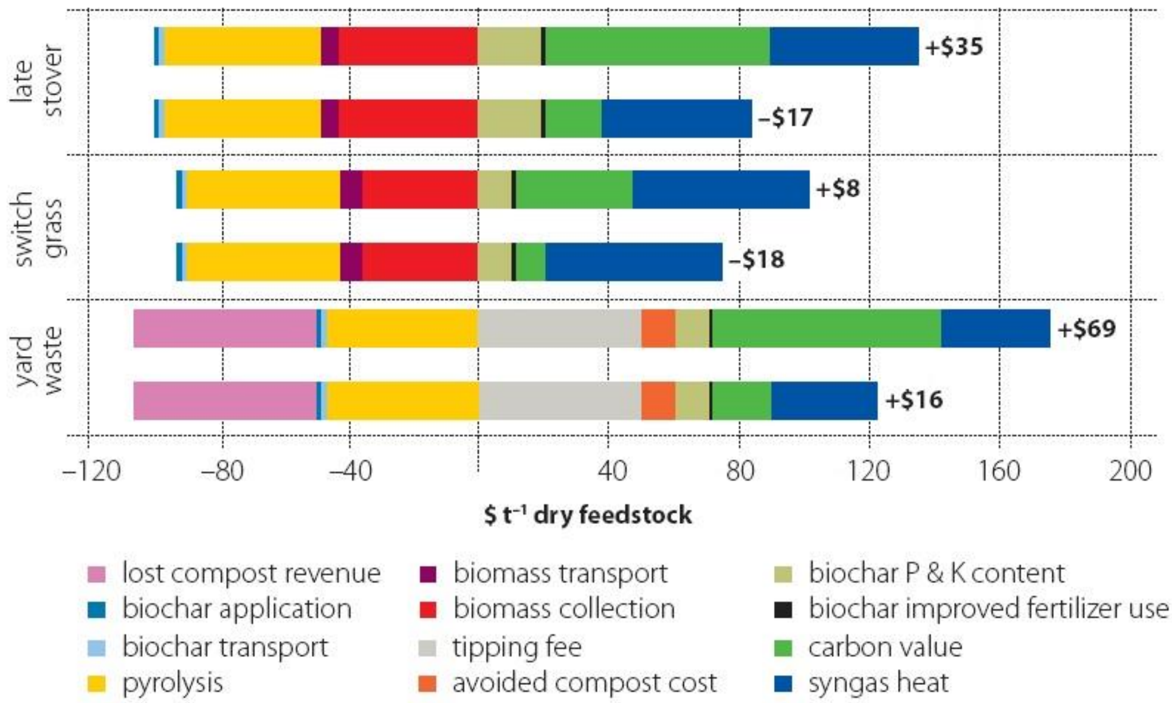
Production of biochar from yard waste (such as grass, leaves and other wastes from lawns for composting) and manures may also prove beneficial as it may reduce waste disposal costs and minimise greenhouse gas emissions from the normal breakdown of these waste feedstocks. Roberts *et al.* [13] found that biomass sources that need waste management have the highest potential to become commercially profitable. This is primarily due to the avoided costs of waste management, as well as the potential to avoid greenhouse gas emissions (methane and nitrous oxide). However, the volume of feedstock produced and the moisture content of the biomass must be carefully examined. If the feedstock has high moisture content, any additional energy needed to dry the biomass and initiate pyrolysis may reduce the financial benefit of the system.

Biochar production systems vary greatly in location and size. Both factors have major impacts on the profitability of the system. Generally, two processing options are available to producers: the pyrolysis plant can be located either on-farm with biomass processed on-site or at a communal site with biomass transported to the plant [110]. Generally, a centralised plant will be large and capable of high throughputs, but will also require large capital investment. In contrast, the small, generally mobile pyrolysis plants require less capital investment, but labour costs are typically high and little to no potential excess bioenergy from pyrolysis is used [29]. One study found that only large-scale stationary pyrolysis plants were viable, where biochar was produced in conjunction with bio-oil [29]. The cost of biochar production was estimated at US$87 per tonne of biochar using a large-scale fast pyrolysis plant.

The transportation distance of feedstocks may also decrease the profitability of the system [111]. Lehmann and Joseph [110] identified that 20 per cent of feedstock cost was attributable to transportation and that the cost would significantly decrease if the processing plant was located close to the biomass feedstock. Transportation distance not only has an effect on net profitability of a processing system, but will also affect other potential benefits such as net renewable energy production and net reductions in greenhouse gases as a result of the production of biochar and bio-fuels.

The financial benefits of biochar production comes from a number of potential sources depending on the type of pyrolysis used, and includes energy production, biochar production and as a carbon offset in future emissions trading schemes. As shown in Table 2.5, both fast and slow pyrolysis plants are unprofitable under current United States conditions [109]. However, if the value of biochar increased from US$47 per tonne to more than US$246 per tonne, slow pyrolysis would be viable for the biochar producer. In Australia, anecdotal reports indicate a cost of $5000 per tonne to purchase biochar from processing companies.

Figure 2.11 illustrates the potential for both high and low income scenarios when a greenhouse gas offset is considered ($80 per tonne versus $20 per tonne). Although income is received through the sale of biochar and bioenergy, the overall profitability of the process is minimised by the costs of production, even when carbon offsets are valued at US$80 per tonne carbon dioxide equivalents [13].



Note: The top bar in each feedstock type represents the high greenhouse gas revenue scenario and the bottom bar in each feedstock type represents the low revenue scenario. The value at the end of each bar represents net profit/loss for each scenario.

Figure 2.11 Analysis of the costs of biochar production and potential attainable revenue per tonne dry feedstock for late harvest corn stover, switchgrass and yard waste [13].

The financial justification for developing a biochar pyrolysis system would depend on the price received for biochar and bioenergy products, and any value of avoided carbon dioxide equivalent emissions, the cost of feedstocks used and the cost of pyrolysis itself. Development and commercial viability of a biochar industry would be highly reliant on proven benefits to ensure demand for specific biochar products. Feasibility studies are scarce in this emerging industry, and as such, the commercial viability of biochar production remains unclear, especially in the Australian context. Further research is needed to ensure the viability of pyrolysis plants and confirm the potential benefits of biochar application to soils [15].

The Australian Government's Carbon Farming Initiative may also influence uptake of biochar use in agricultural systems [15]. The Carbon Farming Initiative is a carbon offset scheme for crediting emission reductions and sequestration in land-based sectors.

These offset credits will be able to be sold on domestic and international carbon markets [15]. The application of biochar to soils has been placed on the draft Carbon Farming Initiative Positive List, meaning this activity is likely to be eligible for crediting. However, all eligible activities need an approved methodology to enable the quantification of emission reductions or sequestration [15]. There are currently no approved methodologies for biochar. Further research may be needed before a methodology can be found to meet the integrity standards of the Carbon Farming Initiative [15]. To fast track this process, the Australian Government is providing additional funding under the Carbon Farming Initiative for the Biochar Capacity Building Program [15]. This program will help provide practical mitigation options for land holders by assessing the greenhouse gas mitigation potential of biochar. These options may then be considered for the generation of offset credits under the Carbon Farming Initiative [15].

However, estimating biochar production costs is fraught with uncertainties. It is none- the less important that attempts to provide such estimates are undertaken since costs are a crucial indicator in directing future investments in research and development. From this analysis is that there is a very wide variation in biochar production costs and what is clear is that greater certainty on biochar production costs will not be forthcoming without much better data being available on the costs of constructing and operating slow pyrolysis facilities [112].

CHAPTER 3

METHODOLOGY

3.1 Overviews

Financial costs associated with biochar production and application includes both the direct and indirect costs. Since the indirect cost estimate involves complex requirements in terms of methodology and data needs, this study focuses only in estimating the direct costs of biochar applications to agricultural soils. Cost of different feedstock available in Thailand and the potential soil carbon sequestration and greenhouse gas mitigation were investigated. The study started from the step for feedstock production, pyrolysis of feedstock yielding biochar, and the application of biochar to increase soil carbon sequestration and reduce greenhouse gas emission. The amount of inputs (such as fertilizers, fuels, labor, water, etc.) as well as investment cost and incomes were collected from field surveys and questionnaire. Other indirect benefits such as the benefits due to increasing crop yield results from biochar application, improve soil fertility or other environmental benefits were not considered in the current study. The overview of the research framework in this study is illustrated in Figure 3.1.

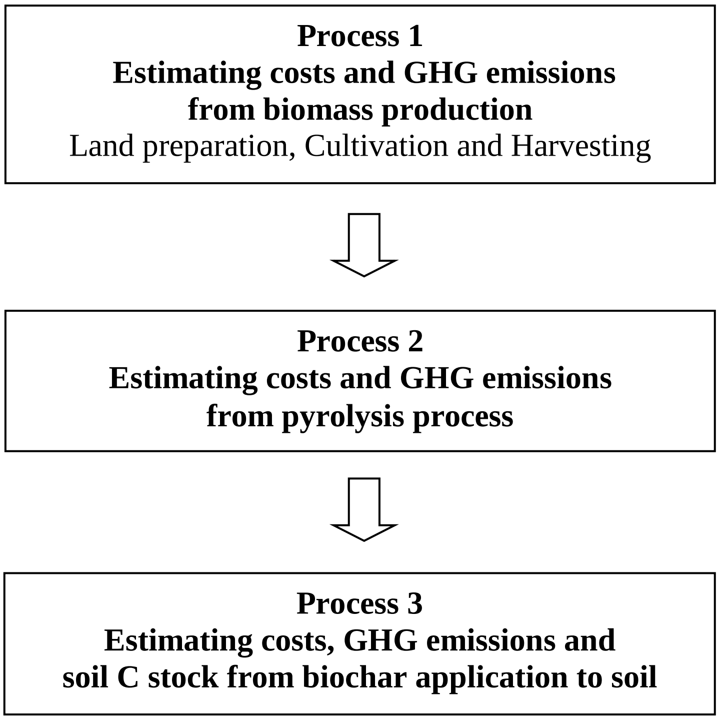


Figure 3.1 Schematic diagram of research framework

3.2 Study sites

This study is based on data collection activities from 3 farms/sites where biochar is being used for soil amendment (Figure 3.2). Several field surveys and farmer interviews to collect data were made in 2013-2014 at these 3 study sites. The first site was at the New Theory Farming Center, Mae Taeng District, Chiangmai Province. The farmer is growing rice with alternative wet and dry technique. The produced biochar from rice husk and bamboo was applied directly to soil. The purpose of this practice is to enhance crop productivity and to reduce the use of chemicals accompanied with crop production. The second site was at Yeesarn Community, Ampawa District, Samut Songkarm Province, central Thailand. Mangrove plantation (*R. apiculata*) here was under intensive management specifically for charcoal production. Generally, the owners of the plantation are responsible for management and utilization of the mangrove resources. The third site was Huay Sai Royal Development Study Center, Phetchaburi province. Here biochar was made from two main feedstocks; corn cobs and many types of softwood such as acacia, mango and neem, collectively termed “mixed woods” in this study. These were the wastes from pruning, lawn mowing and other routine plant care activities.

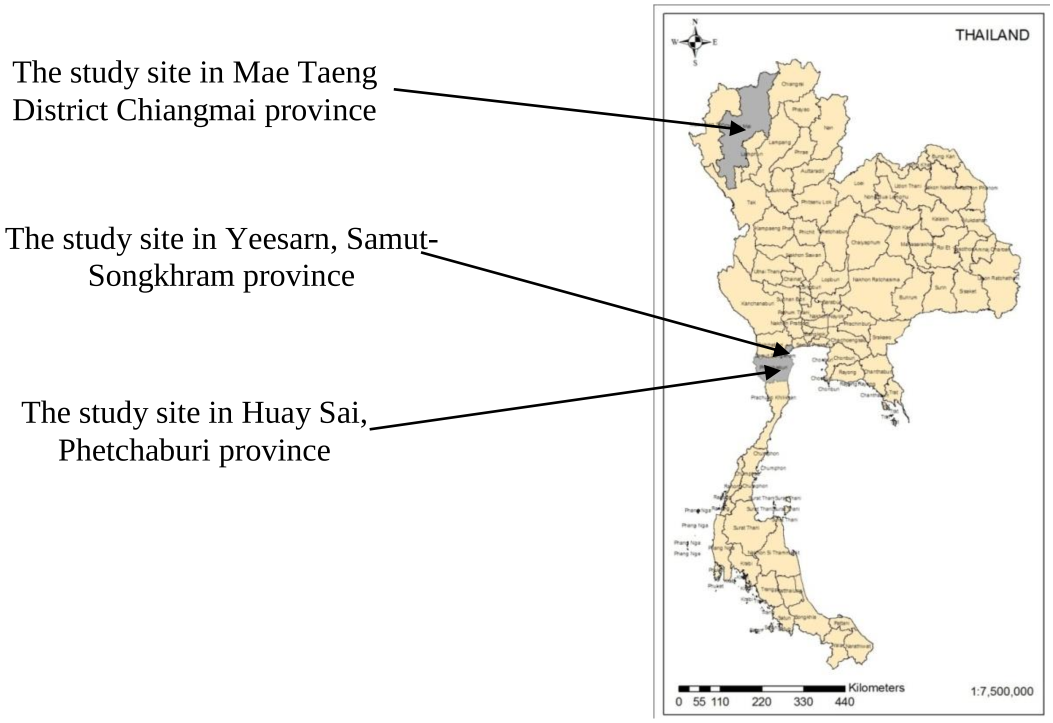


Figure 3.2 Map showing the location of study sites

The reason for selecting these 3 study sites to get their knowledge farther from the previous studies by develop/expand from the research to cover a variety of activities.

3.3 Data collection and analysis

Several field surveys were made to collect data on cultivation practices, biochar production and costs associated with these activities.

3.3.1 Production of feedstock

The information about the general features of farms, farm operations and energy utilization was obtained through a questionnaire. The costs for cultivation was taken from the agricultural farms directly and consisted of rental fees, transportation, labor, seed, equipment, fertilizer and fuel. For mechanical equipment that lasts for long term, the cost was estimated on a yearly basis by considering the lifetime of that equipment. Cost of harvest was consisted of transportation of products, labors, equipment used, feedstock and diesel or gasoline. Pyrolysis process cost was consisted of the equipment cost, feedstock, fuel and labors. Applying biochar to soils was also associated with the costs such as those with transportation, labors, equipment, biochar and fuels. In addition, greenhouse gas emissions during feedstock production such as fertilizer application, other farm activities, and from burning of feedstock, if applicable, were also included. In the interview, the following information was recorded; the amount of electricity use during cultivation and harvest, the type and the amount of fertilizer use such as compost or application of crop residues, the amount of fuel use during land preparation, maintenance and harvest, irrigation, and transport of the product and feedstock and plant production parameters such as yield and the amount of residue produced. The information about the cost features of farms, farm operations and cost utilization was also obtained through the questionnaire and interviews.

3.3.2 Pyrolysis of feedstock

Under the limited oxygen availability, feedstock is pyrolysed to yield biochar. The associated costs during this step came from the use of energy and equipment. The characteristics of existing technology for biochar production in Thailand was collected through interviews and questionnaire. Data on type and source of energy, energy consumed per the unit quantity of biochar yield was collected. Pyrolysis conditions such as temperature, duration and labor requirements and other parameters involved costs were recorded.

3.3.3 Application of biochar to soil

In all cases, except mangrove, the application of biochar to soil occurred within the vicinity of its production sites. For mangrove, the biochar production site was in Yeesarn, Samut Songkhram, while the application was in Rajchaburi, about 60 km to the southwest. During the farm surveys, the information on the rate of biochar application, the amount of sequestered carbon or reduced greenhouse gas emission, crop yield, and other auxiliary parameters were collected. Soil samples were also collected from each farm at the depth up to 30 cm using soil core. At least triplicate samples were taken from each application plot. Soil samples were analyzed for bulk density and carbon content.

Soil samples were collected within 30 cm of a center point at each sampling site and 0-30 cm soil depths were sampled. With this technique the whole soil sampled in each soil series was homogenized and a sub-sampled was taken for laboratory analysis.

Soil organic carbon in the study site was estimated by the formula in Equation 1. The amount of soil organic carbon in the field applied with and without biochar was then compared to estimate the carbon sequestration.

$$\text{Soil C stock (g C/m}^2\text{) = Bulk density (g soil/m}^3\text{)} \times \text{soil C content (g C/g soil)} \quad (1)$$

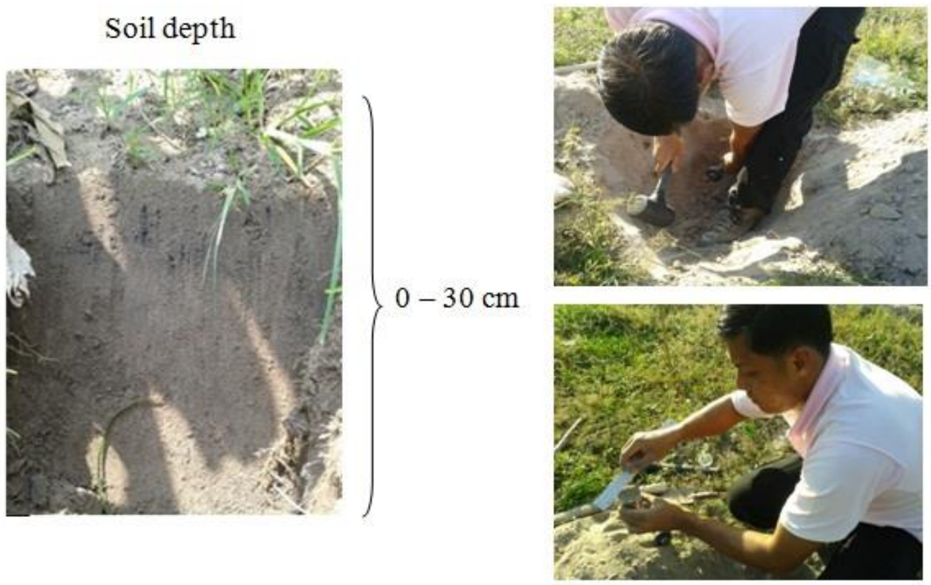


Figure 3.3 Method of soil sampling and preparation for soil carbon analysis.

3.4 Estimation of GHG emissions and sequestration

Emissions of GHG were calculated based on activity data collected during field surveys and interviews. The emission factors (EF) used to calculate the emission were mainly obtained from IPCC 2006 [113]. Summary of emission factors used was given in Table 3.1. On the other hand, it this study it is assumed that the amount of carbon sequestration or mitigated through the application of biochar is equal to the carbon incorporated into the soil for each type of feedstock. For example, with the application rate of 0.1125 ton/ha of rice-husk biochar in case of Chiangmai and the carbon content of 0.51 gC/g dry weight of biochar, the mitigated GHG is 1.87 ton CO_2e/ton biochar or 510 kgC/ton biochar applied to soil. The detailed carbon contents of each type of feedstock-biochar are as shown in Table 4.8 (Chapter 4). All greenhouse gas emissions and sequestration were converted to CO_2 equivalent (CO_2e) using global warming potential (GWP) as indicated by IPCC 2001a [114] (time span of 100 years). Details of greenhouse gas emissions are as follows;

(1) Fuel

The emissions of greenhouse gases from the energy utilization of farm management were calculated. The energy utilization includes energy for biomass production (land preparation, cultivation, harvesting), pyrolysis, transportation and biochar application to soil. The amount of energy use was multiplied with the conversion coefficients using the conversion factor as presented in Table 3.1. Most data in the questionnaires were calculated and represented by using median, minimum and maximum value.

The emissions in units of carbon equivalents of energy utilization from farm operations were calculated from Equation 2 and Table 3.1.

$$\text{Emissions}_{\text{GHG, fuel}} = \text{Fuel Consumption} \times \text{Emission factor}_{\text{GHG, fuel}} \quad (2)$$

Where:

Emissions $_{\text{GHG, fuel}}$ = emissions of a given GHG by type of fuel (kg GHG),

Fuel Consumption = the amount of fuel combusted

Emission factor $_{\text{GHG, fuel}}$ = default emission factor of a given GHG by type of fuel. The GWPs (time span of 100 years) of CO_2 is 1 [111].

(2) Electricity

The carbon emission equivalents from electricity utilization from the process were calculated from Equation 3.

$$\text{Emissions}_{\text{GHG, fuel}} = \text{Fuel Consumption} \times \text{Emission factor} \quad (3)$$

Where:

Emissions $_{GHG,\ fuel}$	= emissions of a given GHG by type of fuel (kg GHG),
Fuel Consumption	= the amount of fuel combusted
Emission factor $_{GHG,\ fuel}$	= default emission factor of a given GHG by type of fuel

(3) Water management (Alternate wet/dry irrigation in rice cultivation or AWDI)

The carbon emission equivalents from rice plant were calculated from Equation 4.

$$CO_2\text{-C Emission} = CH_{4\ rice} \times GWP \quad (4)$$

Where:

CO_2-C Emissions	= Annual C emissions from rice field (CH_4) (kg CO_2 e per year)
$CH_{4\ rice}$	= Annual amount of CH_4 emissions from rice field (kgCH_4 per year)
EF	= Emission (CH_4/kg)
GWP	= Global warming potential (25 kgCO_{2eq}/ kg)

Where:

$$CH_{4\ rice} = \sum (EF_{i,j,k} \times t_{i,j,k} \times A_{i,j,k} \times 10^{-6}) \quad (5)$$

$$EF_i = EF_c \times SF_w \times SF_p \times SF_o \times SF_{s,r} \quad (6)$$

$$SF_o = [1 + \sum_i ROA_i \times CFOA_i]^{0.59} \quad (7)$$

A	= Area for harvesting (ha)
t	= Planting time (days)
EF_c	= Continuously flooded without organic amendment

SF_w = Scaling factors for water regimes during the cultivation period (Irrigated, Intermittently flooded-multiple aeration = 0.52)

SF_p = Scaling factors for water regimes before the cultivation period (Non-flooded pre-season›180 d = 0.68)

SF_o = Scaling factors for both types and amounts of organic amendment applied

CFOA = Conversion factor for different types of organic amendment (Straw incorporated long (›30 days) before cultivation = 0.29 and Compost = 0.05)

Remark: 70% CH_4 reduction was assumed by AWD-water management [115]

(4) Greenhouse gas emissions from chemical fertilizer (N-P-K)

Emission factors for fertilizers are divided according to types of fertilizer (N-P-K) and are presented in Table 3.3 [113]. The amounts of inorganic fertilizer input were used to estimate C emission in the field by using emissions factor (carbon equivalent of fertilizer) for the production of fertilizer (N, P_2O and K_2O). The value are 857.5 g CO_2-eq/kg N, 165.1 g CO_2-eq/kg P_2O_5 and 120.28 g CO_2-eq/kg K_2O for N, P_2O_5, K_2O application, respectively [116] [117] [118] [119]. Equation for this purpose is given below [113].

$$CO_2\text{-C Emissions} = M \times EF \tag{8}$$

Where:

CO_2-C Emissions = Annual C emissions from N, P_2O_5 or K_2O Fertilizer application (tonnes C per year)

M = Annual amount of N, P_2O_5 or K_2O fertilization (tonnes N, P_2O_5 or K_2O per year)

EF = Emission factor (g CO_2-eq/kg N, P_2O_5 or K_2O)

(5) Greenhouse gas emissions from compost

Emission factors for fertilizers are divided according to type of fertilizer NO_2 and CH_4 [113]. The amounts of organic fertilizer input were used to estimate C emission in the field by using emissions factor (carbon equivalent of fertilizer) for the production of fertilizer (NO_2 and CH_4). The value is 0.3g N_2O/kg and 4 g CH_4/kg for NO_2 and CH_4 application, respectively. Equation for this purpose is given below [113].

$$CO_2\text{-C Emissions} = M \times EF \times GWP \tag{9}$$

Where:

CO_2-C Emissions	= Annual C emissions from NO_2 or CH_4 Fertilizer application (tonnes C per year)
M	= Annual amount of fertilizer (tonnes per year)
EF	= Emissions (N_2O/kg and CH_4/kg)
GWP	= Global warming potential (25 kgCO_{2eq}/ kg and 298 kgCO_{2eq}/ kg)

(6) Greenhouse emissions from transportation

$$\text{Emissions}_{GHG} = \text{Distance (km)} \times \text{Emission factor}_{GHG} \tag{10}$$

Where:

Emissions $_{GHG}$	= emissions of a given GHG by type of fuel (kg GHG),
Distance	= the distance of transportation (km),
Emission factor $_{GHG,\ fuel}$	= default emission factor of transportation.

Table 3.1 Emission factors used in this study to calculate greenhouse gas emissions during biochar production

Type	Emission factor	Unit	Remark	References
1. Electricity	0.561	kg CO_2/kWh		[120]
2. Fuel wood	300	kg CH_4/TJ	Heating value	
	4	kg N_2O/TJ	= 15.99 MJ/unit	

Table 3.1 Emission factors used in this study to calculate greenhouse gas emissions during biochar production (con't)

Type	Emission factor	Unit	Remark	References
3. Gasoline (production)	0.3409	$kgCO_{2eq}/kg$		[120]
4. Gasoline (combustion)	2.1896	$kgCO_{2eq}/L$	Assume Density 0.74 kg/L (Wikipedia)	[120]
5. Diesel (production)	0.325	$kgCO_{2eq}/kg$		[120]
6. Diesel (combustion)	2.7080	$kgCO_{2eq}/L$	Density 0.832 kg/L	[120]
7. Rice cultivation (CH_4)				[113]
7.1 Continuously flooded without organic amendment; EFc	1.3			
7.2 Scaling factors for water regimes during the cultivation period; SF_w (Irrigated, Intermittently flooded-multiple aeration)	0.52			
7.3 Scaling factors for water regimes before the cultivation period; SF_p (Non flooded pre-season›180 d)	0.68			
7.4 Conversion factor for different types of organic amendment; CFOA				
- Straw incorporated long (›30 days) before cultivation	0.29			
- Compost	0.05			
8. Chemical fertilizer (N-P-K)				[116]; [117]; [118]; [119]
8.1 Nitrogen (N)	857.54	g CO_2-eq/kg N		
8.2 Phosphorus (P_2O_5)	165.10	gCO_2-eq/kg P_2O_5		
8.3 Potassium (K_2O)	120.28	gCO_2-eq/kg K_2O		
9. Compost fertilizer				[113]
9.1 Nitrogen (N)	0.3g	N_2O/kg		
9.2 Methane (CH_4)	4	g CH_4/kg		
10. Transportation				[120]
10.1 Pickup 4 wheels, full load 7 ton, 0 % loading (วิ่งแบบทางเรียบ)	0.3111	kg CO_2/km		
10.2 Pickup 4 wheels, full load 7 ton, 0 % loading (วิ่งแบบทางสมบุกสมบัน)	0.3726	kg CO_2/tkm		
10.3 Pickup 4 wheels, full load 7 ton, 50 % loading (วิ่งแบบทางเรียบ)	0.2681	kg CO_2/tkm		
10.4 Pickup 4 wheels, full load 7 ton, 100 % loading (วิ่งแบบทางเรียบ)	0.1402	kg CO_2/tkm		
10.5 Pickup 4 wheels, full load 7 ton, 100 % loading (วิ่งแบบทางสมบุกสมบัน)	0.1616	kg CO_2/tkm		

3.5 Mitigation costs

The costs of greenhouse gas mitigation associated with biochar applications to soil in this study included the costs occurred during the production of feedstock, the costs of biochar production during pyrolysis and the costs of biochar applications to soil during crop cultivation.

The final result was expressed as the mitigation cost per ton CO_2e, as indicated in Equation 11 where total cost indicates all costs associated with biochar production and application to soil (THB). The total GHGs emitted and mitigated were calculated from activities involved in biochar production, application to soil and sequestration (ton CO_2e).

$$\text{Mitigation cost}_{\text{(THB/ton CO2e)}} = \frac{\text{Total cost of biochar production}_{\text{(THB/ton.biochar)}}}{\text{C sequester}_{\text{(ton CO2e/ton biochar)}} - \text{GHG emission}_{\text{(ton CO2e/ton biochar)}}} \quad (11)$$

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Cultivation practices, costs and GHG emissions

4.1.1 Mangrove biochar

For the current case study at Yeesarn, the size of the mangrove plantation was 40 rais/year. The cultivation area was situated along the northern coastline of the Gulf of Thailand. To access to the land, farmer used a boat (Honda, 13 hp) with the initial investment cost of 14,000 THB.

The expense data of mangrove biochar were collected as followings.

a) The expenses of transportation for access to the mangrove plantation:

- The lifetime of the boat was estimated at 20 years, and the cost each year was calculated by the depreciation rate of price/year = 700 THB, with a maintenance cost per year of 1,000 THB.

- The gasoline for transportation of 48 litres/year at 42.5 THB/litre (total cost 2,040 THB/year). GHG emissions from gasoline in this process was 117.20 kg CO_2-eq/year.

b) The land preparation process:

- Labor hiring for 5 persons with 16 days/year were used. The cost was 150 THB/day/person. Thus, the total labor costs is 12,000 THB/year.

c) The rental fee for the land used:

- The plantation-harvest cycle of mangrove was 9-10 years.

- The rental fee for the land was100 THB/rai. Thus, total cost of rental fee was 4,000 THB/year.

d) The seeding and planting activity:

- Amount of seeds used were 3,000 seeds/rai with 0.25 THB each. Thus, total cost was 30,000 THB/year.

-The labor cost for planting for 40 days with 2 persons was 150 THB/day/ person. Thus, total cost was 12,000 THB/year.

- Gasoline was consumed for transport of seedling and planting activities. The amounts used were 120 litres with 42.5 THB/litre for cultivation process. Thus, total cost was 5,100 THB/year. GHG emission from gasoline in this process was 293 kg CO_2-eq/year.

Figure 4.1 Mangrove seeds used for plantation at Yeesarn

e) Costs of harvesting (mangrove biomass):

- After 9-10 years, farmers can harvest the mangrove wood.
- The total yield of mangrove gained by this farmer was 640 tons/year.
- To harvest, the farmer used a boat to transport the wood along the canal approximately 40 kilometers for a round trip, using the fuel (gasoline) 5 litres/round trip and boat was used to transport 112 times (total fuel 560 litres/year). The cost of fuel (gasoline)/liter was 42.5 THB (total cost of fuel 23,800 THB/year). GHG emission from gasoline in this process was 1,367.44 kg CO_2-q/year.
- The labor cost for harvesting activities was 300 THB/person/day. Totally 56 days with 5 persons were used (total cost of labor 84,000 THB/year).

Figure 4.2 Wood of mangrove after harvesting, awaiting to be used for charcoal production

f) Costs of producing biochar:

- Farmers used traditional kilns (slow pyrolysis) for producing biochar, spending 30 – 50 days/kiln (approximately 45 days). Each kiln can contain mangrove wood of 24 tons and produced biochar 8 tons/kiln.

- The fuel (wood) was of 72,000 kilograms/year. A kiln cost was estimated at 150,000 THB per kiln and farmer possessed 2 kilns for producing the charcoal.

- The lifetime of this kiln was estimated at 30 years and the cost each year was calculated by the depreciation rate of price/year = 10,000 THB, with maintenance costs of 8,000 THB/year.

- The labor cost was 2,000 THB/kiln/time by hiring 2 persons (all day and all night), 7 times/year, thus the total cost of labor is 28,000 THB/year. GHG emission from fuel (woods) was estimated at 10,007 kg CO_2-eq/year.

Figure 4.3 Traditional Kiln for charcoal production from mangrove wood at Yeesarn Community

Figure 4.4 Charcoal produced from mangrove feedstock at Yeesarn

g) Biochar application:

- Biochar from the mangrove feedstock (Yeesarn Community) was applied to soil for the cultivation of the sweet sorghum crops at the experimental plot of King Mongkut's University of Technology Thonburi, Rajchaburi Campus (KMUTT).

- The costs for biochar application included fuel (diesel) for transportation from Yeesarn to KMUTT. This was estimated at 30 THB/litre with the total use of 12 litres/day (total cost of diesel of 360 THB, transportation for 90 kilometer) and a hiring cost of a pickup 4 wheels for transportation at the rate of 300 THB/day. GHG emissions from this transportation was estimated at 40.62 kg CO_2-eq/year.

- When biochar was applied to the soil, a tractor (36 horsepower), crusher for grinding biochar into small grain size. The costs incurred were 375 THB/day for hiring a tractor (consuming a fuel (diesel) of 2 litres in total), 300 THB/day for biochar crusher, and 300 THB/day for labor. GHG emission from diesel consumption in this process was 37.19 kg CO_2-eq/year.

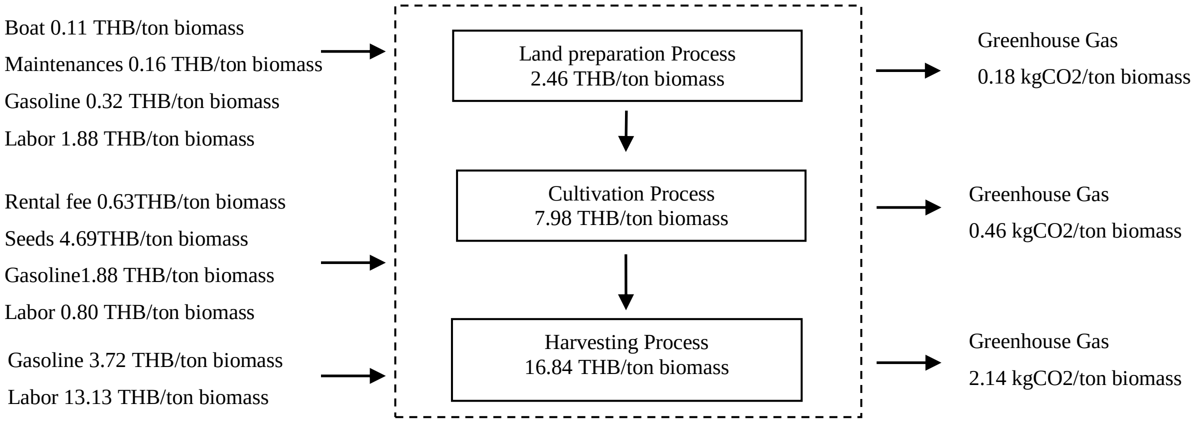
Figure 4.5 Mangrove biochar after grinding for application to soil

Figure 4.6 Mangrove biochar when it was applied on the soil surface before incorporation to 30 cm by a tractor

From these basic field data, the cost and greenhouse gas emissions were grouped into each process from mangrove feedstock production to biochar application to soil as follows.

1) Costs of mangrove feedstock production

The cost can be expressed based on the quantity of 1 ton of biomass produced as presented in Figure 4.7. It was found that the cost was 27.29 THB/ton biomass. This can be disaggregated into costs 2.46**,** 7.98 and 16.84 THB/ton biomass for land preparation, planting and harvest, respectively. The GHG emissions were from fossil fuel use, and these were 0.18, 0.46 and 2.14 kg CO_2-eq/ton biomass, respectively.

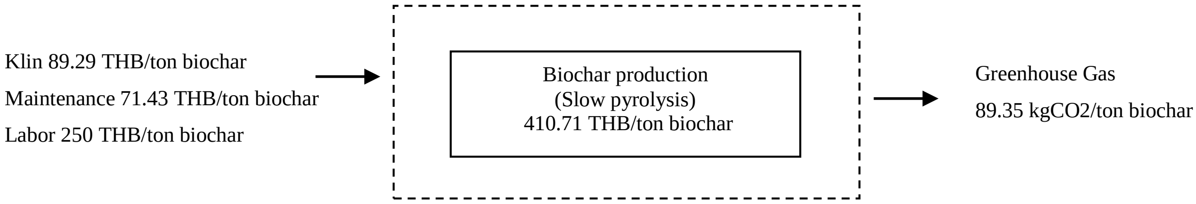


27.29 THB/ton biomass

Figure 4.7 Costs and greenhouse gas emissions associated with mangrove feedstock production

2) Costs of biochar production from mangrove

Biochar was produced at the farmer's house not far away from the plantation site. The transport of biomass by both, kiln construction and maintenance and labor were the sources of costs and greenhouse gas emissions. From field survey it was found that the ratio between the amount of mangrove use and charcoal yield was 3:1. Base on the quantity of 1 ton biochar produced, a total cost of 410.71 THB was used. These come from kiln, maintenance and labor for 89.29, 71.43 and 250 THB/biochar, respectively. The total GHG emission during these processes was 89.35 kg CO_2-eq/ton biochar.

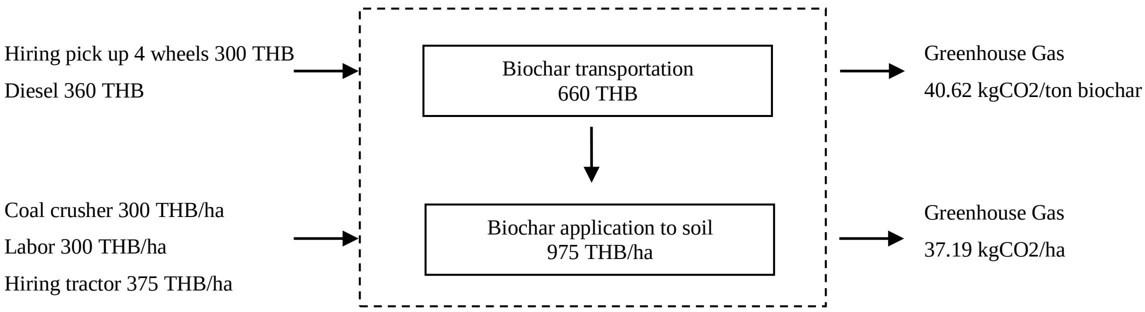


410.71 THB/ton biochar

Figure 4.8 Costs and greenhouse gas emissions associated with mangrove biochar production

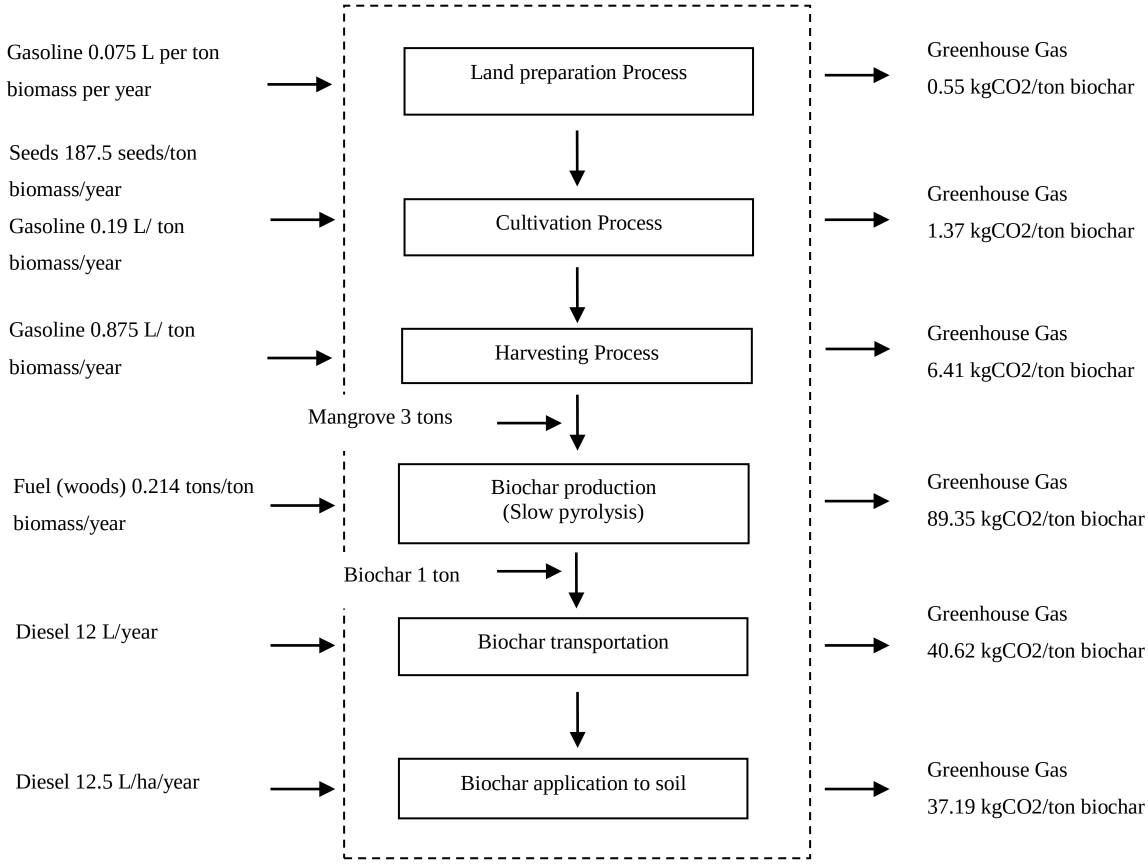
3) Costs of biochar application to soil

The total costs of mangrove biochar application per hectare was 1,635 THB/hectare. These included the transportation cost of 660 THB and biochar application to soil cost of 975 THB per/hectare. The GHG emissions from biochar transportation was 40.62 kgCO_2-eq/ton biochar and from the biochar application to soil was 37.19 kgCO_2-eq/hectare, as shown in Figure 4.9.



1,635 THB/hectare

Figure 4.9 Costs and greenhouse gas emissions from mangrove biochar application to soil



4.1.2 Rice husk biochar

Every year at the New Theory Farming Center, Mae Taeng District, Chiangmai Province, paddies are planted once a year (8 Rais) between July and November. Farmers collect the seeds for the next crop before harvesting. The land preparation was started by preparing soil with plowing 3 times by tractor (8 horsepower) with the initial investment cost of 38,000 THB. The lifetime of this tractor was estimated at 20 years and the cost each year was calculated by the depreciation rate of price/year = 1,900 THB with a maintenances cost of 80 THB.

The expense data of risk husk biochar were collected as follow.

a) Land preparation:

- A fuel (diesel) cost for land preparation was 1,000 THB/year with 40 litres. GHG emissions from diesel in this process was 118.99 kg CO_2-eq/year.

- Labor cost for land preparation of 200 THB per person per day for 6 workdays, thus total cost of labor 1,200 THB/year.

b) Paddy cultivation:

- Rice was planted by using seeds at the rate of 4 kilograms/rai. Thus, total seed consumed was 32 kilograms for 8 rais/year.

- Seed cost was 30 THB/kilogram, thus the total cost of seeds was 960 THB/year.

- Labor cost for cultivation was 200 THB/person/day with 1 workday. Thus, the total cost of labor was 200 THB/year.

- This farmer used water from the Hao River to irrigate her fields (a water management by alternate wet/dry irrigation in rice cultivation or AWDI of which, 70% CH_4 reduction was assumed). A compost at 4,000 kilograms/year for 8 rai was applied. GHG emission from methane (CH_4) was 1,923.04 kg CO_2-eq/year and from compost was 757.60 kg CO_2-eq/year.

c) Paddy Harvesting:

- After 110 - 120 days of plantation, the farmer harvests the rice by using a harvester (6.3 horsepower) for a duration of 10 days. The initial investment cost was 37,000 THB, the lifetime of this harvester was estimated at 20 years and the cost each year was calculated by the depreciation rate of price/year = 1,850 THB.

- A fuel (gasoline) was used for harvesting at 15.66 litres/year with cost at 500 THB /year. GHG emissions from gasoline was 38.24 kg CO_2-eq/year.

- Labor cost was 200 THB/person/day with 2 workdays (total cost of labor 400 THB/year).

d) Paddy transportation:

- The paddy was transported to the granary after harvesting by using a harvester with a travel distance of 0.06 km.

- Fuel (gasoline) cost for transportation was 30 THB/year and GHG emissions from gasoline was 2.44 kg CO_2-eq/year.

- The farmer used a rice huller machine (3 horsepower) to separate the rice from the rice husks at a rate of 120 kilograms per hour. From the total rice yield of 8.8 ton and rich husk yield of 2.2 tons, it can be estimated that the farmer took 74 hours/year with the total use of electricity of 165.621 kilowatt-hours. Cost of a rice huller machine was 128,000 THB, the lifetime of this rice huller machine was estimated at 20 years and the cost each year was calculated by the depreciation rate of price/year = 6,400 THB. An electric power cost of 620 THB/year. GHG emission from electricity was 91.91 kg CO_2-eq/year.

- Labor cost of 200 THB per person per day with 9.25 workdays (total cost of labor 1,850 THB/year) were estimated for these milling activities.

Figure 4.10 Rice grinding machine at the granary, Mae Taeng District, Chiangmai Province

e) Biochar production from rice husk:

- Farmers used a tank with the size of 200 litres and cost of 1500 THB to make kiln (slow pyrolysis) for biochar production. The lifetime of this kiln was estimated at 5 years and the cost each year was calculated by the depreciation rate of price/year = 300 THB/kiln.

-A labor cost of 200 THB/person/day with 4.16 workdays, thus the total cost of labor 832 THB/year.

- A fuel (woods) of 750 kilograms/year was estimated. GHG emissions from fuel (woods) was 104.24 kg CO_2-eq/year.

f) Biochar application:

- Farmer applied biochar from rice husk to rice field at the rate of 18 kg/rai (yielding total biochar of 144 kg/year or 0.1125 ton/hectare/year).

- Biochar was mixed with compost before applying to soil with a labor cost of 50 THB/rai (or 312.5 THB/hectare).

Figure 4.11 Kiln used in biochar production at Mae Taeng District, Chiangmai Province

Cost disaggregation for biochar production from rice husk are as follows.

1) Costs of feedstock production

As summed up in Figure 4.12 below, the cost of one tone biomass production is 1,927.22 THB. This includes: land preparation cost was 474.97 THB/ton biomass**,** cultivation cost was 131.82 THB/ton biomass, harvesting cost was 309.09 THB/ton biomass, rice transportation was 3.41 THB/ton biomass and rice production was 1,007.95 THB/ton biomass. The GHG emissions was produced with each process as show in this diagram by land preparation process was 13.52 kg CO_2-eq/ton biomass, cultivation process was 304.62 kg CO_2-eq/ton biomass, harvesting process was 4.35 kg CO_2-eq/ton biomass, rice transportation 0.28 kg CO_2-eq/ton biomass and rice production 10.56 kg CO_2-eq/ton biomass.

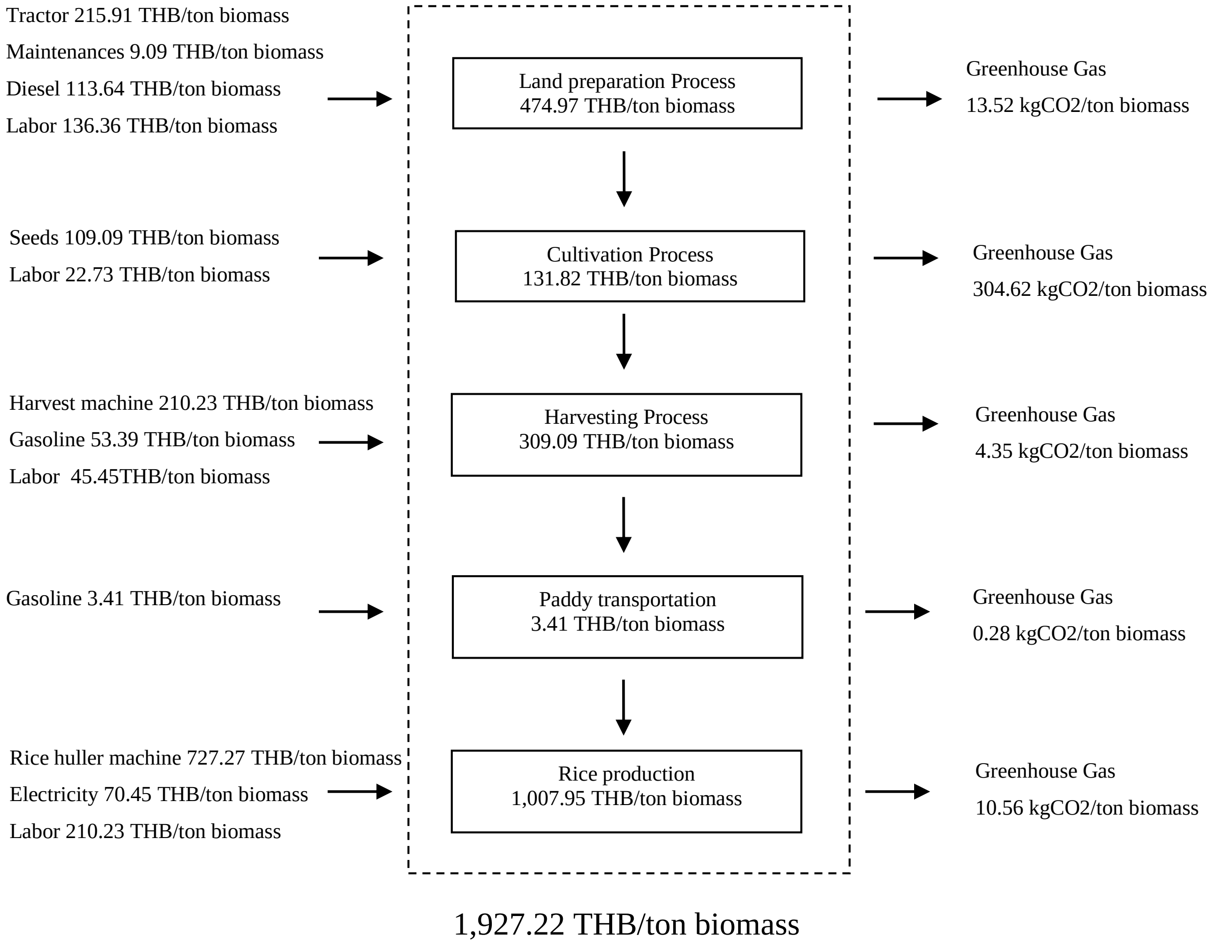


Figure 4.12 Costs and greenhouse gas emissions associated with rice husk feedstock production

2) Costs of biochar production

The total cost of biochar production (pyrolysis) was 2,830 THB/ton biochar and during this pyrolysis process was 260.60 kg CO_2-eq/ton biochar.

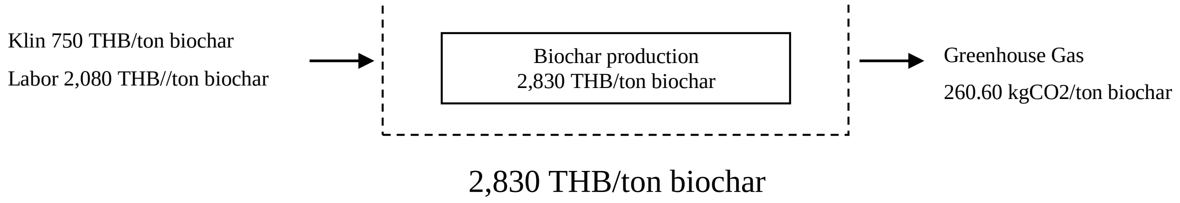
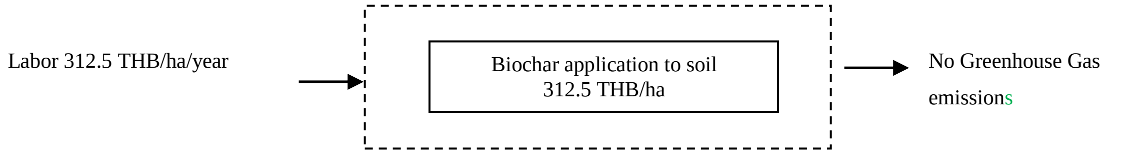


Figure 4.13 Costs and greenhouse gas emissions associated with rice husk biochar production

3) Costs of biochar application to soil

The application of biochar to soil occurred on site, thus there is no transportation cost and emission. The cost estimated in this study solely came from labor, which is 312.5 THB/hectare.



312.5 THB/hectare

Figure 4.14 Costs from rice husk biochar application to soil

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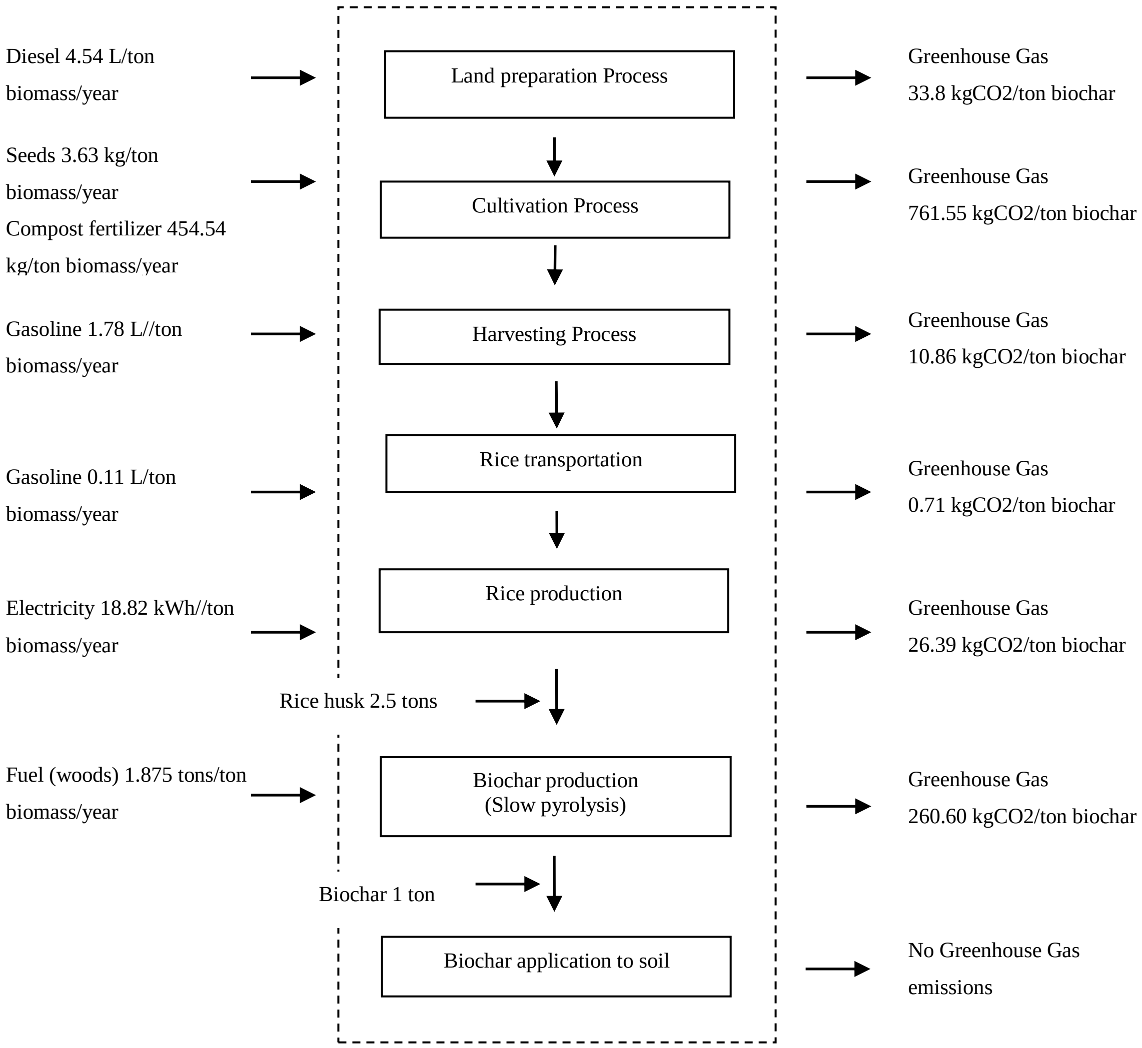


4.1.3 Bamboo biochar

The expense data of bamboo biochar were collected as follows.

a) Land preparation:

- A labor cost for land preparation for bamboo plantation (soil digging) was 5 THB/tree and 30 THB/seedling. With the planting rate of 17 trees/rai yielded (the total labor cost was 85 THB and seedling cost was 510 THB).

b) Bamboo harvesting:

- After planting for 1-1.5 years, bamboo was harvested manually with a labor cost of 300 THB/person/day and with labor use of 1 workday/rai (total cost of labor 300 THB).

c) Bamboo biochar production:

- For biochar production, the farmer used a tank 200 litre to make a kiln (slow pyrolysis) which cost 1,500 THB. The lifetime of this kiln was estimated at 5 years and the cost for each year was calculated by the depreciation rate of price/year = 300 THB/kiln.

- Bamboo of 10 kilograms can produce biochar of 6 kilograms and it can be estimated that biochar 1 tons required the use of bamboo feedstock of approximately 1.67 tons with a fuel (woods) use of 750 kilograms.

- The labor cost was 200 THB per person per day for duration of 6.25 workdays (total cost of labor 1,250 THB).

- GHG emissions from fuel (woods) was 104.24 kg CO_2-eq/year.

d) Bamboo biochar application:

- Biochar was transported from the New Theory Farming Center, Mae Taeng district to the Office of Land Development Region 6 by a pickup truck full load of 7 tons. A fuel (diesel) cost was 30 THB/litre with the total amount of 2.7 litres per round trip (assumed the fuel consumption of 17 kilometer/litre).GHG emission from transportation was 10.38 kg CO_2-eq/year

-The labor cost for transportation was 200 THB/person/day by using 1 person for transportation.

- The Office of Land Development Region 6 (Chiangmai Province) applied biochar to soil planted with lettuce with the cultivation period of 45 days. A labor cost for application biochar to soil was estimated at 37.5 THB/person/rai or 234.4 THB/hectare.

Figure 4.15 Biochar produced from bamboo feedstock at the Office of Land Development Region 6 (Chiangmai)

The cost of each step from biomass feedstock production to application of biochar to soil can be summarized as follows.

1) Costs of feedstock production

The total cost of 1 ton biomass production was 895 THB. This is made up of 85 THB for land preparation, 510 THB for planting and 300 THB for harvest. There are no greenhouse gas emissions during this process because no fossil fuel was used (Figure 4.16).

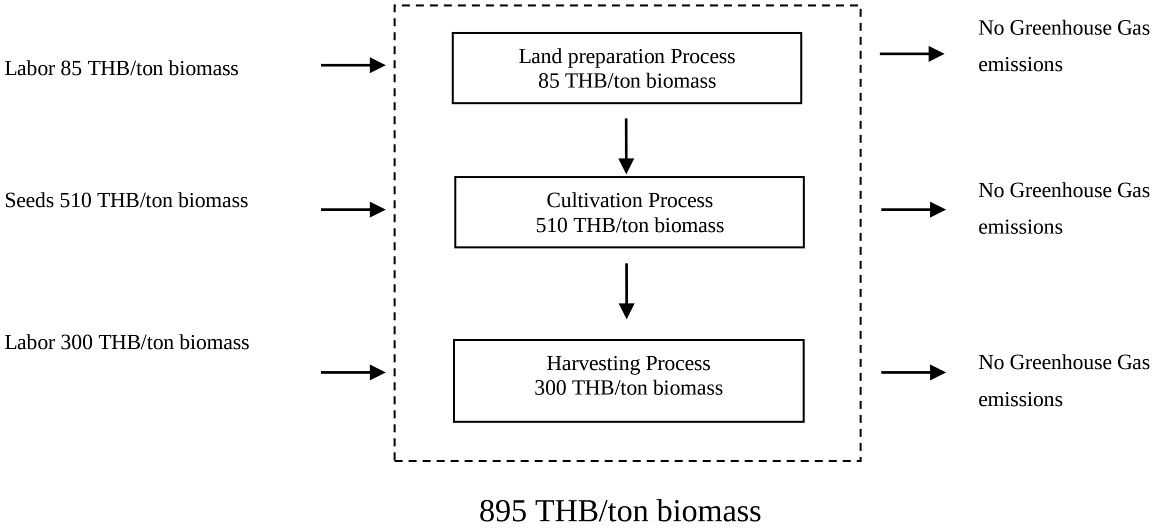
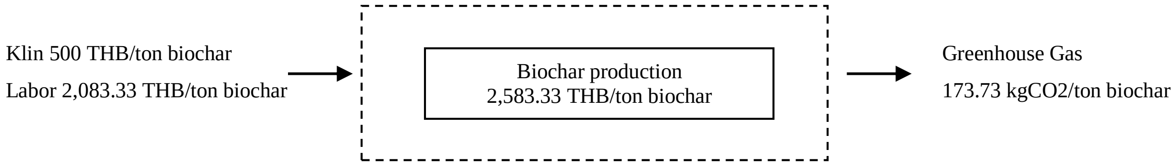


Figure 4.16 Costs and greenhouse gas emissions associated with bamboo feedstock production

2) Costs of biochar production

The information obtained from the interviews indicated that for the production of one ton biochar, 1.67 tons of bamboo biomass was needed. The total cost was 2,583.33 THB/ton biochar. The GHG emission of biochar production (pyrolysis) was 173.73 kg CO_2-eq/ton biochar.

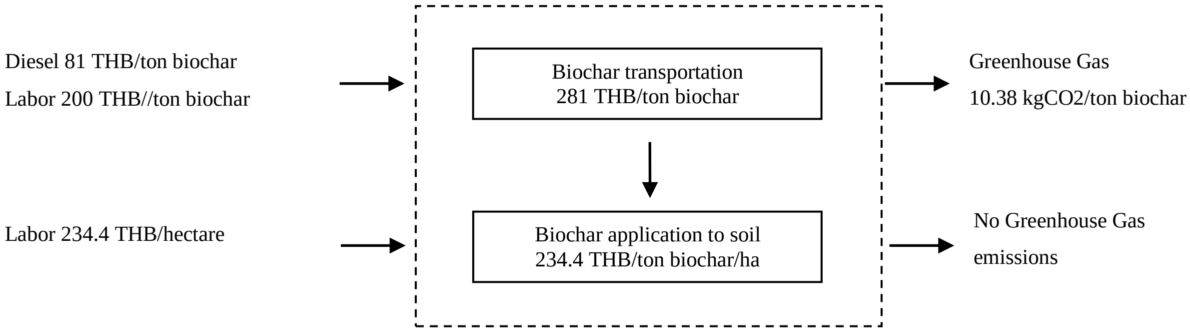


2,583.33 THB/ton biochar

Figure 4.17 Costs and greenhouse gas emissions associated with bamboo biochar production

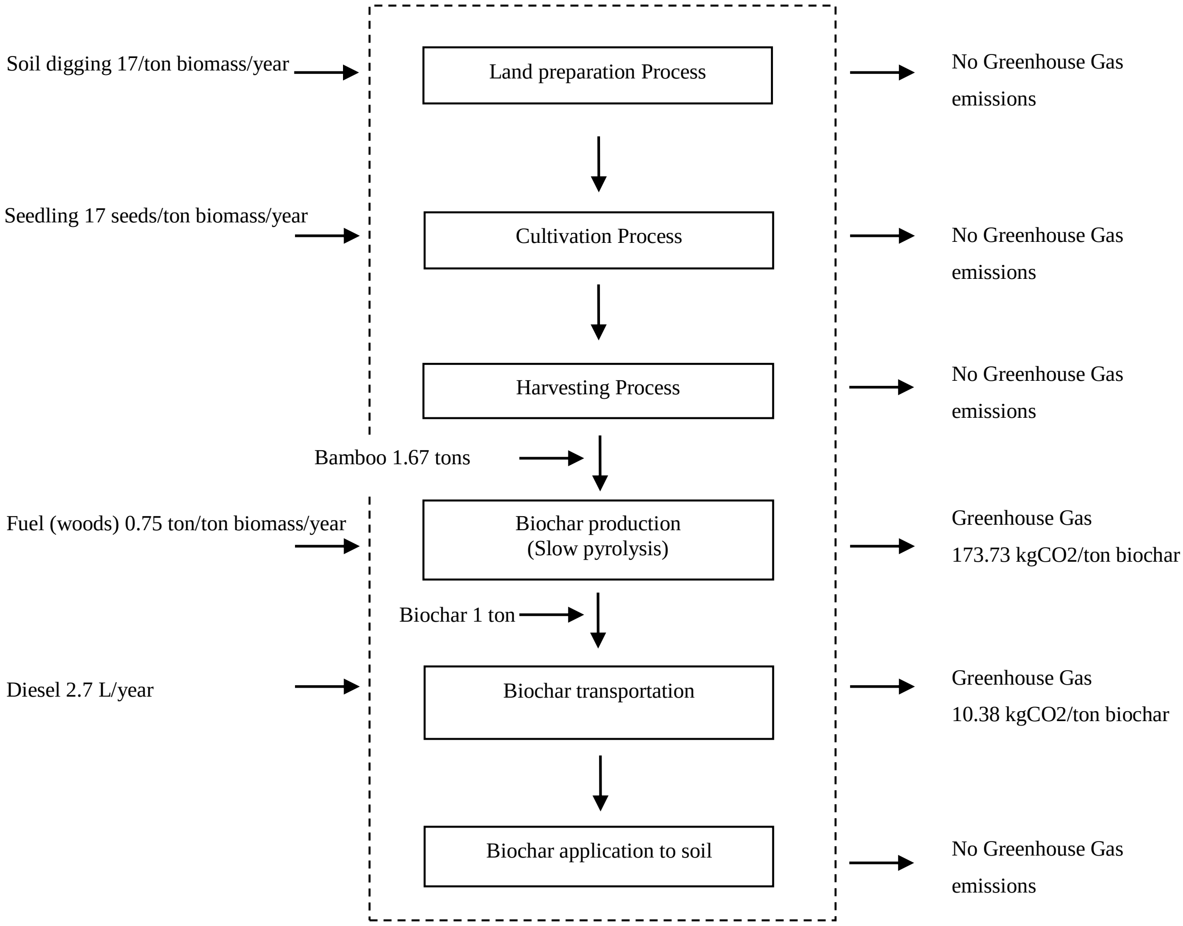
3) Costs of biochar application to soil

The total cost of bamboo biochar application was 515.4 THB/hectare. This included the cost for biochar transportation of 281 THB and biochar application to soil (labor) of 234.4 THB/hectare. The GHG emissions from biochar transportation was 10.38 $kgCO_2$-eq/ton biochar (Figure 4.18).



515.4 THB/hectare

Figure 4.18 Costs and greenhouse gas emission from bamboo biochar application to soil



4.1.4 Corn cob biochar

The expense data of corn cob biochar were collected as follows.

a) Corn cultivation:

- Before corn planting, farmers plowed the land two times by hiring a tractor at the rate of 300 THB/time (total cost 600 THB) and using a fuel (diesel) 4 litres for plowing. GHG emissions from diesel was 11.90 kg CO_2-eq/year.

- After land preparation process, corn was planted by using seeds at 15 kilograms/rai with the seeds cost of 45 THB/kilogram (total cost of seeds 675 THB/rai).

- They used a chemical fertilizer at the rate of 8 kilograms/rai with the cost of 14 THB/kilogram (total cost of chemical fertilizer 112 THB). GHG emissions from chemical fertilizer was 9.29 kg CO_2-eq/year.

- Compost was used in the area at the rate of 4,000 kilograms/rai. GHG emissions from applying compost was 757.60 kg CO_2-eq/year respectively.

- Labor cost for cultivation was 300 baht/person/day for a total duration of 1 day (total cost of labor 300 THB/day).

b) Corn harvesting;

- Harvesting process was done after planting for 90 days with a labor cost of 300 THB/person/day.

- After harvesting, corn was transported to a corn sorter machine nearby. The initial investment cost of a corn sorter machine was 16,500 THB. The lifetime of this corn sorter machine was estimated at 20 years and the cost each year was calculated by the depreciation rate of price/year = 825 THB. Corn and corn cob are separated at the rate of 1,000 kilograms/hour. The farmer used fuel (gasoline) 2.5 litres with corn sorter machine by a cost of fuel (gasoline) 100 THB. GHG emission from gasoline was 6.10 kg CO_2-eq/year.

- The labor cost was 200 THB/person/day.

c) Corn cob biochar production:

- Corn cob was transported (approximately 140 kilometers) from Padeng – Kaeng Krachan District to Huay Sai Royal Development Study Center, Phetchaburi Province by a pickup truck, 7 ton full load. The amount of fuel (diesel) for transportation was 8.235 litres/round trip and a cost of fuel (diesel) was 30 THB/litre. Thus, total cost of diesel 247 THB. GHG emissions from transportation was 37.39 kg CO_2-eq/year.

- The labor cost for transportation was 300 baht/person/day by transported for 1 workday with 1 person (total cost of labor 300 THB).

- Production of biochar from corn cob was carried out by using a 200 L-tank as described above, with the cost of 1,000 THB (Figure 4.19). The lifetime of this kiln was estimated at 5 years and the cost each year was calculated by depreciation = price/year = 200 THB/kiln. GHG emissions from fuel (woods) was 104.24 kg CO_2-eq/year.

- The labor cost for biochar production with 1 person was 1,000 THB.

d) Corn cob biochar application:

- Biochar from corn cob feedstock was applied to soil at Huay Sai Royal Development Study Center at the application rates of 0, 1.946, 3.892, 5.838 and 7.784 kgC/hectare (0, 2.5, 5, 7.5 and 10 ton of biochar/hectare).

- The hiring cost of tractor for application was 700 THB per day with a fuel (diesel) 12.5 litres and a labor cost 300 THB/person/day. GHG emissions from diesel was 37.19 kg CO_2-eq/year.

Figure 4.19 Kiln used in biochar production at Huay Sai Royal Development Study Center, Phetchaburi Province

Figure 4.20 Biochar produced from corn cob feedstock

The cost of each process from feedstock production, biochar production to biochar application can be summarized as follows.

1) Costs of feedstock production

Cost for 1 ton biomass production was 1,244.80 THB. This included costs for land preparation cost of 240 THB, cultivation cost of 434.80 THB, harvest cost of 120 THB/ton biomass and corn milling of 450 THB. The GHG emissions included 4.76, 306.75 and 2.44

kg CO_2-eq/ton biomass from land preparation, cultivation and corn milling, respectively (Figure 4.21).

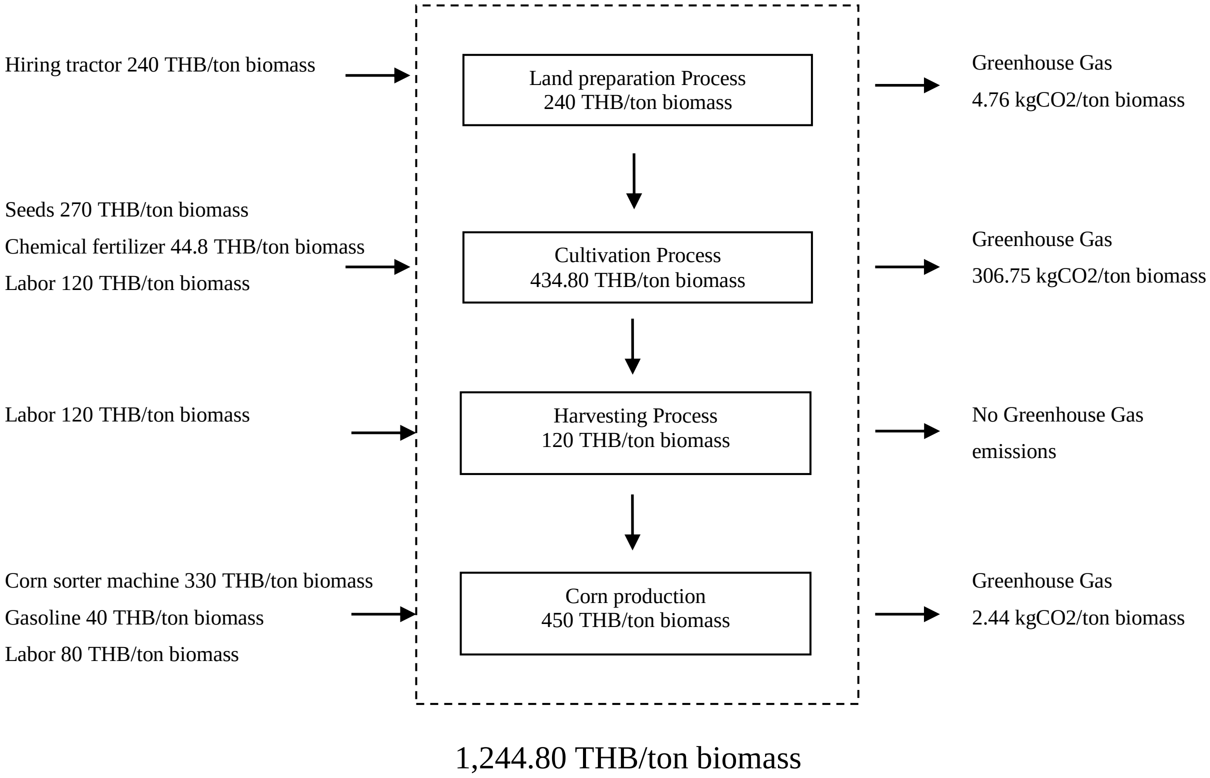


Figure 4.21 Costs and greenhouse gas emissions associated with corn cob feedstock production

2) Costs of biochar production

The total cost of corn cob biochar production was 8,735 THB/ton biochar, including 2,735 THB from transportation and 6,000 THB from pyrolysis. The GHG emissions was 186.97 kg CO2-eq/ton biochar from transportation 521.19 kg CO2-eq/ton biochar from the pyrolysis of biomass.

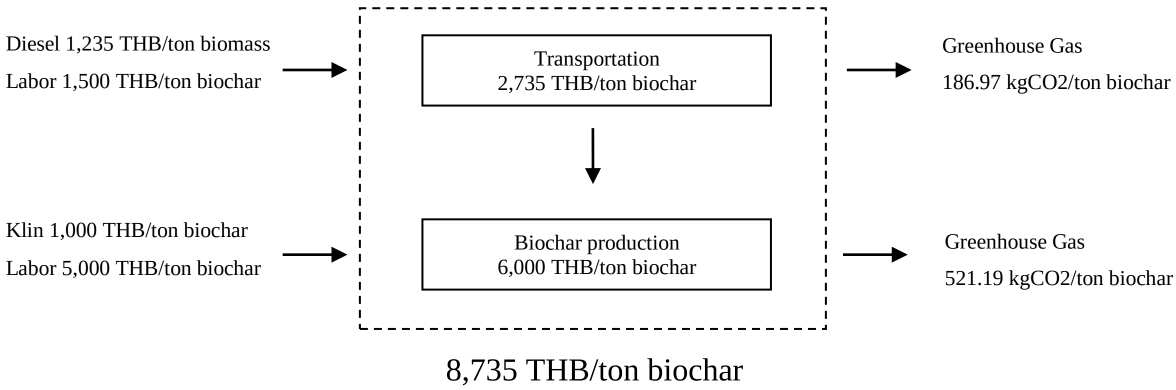


Figure 4.22 Cost and greenhouse gas emissions associated with corn cob biochar production

3) Costs of biochar application to soil

The total cost of corn cob biochar application per hectare was 1,000 THB/hectare, including hiring a tractor of 700 THB/hectare and labor of 300 THB/hectare. The GHG emissions of biochar application to soil was 37.91 kgCO_2-eq/hectare.

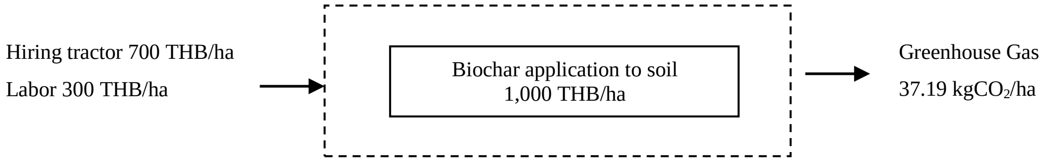
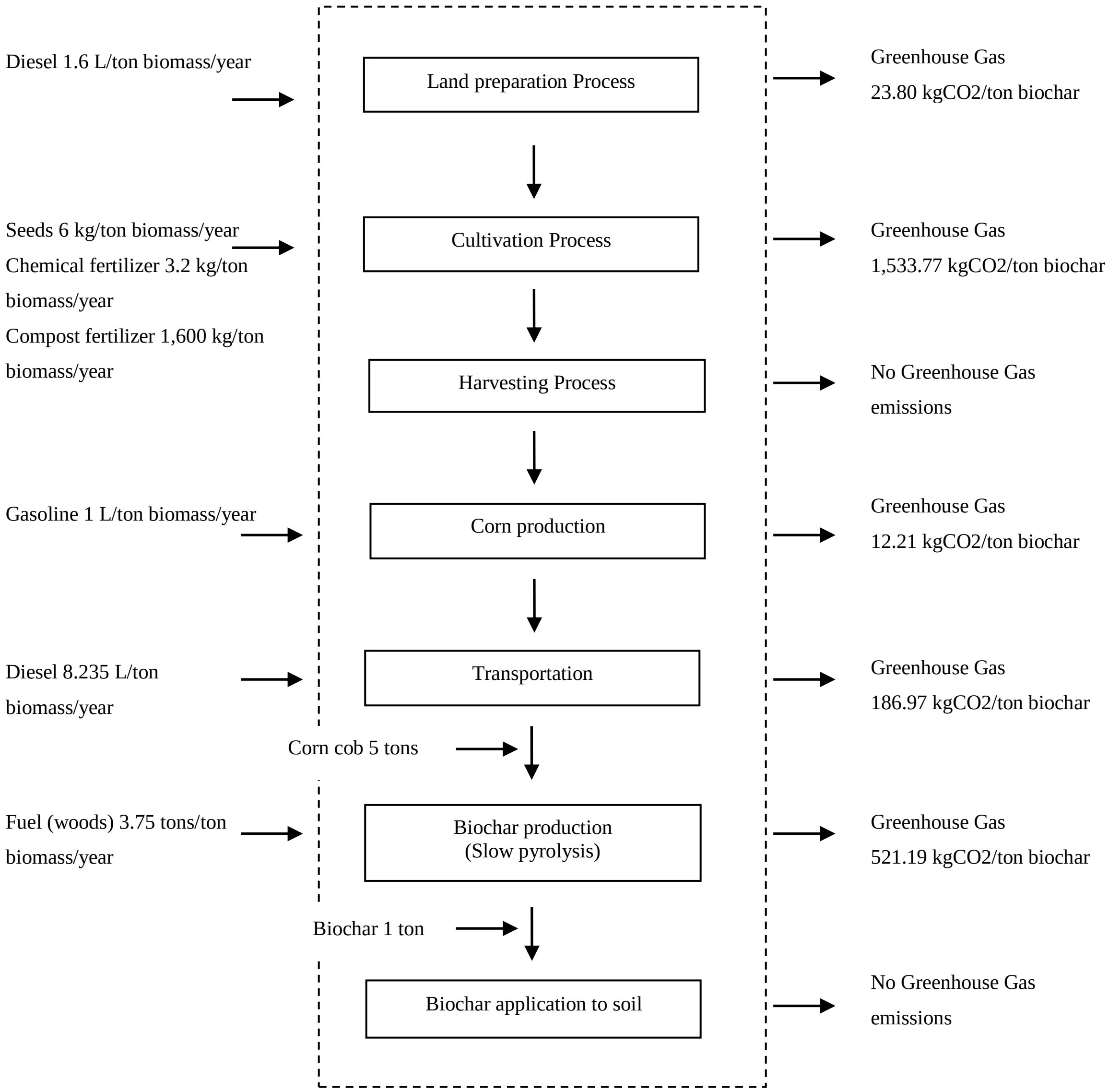


Figure 4.23 Costs and greenhouse gas emissions from corn cob biochar application to soil



4.1.5 Mixed softwoods biochar

Huay Sai Royal Development Study Center has many types of softwood, such as acacia, mango and neem. Waste from pruning, lawn mowing and other routine plant care activities were collectively used for biochar production. For the pruning process, a labor cost was 300 baht/person/day with 4 working days in total (total cost of labor is 1,200 THB).

After pruning, the mixed softwoods are transported by a pickup truck, fully loaded to the pyrolysis site with the distance about1 kilometer/day for a round trip. The fuel (diesel) cost was 30 THB/litre (assuming the fuel economy of 15 kilometer/litre). GHG emissions from this transportation was 0.58 kg CO_2-eq/year.

The labor cost for transportation was 100 THB/person/day.

Biochar from the mixed softwoods was produced by using 200 litre and 50-litre tanks that acted like a kiln (slow pyrolysis). The cost for purchasing these tanks was 1,000 THB. The lifetime of this kiln was estimated at 5 years and the cost each year was calculated by the depreciation rate of price/year = 200 THB.

The labor cost for producing biochar was 1,000 THB.

For one cycle of biochar production, the mixed softwoods of 20 kilograms produced 6.67 kilograms biochar and took about 4 hours, using 750 kilograms of fuel (woods). GHG emissions from fuel (woods) was estimated at 104.24 kg CO_2-eq/year.

Figure 4.24 Biochar produced from mixed softwoods feedstock

Biochar from mixed softwoods feedstock was applied to the experimental plots planted with corn at Huay Sai Royal Development Study Center. The cost for this activity included that for hiring a tractor (700 THB/day), and fuel cost (diesel 12.5 litres for land preparation). GHG emissions from diesel was 37.19 kg CO_2-eq/year.

The labor cost for biochar application to soil was 300 THB/person/day and the application rate was 0, 3,450, 6,900, 10,350 and 13,800 kgC/hectare (0, 5, 10, 15 and 20 tons/hectare).

The cost of each process is summarized as follows.

1) Cost of feedstock production

The cost of one ton biomass production was 1,200 THB and included solely from pruning activity. No greenhouse gas emissions occurred as no fossil was used.

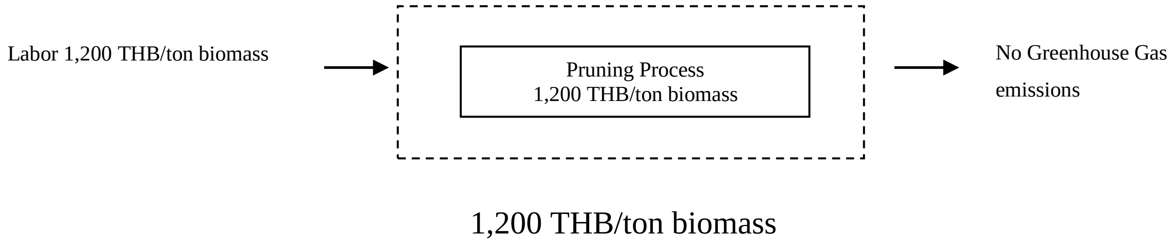


Figure 4.25 Cost and greenhouse gas emissions associated with mixed softwood feedstock production

2) Costs of biochar production

The total cost of biochar production was 3,906 THB/ton biochar. This included 306 THB/ton biochar from transportation and 3,600 THB/ton biochar from pyrolysis. The GHG emission from transportation was 1.74 kg CO_2-eq/ton biochar and from pyrolysis was 312.72 kg CO_2-eq/ton biochar.

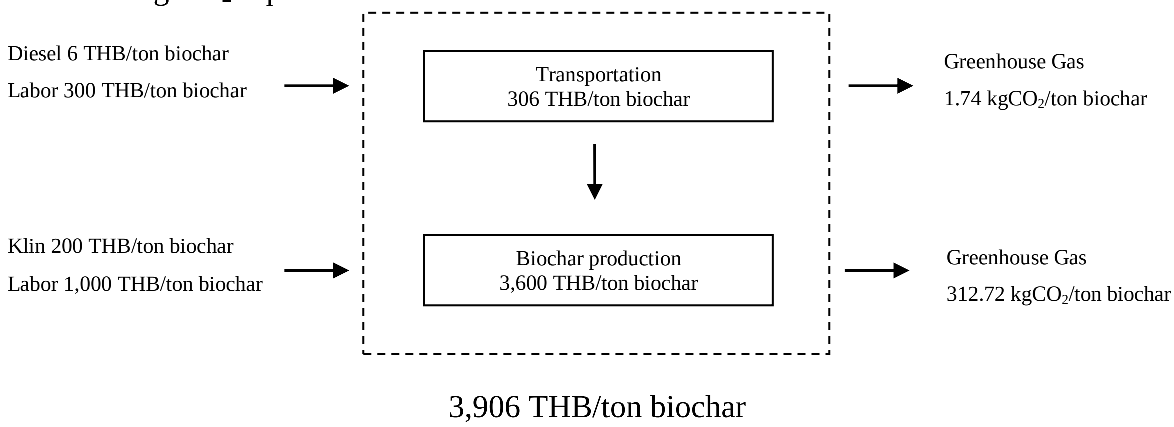
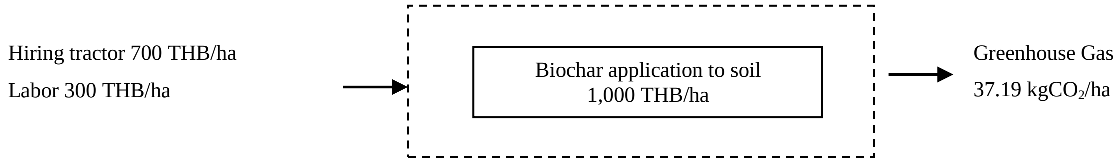


Figure 4.26 Costs and greenhouse gas emissions associated with mixed softwood biochar production

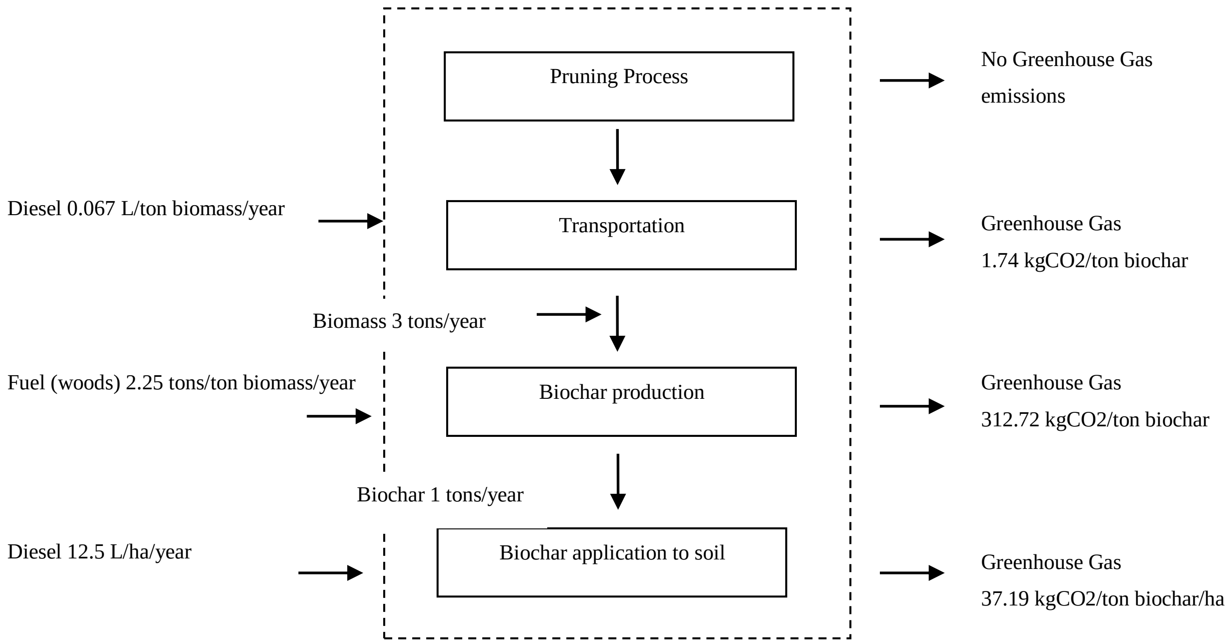
3) Costs of biochar application to soil

The total cost of mixed softwoods biochar application per hectare was 1,000 THB/hectare, including 700 THB/hectare for hiring a tractor and 300 THB/hectare for labor. The GHG emissions from biochar application activity to soil was 37.91 $kgCO_2$-eq/hectare.



1,000 THB/hectare

Figure 4.27 Costs and greenhouse gas emissions from mixed softwoods biochar application to soil



4.2 Plant yield and soil characteristics

4.2.1 Mangrove biochar application

Applying mangrove biochar to a sorghum field resulted in an increase in plant performance. The results shown in Table 4.1 indicate that height, cane yields, grain yields, and amount of juice had significantly increased.

Table 4.1 Sweet sorghum yield after mangrove biochar application in soil

Application rate (ton/ha)	Plant heights (cm)	Cane yields (t ha^{-1})	Grain yields (t ha^{-1})	Amount of juice (m^3 ha^{-1})
Control	218.07±16.50	23.20±5.70	3.80±0.30	9.90
10	247.27±2.41	30.10±4.6	5.20±0.90	14.02

Source: Suekhum *et al*. [121]

The characteristics of the soil underlying the sweet sorghum crop shows that the application increases soil pH, bulk density and carbon, while nitrogen content slightly decreases as shown in Table 4.2

Table 4.2 Characteristics of the soil underlying the sweet sorghum crop at the study site

Biochar	Depth	BD[a]	Soil particle (%)				pH	EC (1:5)	%Total	%Total	Phosphorus
kg/ha	(cm)	(g/cm^3)	Sand	Silt	Clay	Texture	(1:1)	(dS/m)	Carbon	nitrogen	(mg/kg)
Control	0-15	1.52±0.05	-	-	-	Sandy loam	5.20	-	0.61	0.06	-
	15-30	1.58±0.05	-	-	-	Sandy loam	4.67	-	0.37	0.05	-
10,000	0-15	1.59±0.11	-	-	-	Sandy loam	5.40	-	0.78	0.05	-
	15-30	1.60±0.13	-	-	-	Sandy loam	4.57	-	0.42	0.04	-

BD[a] = bulk density±3 samples

Source: Suekhum *et al*. [121]

4.2.2 Rice husk biochar application

Biochar from rice husk feedstock was added to rice field soil at 0.1125 ton per hectare. This practice resulted in increased rice yield and straw by 30%, and 40%, respectively, compared to that without biochar application [122]. The addition of biochar significantly increased tiller number, and as a result, the panicle number increased more than those without adding biochar [39].

The characteristics of the soil underlying the rice crop show that after applying rice husk biochar to soil, the effects are apparent for increasing the cation exchange capacity and reducing soil acidity. Lehmann, J. and Joseph, S. (2009) reported that this also increased water retention by reducing water run-off and flooding [110].

Table 4.3 Characteristics of the soil underlying the rice crop at the Agricultural Center New theory, Mae Taeng District Chiangmai Province of Thailand

Biochar ton/ha	Depth (cm)	BD[a] (g/cm^3)	Soil particle (%) Sand	Silt	Clay	Texture	pH (1:1)	EC (1:5) (dS/m)	%Total Carbon	%Total nitrogen	Phosphorus (mg/kg)
C	0-15	1.54±0.05	74	11	15	Sandy loam	5.61	0.017	0.75	0.14	40.61
	15-30	1.48±0.03	79	7	14	Sandy loam	5.48	0.008	0.46	0.13	32.41
0.1125	0-15	1.53±0.11	28	37	35	Clay loam	5.68	0.025	1.39	0.17	35.65
	15-30	1.54±0.19	25	32	43	Clay loam	6.26	0.037	0.98	0.15	23.33

BD[a] = bulk density±3 samples

4.2.3 Bamboo biochar application

Adding biochar at different rates (5, 10 and 20 tons of biochar per hectare) did not significantly result in increasing average fresh weight yield, average dry weight yield, average height, average yield and average leaf number of lettuce (Figures 4.28, 4.29, 4.30 and 4.31) [123]. For soil, addition of biochar seems to increase (but not always the case) in carbon content, phosphorus and soil conductivity (Table 4.4).

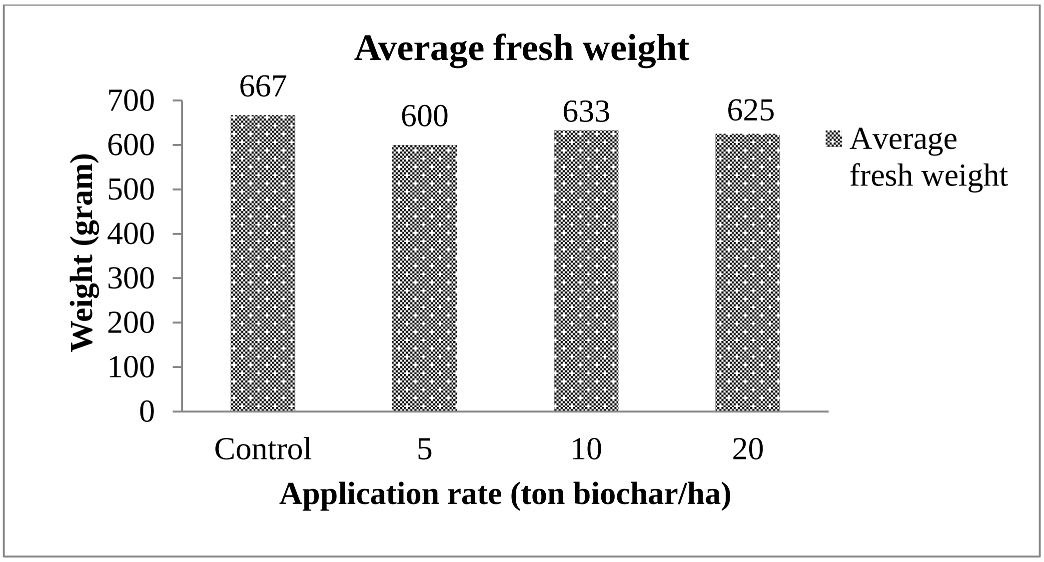


Figure 4.28 Lettuce average fresh weight after bamboo biochar application

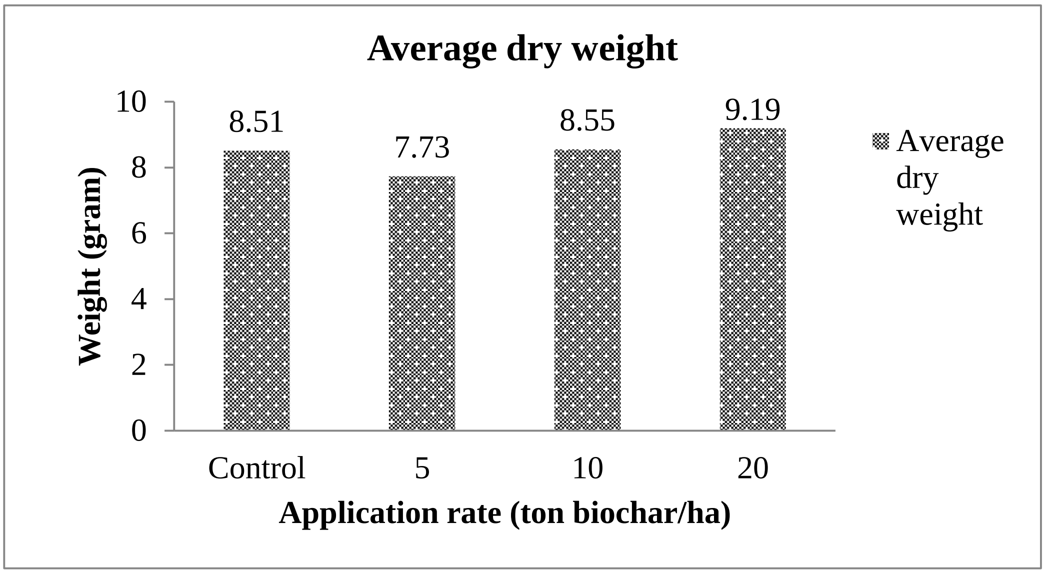


Figure 4.29 Lettuce average dry weight after bamboo biochar application

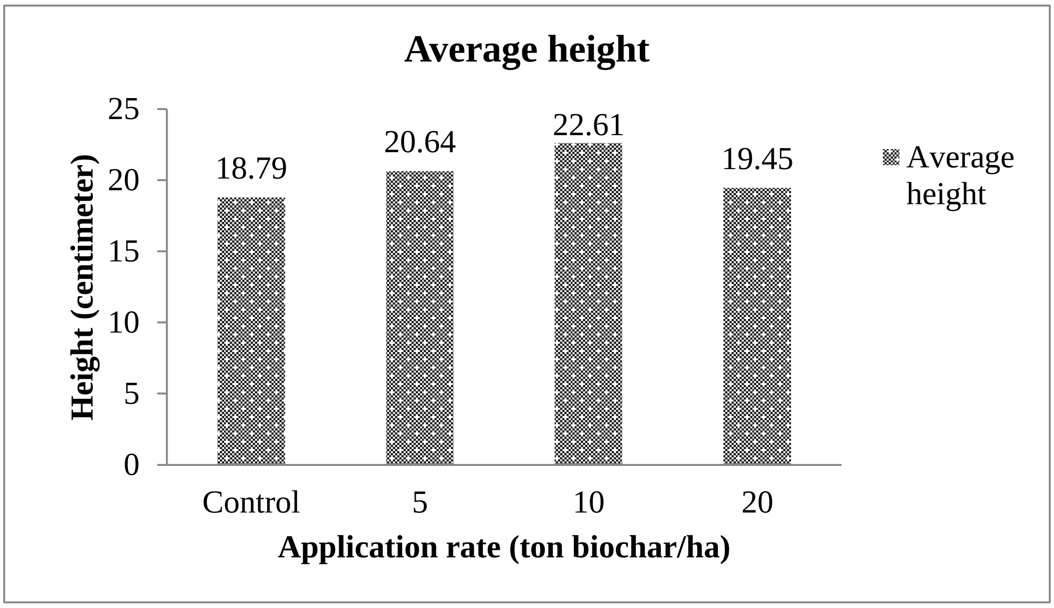


Figure 4.30 Lettuce average height after bamboo biochar application

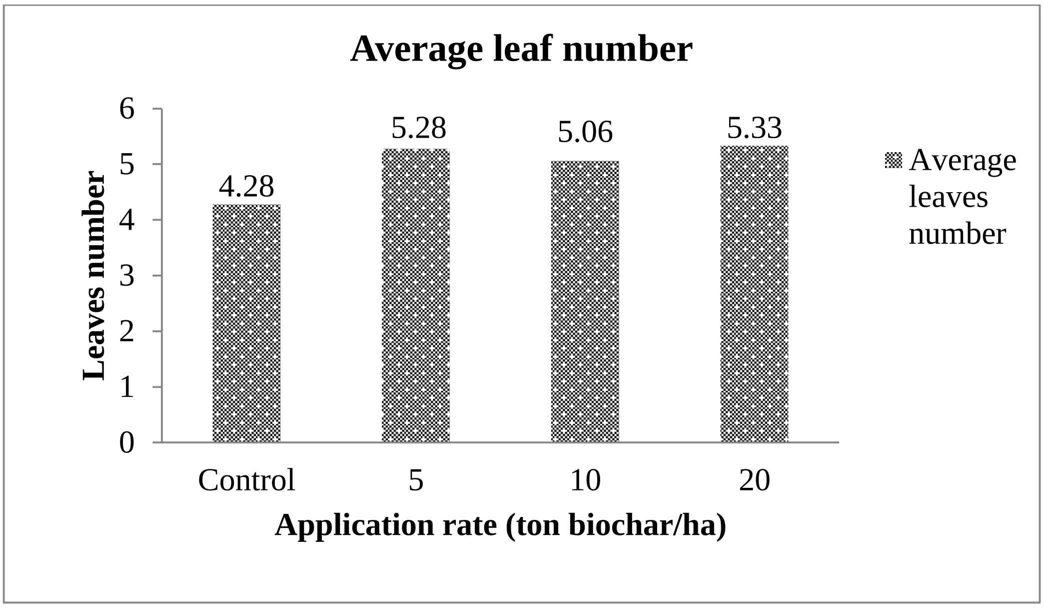


Figure 4.31 Lettuce average leaf number after bamboo biochar application

Table 4.4 Characteristics of the soil underlying the lettuce plots at the Office of Land Development Region 6

Biochar ton/ha	Depth (cm)	BD[a] (g/cm^3)	Soil particle (%) Sand	Silt	Clay	Texture	pH (1:1)	EC (1:5) (dS/m)	%Total Carbon	%Total nitrogen	Phosphorus (mg/kg)
0	-	-	69	12	19	Sandy loam	5.62	0.036	1.77	0.18	126.87
	-	-	76	14	10	Sandy loam	4.96	0.315	1.95	0.22	153.83
	-	-	69	12	19	Sandy loam	5.44	0.059	1.71	0.17	94.49
5	-	-	73	10	17	Sandy loam	5.68	0.028	1.69	0.17	100.39
	-	-	74	12	14	Sandy loam	5.40	0.078	1.73	0.16	130.92
	-	-	79	13	8	Loamy sand	5.63	0.029	1.43	0.15	91.64
10	-	-	70	13	17	Sandy loam	5.63	0.038	2.28	0.17	117.21
	-	-	70	15	15	Sandy loam	5.60	0.030	2.03	0.21	107.12
	-	-	71	12	17	Sandy loam	5.51	0.043	2.05	0.17	116.99
20	-	-	75	16	9	Sandy loam	5.61	0.033	2.16	0.19	79.07
	-	-	73	11	16	Sandy loam	5.78	0.035	2.50	0.18	127.36
	-	-	72	12	16	Sandy loam	5.79	0.037	4.49	0.22	110.61

4.2.4 Corn cob biochar application

Biochar from corn cob feedstock was added to soil planted with corn at the application rate of 2.5, 5, 7.5 and 10 tons of biochar per hectare. It was clear that corn yield had increased along with the increase in the biochar application rates. The corn yields were 19, 20, 23 and 27 ton per hectare, respectively (Figure 4.32) [124].

The characteristics of the soil underlying the corn plantation show that the pH in the soil was increased after applying corn cob biochar (Table 4.5). In addition, applied corn cob biochar to soil can improve the cation exchange capacity of soils too.

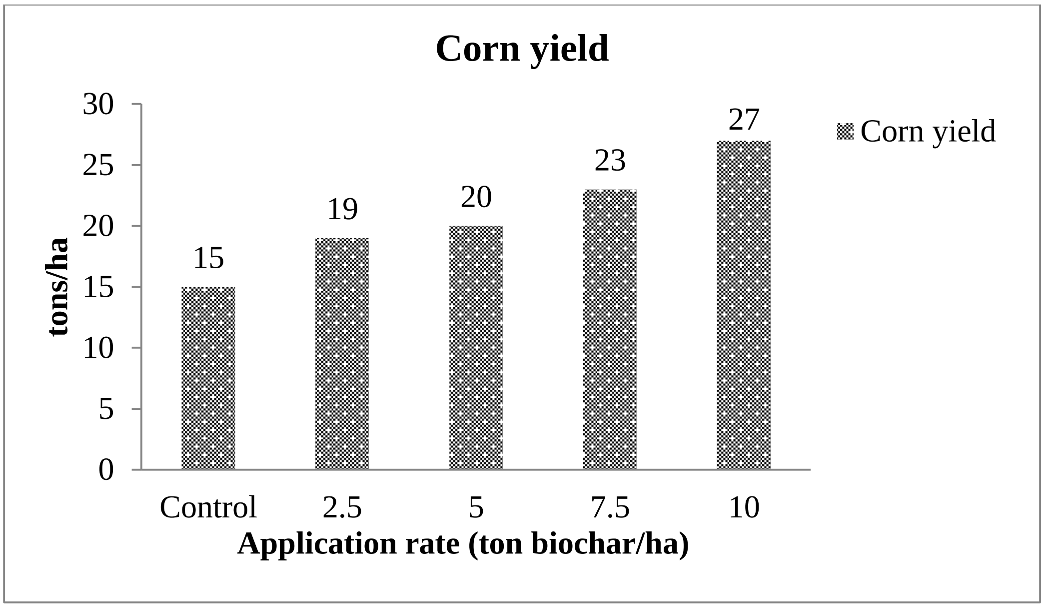


Figure 4.32 Corn yield after corn cob biochar application in soil

Table 4.5 Characteristics of the soil underlying the corn crop at the Huay Sai Royal Development Study Center

Biochar	Depth	BD[a]	Soil particle (%)				pH	EC (1:5)	%Total	%Total	Phosphorus
ton/ha	(cm)	(g/cm^3)	Sand	Silt	Clay	Texture	(1:1)	(dS/m)	Carbon	nitrogen	(mg/kg)
Control	0-15	1.67±0.08	84	6	10	Loamy sand	7.26	0.062	0.39	0.15	187.09
	15-30	1.65±0.09	83	9	8	Loamy sand	6.14	0.053	0.35	0.12	198.85
2.5	0-15	1.51±0.09	83	8	9	Loamy sand	7.13	0.066	0.37	0.12	80.65
	15-30	1.60±0.04	82	8	10	Loamy sand	6.22	0.035	0.27	0.07	64.85

Table 4.5 Characteristics of the soil underlying the corn crop at the Huay Sai Royal Development Study Center (con't)

Biochar ton/ha	Depth (cm)	BD[a] (g/cm^3)	Soil particle (%) Sand	Silt	Clay	Texture	pH (1:1)	EC (1:5) (dS/m)	%Total Carbon	%Total nitrogen	Phosphorus (mg/kg)
5	0-15	1.57±0.09	82	9	9	Loamy sand	6.46	0.054	0.44	0.10	120.29
	15-30	1.53±0.08	85	8	7	Loamy sand	6.40	0.033	0.27	0.09	91.90
7.5	0-15	1.57±0.04	85	8	7	Loamy sand	7.47	0.072	0.45	0.07	125.94
	15-30	1.63±0.05	86	6	8	Loamy sand	6.25	0.039	0.36	0.07	81.68
10	0-15	1.49±0.07	85	7	8	Loamy sand	7.68	0.098	0.51	0.09	173.30
	15-30	1.59±0.04	85	8	7	Loamy sand	6.40	0.054	0.42	0.06	72.13

BD[a] = bulk density±3 samples

4.2.5 Mixed softwood biochar application

Application of mixed softwood biochar at the rates of 5, 10, 15 and 20 tons of biochar per hectare resulted in corn yields of 14.38, 17.97, 25.16 and 28.76 ton per hectare (Figure 4.33). The yield with biochar application was 10.78 ton/ha. Thus, biochar application help increased corn yield significantly at this site. In addition, other plant performance including height and stem diameter were also better in biochar application plots when compared to those without biochar application (Figure 4.35) [124].

The characteristics of the soil underlying the corn crop show that soil pH, CEC, carbon content and phosphorus had increased (Table 4.6).

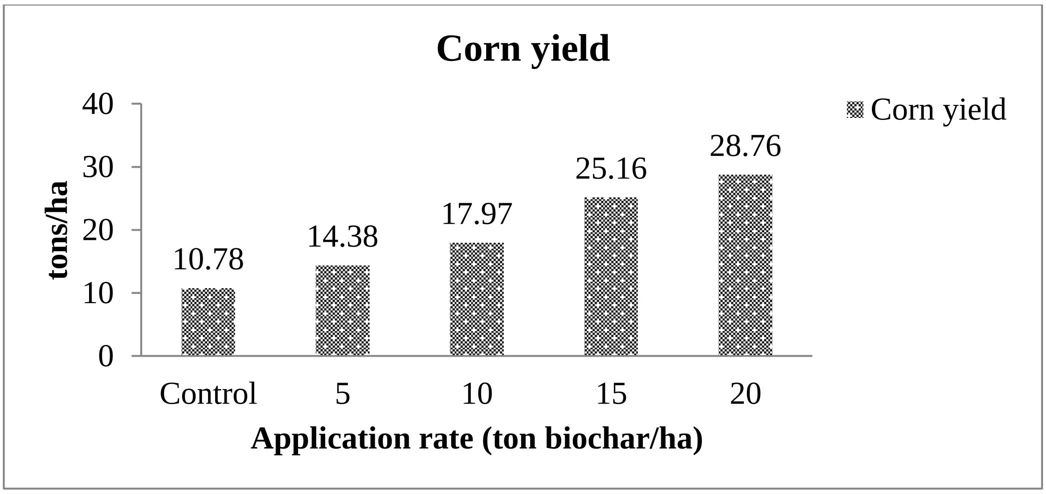


Figure 4.33 Corn yield after mixed softwood biochar application

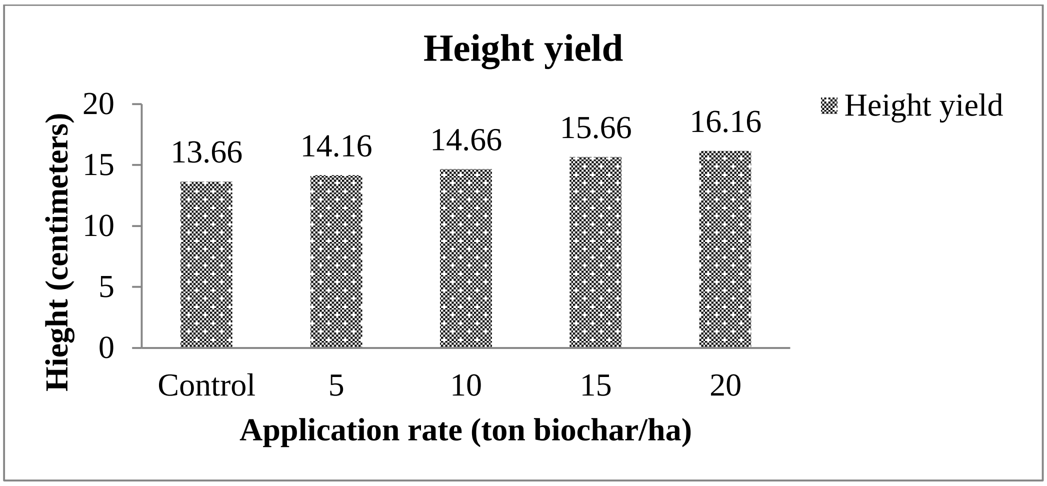


Figure 4.34 Height of corn after mixed softwood biochar application

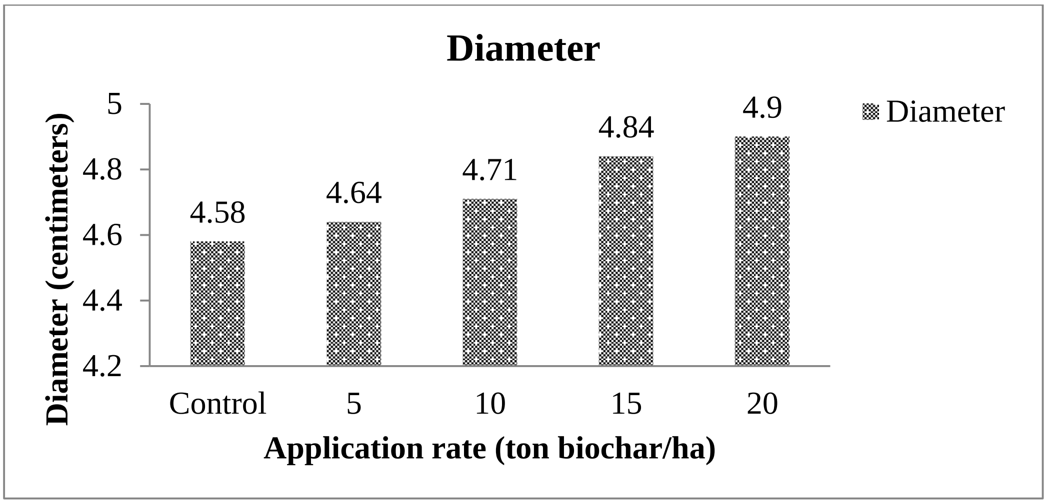


Figure 4.35 Diameter of corn after mixed softwood biochar application

Table 4.6 Characteristics of the soil underlying the biochar from mixed softwoods feedstock at the Huay Sai Royal Development Study Center

Biochar ton/ha	Depth (cm)	BD[a] (g/cm³)	Soil particle (%) Sand	Silt	Clay	Texture	pH (1:1)	EC (1:5) (dS/m)	%Total Carbon	%Total nitrogen	Phosphorus (mg/kg)
Control	0-15	1.67±0.08	84	6	10	Loamy sand	7.26	0.062	0.39	0.15	187.09
	15-30	1.65±0.09	83	9	8	Loamy sand	6.14	0.053	0.35	0.12	198.85
5	0-15	1.63±0.06	81	11	8	Loamy sand	7.19	0.084	0.42	0.05	179.95
	15-30	1.59±0.02	82	9	9	Loamy sand	6.26	0.026	0.26	0.04	38.58
10	0-15	1.67±0.05	79	11	10	Sandy loam	7.64	0.075	0.56	0.06	222.86
	15-30	1.62±0.10	78	11	11	Sandy loam	6.97	0.067	0.51	0.07	103.03
15	0-15	1.57±0.04	84	8	8	Loamy sand	7.13	0.079	0.60	0.07	600.80
	15-30	1.53±0.16	86	5	9	Loamy sand	6.76	0.035	0.38	0.05	156.79
20	0-15	1.55±0.08	82	9	9	Loamy sand	7.61	0.086	0.30	0.04	560.19
	15-30	1.57±0.02	81	10	9	Loamy sand	6.85	0.048	0.41	0.05	180.20

BD[a] = bulk density±3 samples

From analyzing crop performance and soil properties upon biochar applications, it could be said that in general, biochar applications is resulted in increases of pH, cation exchange capacity, and carbon content. However, nitrogen content was found to decrease for all cases. For bulk density and phosphorus, the results varied from place to place, and also on feedstock types. These later features therefore warrant further investigation, especially on the interactions between different biochar and soil types. In addition, for all soil and feedstock types, it was found that biochar application did not change the soil texture.

4.3 Comparison of cost among feedstocks

This part compares the cost among the steps of biomass production, biochar production, and biochar application in soil from all five feedstocks.

Figure 4.36 indicates that per biomass, the cost of biochar was the lowest in mangrove (27.29 THB/ton biomass), followed by bamboo (895 THB/ton biomass), mixed softwood (1,200 THB/ton biomass), corn cop (1,244.8 THB/ton biomass) and rice husk (1,927 THB/ton biomass), respectively (Figure 4.36). The differences in biomass production costs depend on of the method for production of biomass, fuel costs, the transportation costs, fertilizer costs and labor costs.

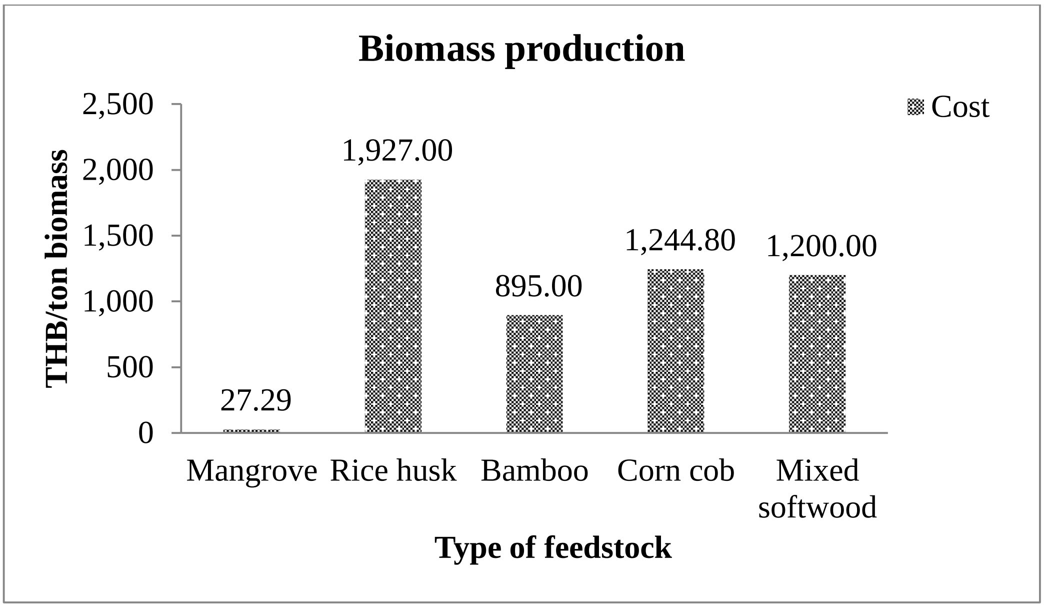


Figure 4.36 Comparison of costs for biomass production from five feedstocks

For the pyrolysis step, the cost for each feedstock was 410.70, 2,830, 2,583, 8,735 and 3,906 THB/ton biochar for mangrove, rice husk, bamboo, corn cob and mixed softwood, respectively (Figure 4.37).

The cost of biochar production from corn cob feedstock was highest due to the ratio of biomass required per biochar produced was high, so that consuming more resources, time and costing more when compared to others.

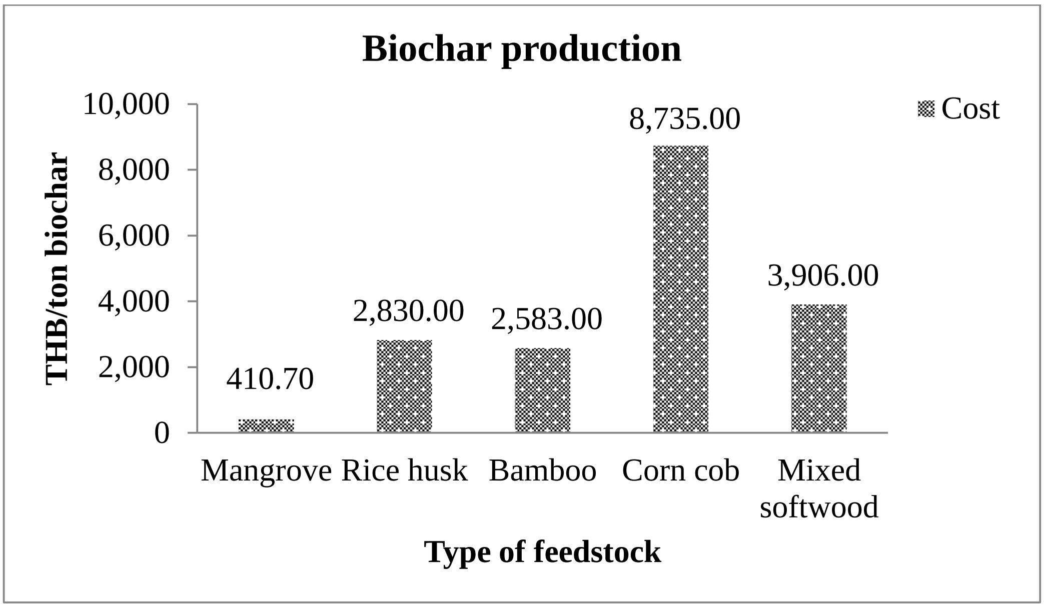


Figure 4.37 Comparison cost of biochar production during pyrolysis from five feedstocks

When considering the cost of biochar production without transportation costs, the result shows that the total cost of corn cob and mixed softwood biomass had slightly declined to 6,000 THB/ton biochar and 3,600 THB/ton biochar (Figure 4.38).

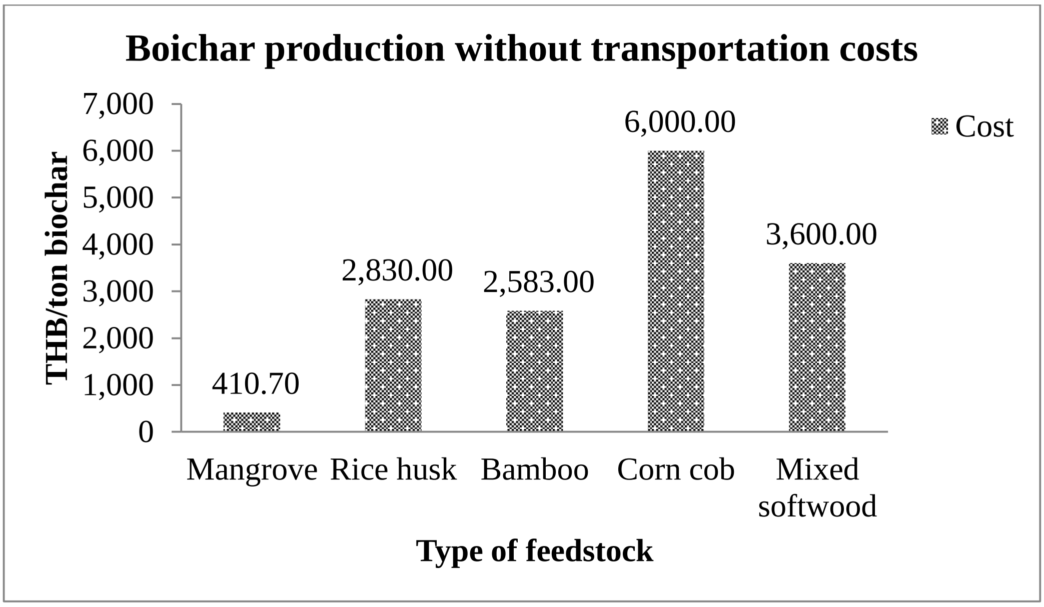


Figure 4.38 Comparison costs of biochar production from five feedstocks without transportation costs

The total cost per ton biochar delivered to the field is shown in Figure 4.39 for individual feedstocks. The result shows that the cost for mangrove biochar was 1,635 THB /hectare, rice husk biochar was 312.50 THB/hectare, bamboo biochar was 515 THB/hectare, corn cob biochar was 1,000 THB/hectare and mixed softwood biochar was 1,000 THB/hectare respectively. However, the total cost of biochar applications to soil increased as the rate of application increased and costs of biochar application are dependent of application methods [36].

In addition, there are some previous studies that have reported on the economic value of biochar application on agricultural cropland for carbon sequestration and its soil amendment properties. It may be profitable to apply biochar as a soil amendment under some conditions if the biochar market price is low enough and/or a carbon offset market exists [40].

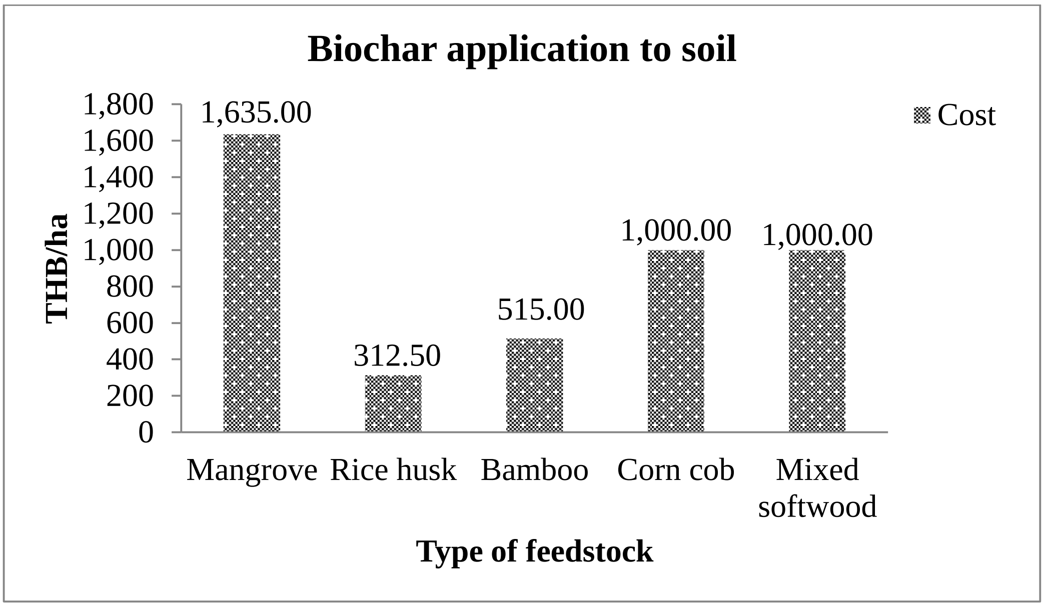


Figure 4.39 Comparison cost of biochar application to soil from 5 feedstocks

When considering the cost of biochar application to soil without transportation costs, the result shows that the total cost of mangrove biochar and bamboo biochar slightly declined to 975 THB/hectare and 234.4 THB/hectare, respectively (Figure 4.40).

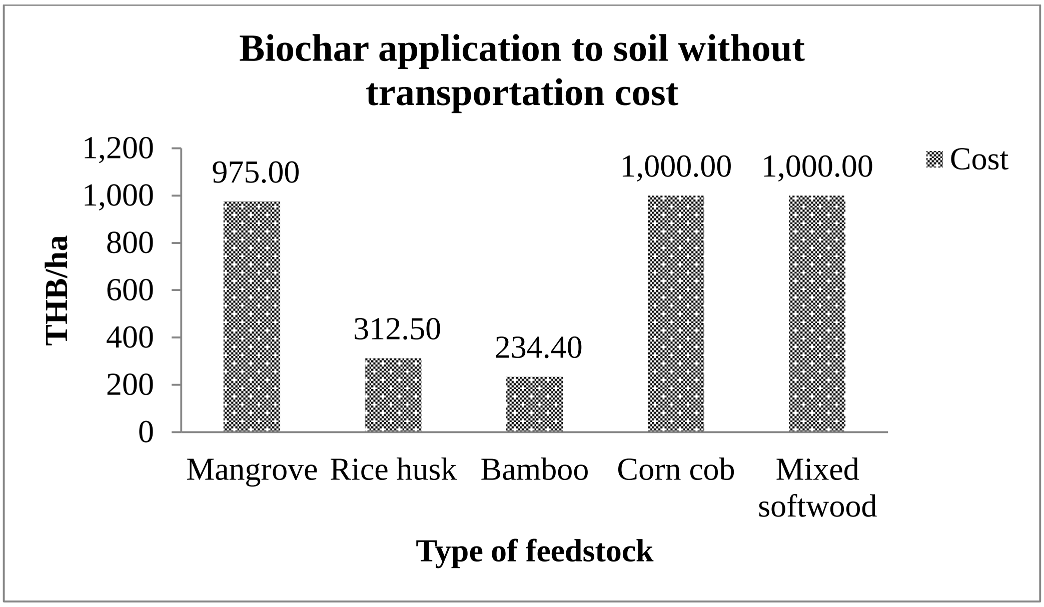


Figure 4.40 Comparison costs of biochar application to soil from five feedstocks without transportation cost

4.4 Soil carbon stock and costs of mitigation

4.4.1 Soil carbon stocks after biochar application to the study site

Soil carbon stocks were estimated to a depth of 30 cm. after biochar applications to soil for one crop. The details are as follows.

1) Mangrove biochar

Applying mangrove biochar at the application rate of 10 tons/hectare to soil was resulted in an increase of soil carbon both in surface and subsurface layers, and on average the soil carbon sequestration was increased about 50 kgC/hectare (Table 4.7).

2) Rice husk biochar

The estimated amount of soil carbon stock resulted from the rice husk biochar with the application rate 0.1125 tons/hectare or 57.375 kgC/hectare was an increase from 275.37 to 538.65 kgC/hectare, or increase by 263.38 kgC/hectare (Table 4.8).

3) Bamboo biochar

Soil carbon stocks underlying the lettuce plots at the Office of Land Development Region 6 (Chiangmai Province) cannot be estimated due to the fact that the experiment was carried out in a small pot, and thus the bulk density cannot be measured.

4) Corn cob biochar

The estimated amount of soil carbon stock from the corn cob biochar at the application rates of 2.5, 5, 7.5 and 10 tons/hectare or 1,946, 3,892, 5,838 and 7,784 kgC/hectare at 0-15 cm depth level was 92.69, 110.22, 112.73 and 127.76 kgC/hectare and 15-30 cm depth level, or increased by 66.83, 66.83, 89.10 and 103.95 (Table 4.9).

5) Mixed softwoods biochar

The estimated amount of soil carbon stock from the mixed softwoods biochar at the Huay Sai Royal Development Study Center with the application rate 5, 10, 15 and 20 tons /hectare was found for both decreases and increases in soil carbon content (Table 4.10). This may be the result of an error in measuring soil bulk density that consequently resulted in lower soil carbon estimate.

Table 4.7 Soil C stock underlying the sweet sorghum cultivation with mangrove biochar application

Biochar (ton/ha)	**Carbon** (kgC/ha)	**Depth** (cm)	**BD[a]** (g/cm^3)	**OC** (%)	**Soil C stock** (kgC/ha)	**Total C** (kgC/ha)	**Sequestration** (kgC/ha)
Control	0	0-15	1.52±0.05	0.61±0.09	139.08	226.77	
		15-30	1.58±0.05	0.37±0.08	87.69		
10	5,189	0-15	1.59±0.11	0.78±0.18	177.84	227.38	50.61
		15-30	1.60±0.13	0.42±0.13	99.54		

BD[a] = bulk density±standard deviation of 3 samples
Percentage of carbon in biochar from mangrove = 51.89%
Source: Suekhum *et al*. [121]

Table 4.8 Soil C stock underlying the rice field after rice husk biochar application

Biochar (ton/ha)	**Carbon** (kgC/ha)	**Depth** (cm)	**BD[a]** (g/cm^3)	**OC** (%)	**Soil C stock** (kgC/ha)	**Total C** (kgC/ha)	**Sequestration** (kgC/ha)
Control	0	0-15	1.54±0.05	0.75	173.25	275.37	
		15-30	1.48±0.03	0.46	102.12		
0.1125	57.375	0-15	1.53±0.11	1.39	321.09	538.65	263.28
		15-30	1.54±0.19	0.98	217.56		

BD[a] = bulk density± standard deviation of 3 samples
Percentage of carbon in biochar from rice husk = 51%

Table 4.9 Soil C stock underlying the corn crop after corn cob biochar application

Biochar (tons/ha)	Carbon (kgC/ha)	Depth (cm)	BD[a] (g/cm^3)	OC (%)	Soil C stock (kgC/ha)	Total C (kgC/ha)	Sequestration (kgC/ha)
Control	0	0-15	1.67±0.08	0.39	97.70	184.32	
		15-30	1.65±0.09	0.35	86.63		
2.5	1,946	0-15	1.51±0.09	0.37	92.69	159.51	-24.81
		15-30	1.60±0.04	0.27	66.83		
5	3,892	0-15	1.57±0.09	0.44	110.22	177.05	-7.27
		15-30	1.53±0.08	0.27	66.83		
7.5	5,838	0-15	1.57±0.04	0.45	112.73	201.83	17.51
		15-30	1.63±0.05	0.36	89.10		
10	7,784	0-15	1.49±0.07	0.51	127.76	231.71	47.39
		15-30	1.59±0.04	0.42	103.95		

BD[a] = bulk density± standard deviation of 3 samples
Percentage of carbon in biochar from corn cob = 77.84%

Table 4.10 Soil C stock underlying the corn crop after mixed softwood biochar application

Biochar (tons/ha)	Carbon (kgC/ha)	Depth (cm)	BD[a] (g/cm^3)	OC (%)	Soil C stock (kgC/ha)	Total C (kgC/ha)	Sequestration (kgC/ha)
Control	0	0-15	1.67±0.08	0.39	97.70	184.32	
		15-30	1.65±0.09	0.35	86.63		
5	3,450	0-15	1.63±0.06	0.42	105.21	169.56	-14.76
		15-30	1.59±0.02	0.26	64.35		
10	6,900	0-15	1.67±0.05	0.56	140.28	266.51	82.19
		15-30	1.62±0.10	0.51	126.23		
15	10,350	0-15	1.57±0.04	0.6	150.30	244.35	60.03
		15-30	1.53±0.16	0.38	94.05		
20	13,800	0-15	1.55±0.08	0.3	75.15	176.63	-7.70
		15-30	1.59±0.04	0.42	103.95		

BD[a] = bulk density± standard deviation of 3 samples
Percentage of carbon in biochar from mixed softwood = 69%

4.4.2 Costs of greenhouse gas emission mitigation

The cost-effectiveness of the mitigation potential by biochar application to soil was estimated and compared among different feedstocks using the following equations:

$$\text{Mitigation cost}_{\text{(THB/ton CO2e)}} = \frac{\text{Total cost of biochar production and application}_{\text{(THB/ton.biochar)}}}{\text{C sequester}_{\text{(ton CO2e/ton biochar)}} - \text{GHG emissions}_{\text{(ton CO2e/ton biochar)}}}$$

Remark: at the application rate 1 ton biochar; carbon sequestration was estimated as followed;

1) Mangrove biochar

C sequester = (51.89/100) × 44/12 = 1.90 ton.CO_{2eq}, GHG emission = 0.18 ton.CO_{2eq} and Net C sequester = 1.72 ton.CO_{2eq}

2) Rice husk biochar

C sequester = (51/100) × 44/12 = 1.87 ton.CO_{2eq}, GHG emission = 1.09 ton.CO_{2eq} and Net C sequester = 0.78 ton.CO_{2eq}

3) Bamboo biochar

C sequester = (71.99/100) × 44/12 = 2.64 ton.CO_{2eq}, GHG emission = 0.18 ton.CO_{2eq} and Net C sequester = 2.46 ton.CO_{2eq}

4) Corncob biochar

C sequester = (77.84/100) × 44/12 = 2.85 ton.CO_{2eq}, GHG emission = 2.32 ton.CO_{2eq} and Net C sequester = 0.53 ton.CO_{2eq}

5) Mixed softwoods biochar

C sequester = (69/100) × 44/12 = 2.53 ton.CO_{2eq}, GHG emission = 0.35 ton.CO_{2eq} and Net C sequester = 2.18 ton.CO_{2eq}

The net carbon sequestration was estimated from the carbon content of each biochar by assuming that all biochar carbon had remained in soil. The GHG emissions from biomass production, biochar production and biochar application to soil were as those described under Section 4.1. No other carbon sequestration such as from plant residue incorporation nor emission such as the priming effects of biochar on native soil organic carbon was considered.

Estimations based on THB per tonCO_{2eq} of mitigation costs from 5 biochar types shows that the mitigation costs for mangrove biochar was 381.44 THB/tonCO_{2eq}, rice husk biochar was 9,844.55 THB/tonCO_{2eq}, bamboo biochar was 1,677 THB/tonCO_{2eq}, corn cob biochar was 28,413.20 THB/tonCO_{2eq} and mixed softwood biochar was 3,488.99 THB/tonCO_{2eq} respectively (Figure 4.41). Detailed calculations are shown in Table 4.11 below.

Table 4.11 Detailed calculations and parameters used for mitigation costs using different types of biochar

Biochar	Calculation details	Mitigation cost ($THB/tonCO_2e$)
Mangrove biochar	6,560.70 (THB/ha)/ {(1.90 $tonCO_2e$/ton biochar) – (0.18 $tonCO_2e$/ton biochar)} × 10 (ton biochar/ha)	381.44
Rice husk biochar	76,793.00 (THB/ha) / {(1.87 tonCO2e/ton biochar) – (1.09 tonCO2e/ton biochar)} × 10 (ton biochar/ha)	9,844.55
Bamboo biochar	41,265.00 (THB/ha) / {(2.64 tonCO2e/ton biochar) – (0.18 tonCO2e/ton biochar)} × 10 (ton biochar/ha)	1,677
Corn cob biochar	150,590.00 (THB/ha) / {(2.85 tonCO2e/ton biochar) – (2.32 tonCO2e/ton biochar)} × 10 (ton biochar/ha)	28,413.20
Mixed softwood biochar	76,060.00 (THB/ha) / {(2.53 tonCO2e/ton biochar) – (0.35 tonCO2e/ton biochar)} × 10 (ton biochar/ha)	3,488.99

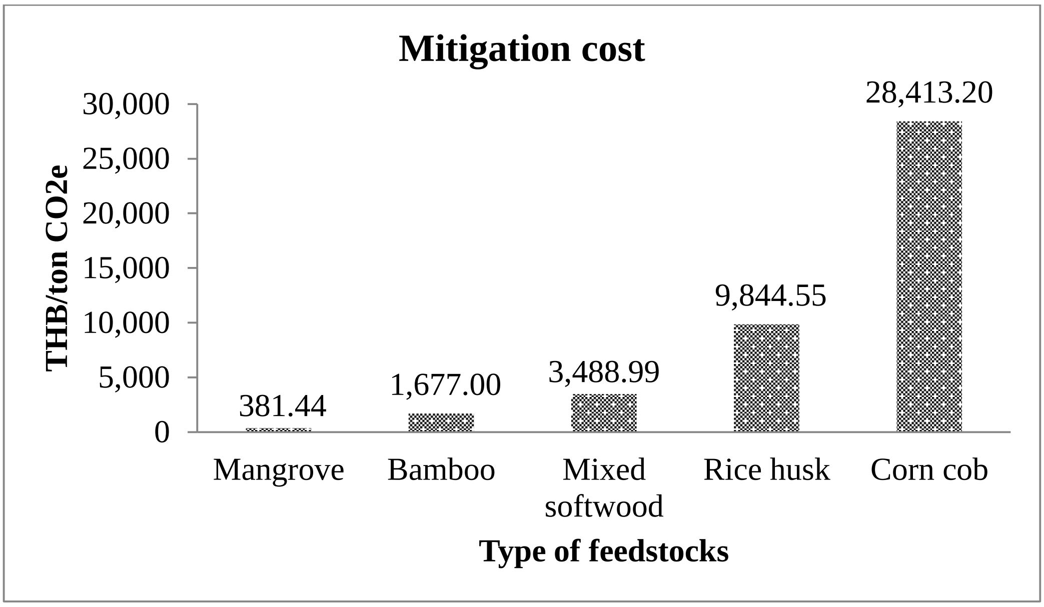


Figure 4.41 Comparison of mitigation costs of biochar from five feedstocks

Considering different sources of biochar with abatement costs indicates that the economic feasibility of biochar projects depends on a range of factors including the price of carbon and significant ancillary benefits in terms of agricultural productivity [125].

It is clear that biochar has potential as a soil amendment and its value as such would likely increase as social and regulatory interests in carbon sequestration increase because of the longevity of carbon in the soil [126]. The ability of biochar to store carbon and improve soil fertility will not only depend on its physical and chemical properties, which can be varied in the pyrolysis process or through the choice of feedstock [127] but also on the technical and economic limitations of handling biochar at quantity in an agronomic setting [36]. Under the current economic situation, growers are unlikely to adopt biochar use without greater payback. Also at this time, even if growers found biochar beneficial, they could face difficulty in sourcing quantities large enough for farm application.

The potential of soil carbon sequestration and costs from using biochar applications in the different crops were that the costs of biochar applications could be varied on factors such as the application methods, labor cost and the biochar production costs. This has the effects on the net incomes, most in a way that when cost increases the net farm income is always lessened. When consider about carbon offset price, it could help minimize the income loss but appropriate offset price needs to be found. The biochar price is another important cost determining the net farm profit by a farmer will get a profit or a loss it depends on the price of biochar and value of sequestered carbon and economic feasibility of all biochar application depends on a range of factors including the price of carbon and significant ancillary benefits in terms of agricultural productivity [125].

Some options that may improve the chances of success of biochar in production are: if farmers are able to obtain biochar at lower costs, if farmers receive premium prices for yield grown on biochar treated soils and if there is a carbon offset market for biochar. However, the high cost of transportation cause prices to rise as biochar production especially mangrove and corncob feedstock. When applied biochar to corn cultivation, biochar application has been shown to double crop yields, improve the cation exchange capacity of soils, reduce soil acidity and the need for fertilizers and increase water retention by reducing water run-off and flooding [110].

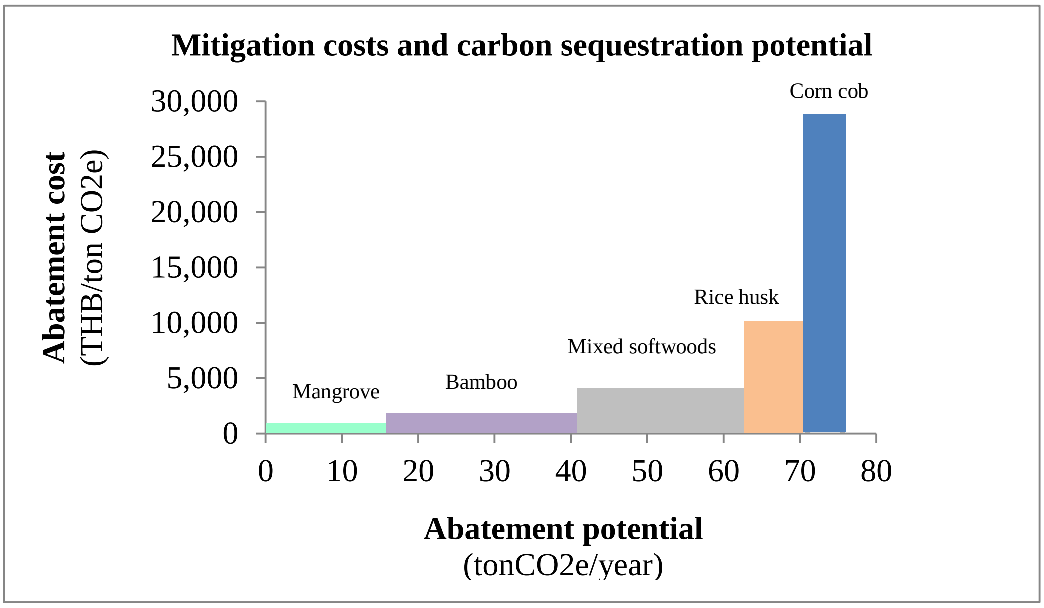


Figure 4.42 Comparison of mitigation costs and carbon sequestration potential of biochar from different feedstocks

4.5 Summary of the results

The results of this study show that the addition of biochar to agricultural soils has been shown to improve crop productivity and sequester carbon in soils by this research has clarified biochars cost from 5 feedstocks related to potential soil improvements. The potential to improve carbon sequestration by adding biochar to soil creates an important opportunity to mitigate greenhouse gas emissions. Biochar applications in soil have the potential to store carbon for very long periods by the amount of carbon stock in soil it depend on the percentage of carbon in each feedstock**.** Biochar can improve soil fertility and water holding capacity, crop productivity and reduce fertilizer costs for farmers. However, this study can summary as a following

The differences in biomass production costs and biochar production costs from 5 feedstocks it depend on the various methods for production, fuel costs, the transportation costs, fertilizer costs and labor costs. Biochar applications to soil costs show that the total cost increased as the rate of application increased and costs of biochar application are dependent of application methods. However, when estimation the total costs without considering the feedstock production cost it tell that the investment cost can reduced.

Mitigation costs show that the low costs with 3 biochars were bamboo biochar, mixed softwood biochar and mangrove biochar. In addition, the high cost with 2 biochars was rice husk biochar and corn cob biochar respectively.

Moreover, when biochar was applied in the study site, the costs from using biochar application in the different crops could be varied on various factors such as the application methods, labor cost and the biochar production costs, which reduces the gross profit when mitigation cost increases.

The benefits gains associated with biochar application show that from product sells plus that of carbon credit it depend on the price of biochar and value of sequestered carbon. It could help minimize the income loss when consider about carbon offset price of each biochar.

Furthermore, biochar application was [103] reported that the average carbon sequestration equal to the fraction that about 1% of carbon in biochar is accumulated within the soil and the carbon sequestration potential and cost reported that the carbon content of biochar varies depending on the feedstock [40]. Nevertheless, if the market price of biochar is low enough so that a farmer will earn a profit after biochar application to the crop field and if biochar increases crop yield, farmer willingness to pay more money [42].

However, the feedstock is appropriate for producing biochar, but we must also consider the quantity of feedstock that enough for producing biochar. From this study, the results tell us that the cost of biochar application itself is substantial enough to become a key factor in considering the overall viability of a biochar market that biochar will likely deter landowners and investors from using biochar in the near future [128].

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Increasing concentrations of greenhouse gases in the atmosphere, especially CO_2 is one of the most important environmental concerns and this results in mounting global air temperatures that leads to climatic change. Reducing greenhouse gas emissions is urgently needed in order to avoid the adverse impacts of climate change. Using biochar in the agricultural sector is one of the options of mitigation technologies. However, to be able to successfully assess mitigation potential technologies, various aspects such an economic cost, and factors effecting mitigation must be known. In Thailand, cost associated with biochar application has not been sufficiently studied. To make biochar application viable so that we could benefit from enhancing soil carbon sequestration and improving crop productivity, consideration of cost associated with its application is necessary. Accordingly, the main objective of this thesis study is to evaluate the cost of biochar application to agricultural soils.

The study started from the step for biochar feedstock production, pyrolysis of feedstock yielding biochar, and the application of biochar to increase soil carbon sequestration and reduce greenhouse gas emission. The amount of inputs (such as fertilizers, fuels, labor, water, etc.) as well as investment cost and incomes were collected from field surveys and questionnaire. Other indirect benefits such as the benefits due to increasing crop yield results from biochar application, improve soil fertility or other environmental benefits were not considered in the current study.

Since applying biochar to cropland soil has not been a common practice in Thailand, the study used case studies under specific settings to investigate the greenhouse gas mitigation costs. Several field surveys and farmer interviews to collect data were made in 2013-2014 at these 3 locations. The first location was at the New Theory Farming Center, Mae Taeng District, Chiangmai province. The farmer is growing rice with alternative wet and dry technique. The produced biochar from rice husk and bamboo was applied directly to soil. The second location was at Yeesarn Community, Ampawa District, Samut Songkarm Province, central Thailand. Mangrove plantation (*R. apiculata*) here was under intensive management specifically for charcoal production. The third location was Huay

Sai Royal Development Study Center, Phetchaburi province. Here biochar was made from two main feedstock; corn cobs and many types of softwood such as acacia, mango and neem, collectively termed “mixed woods” in this study. These were the wastes from pruning, lawn mowing and other routine plant care activities.

Estimating costs associated with each step of biochar production, biomass feedstocks production, biochar production by pyrolysis and biochar application to soils, it was found that:

- the costs of biomass feedstock production for mangrove, rice husk, bamboo, corn cob and mixed softwood were 27, 1,927, 895, 1,245 and 1,200 THB/ton biomass, respectively. The differences in biomass production costs reflect the differences in the methods of the production of biomass, fuel costs, the transportation costs, fertilizer costs and labor costs.
- for the pyrolysis to yield biochar, the estimated costs for mangrove, rice husk, bamboo, corn cob and mixed softwood were 411, 2,830, 2,583, 14,959 and 3,906 THB/ton biochar, respectively. The main factor affecting costs is the ratio between the feedstock required and the biochar yield, which was the highest for corn cob. In addition, transportation and distance between feedstock production location and pyrolysis location was also the important factor.
- the cost of biochar application to soil for mangrove, rice husk, bamboo, corn cob and mixed softwood were 1,635, 313, 515, 1,000 and 1,000 THB/hectare, respectively. Transportation and distance between biochar production and application location was one of the important factors affecting the costs of this step.

Based on these cost estimates, the assumption that the amount of soil carbon sequestration was equal to the amount of carbon in biochar applied, and the emissions of greenhouse gases occurred during the three steps mentioned above (fossil fuel use, fertilizer application, burning of biomass, and emissions of methane for rice cultivation), the greenhouse gas emission mitigation costs were estimated. It was found that the mitigation costs were lowest for mangrove and highest for corn cob biochar. These were as follows: 381.44 THB/ton.CO_{2eq} for mangrove biochar, 1,677 THB/ton.CO_{2eq} for bamboo biochar, 3,488.99 THB/ton.CO_{2eq} for mixed softwood biochar, 9,844.55 THB/ton.CO_{2eq} for rice husk biochar and 28,413.2 THB/ton.CO_{2eq} for corn cob biochar, respectively.

The results from this study indicate that the potential and costs from biochar production and application to soil from these feedstocks are significantly different, depending on various parameters from agricultural management, feedstock type and method of production and application to soil.

5.2 Recommendations

From analyzing crop performances and soil properties upon biochar application, it was found that the effects were quite varied among feedstock types and application location. These could be the results of the interactions between biochar and soils. Thus, the following aspects need to be further investigated for clarification:

- how different pyrolysis systems or technologies affect on biochar properties
- what are the interactions between biochar from different feedstock and soil types, biochar properties and the effects on soil perties, etc.
- some crops, such as corn, respond to biochar application by a clear yield increase, but it was not quite clear for other crops. It was also found that soil phosphorus was increased when applied mixed softwoods biochar to corn cultivation, but this was not clearly observed in other crops. Thus interaction among biochar-plant and soil needs further study.

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APPENDIX A

(Data collection)

Table A-1 Estimating costs and greenhouse gas emissions from biochar production from 5 feedstocks

Process	Amounts	Cost (THB/unit)	Total Cost THB/year	Total GHG kgCO2eq/year
1) Mangrove				
• **Land preparation**				
- Area (Rais)	40			
- Boat		700	700	
- Maintenances	1	1,000	1,000	
- Gasoline (L)	48	42.5	2,040	117.21
- Labor (man-day)	80	150	12,000	
Subtotal			**15,740**	**117.21**
• **Cultivation**				
- Rental fee (Rais)	40	100	4,000	
- Seedling (seedling)	30,000	0.25	30,000	
- Labor (man-day)	80	150	12,000	
- Gasoline (L)	120	42.5	5,100	293.024
Subtotal			**51,100**	**293.024**
• **Harvesting**				
- Duration (km)	40			
- Labor (man-day)	280	300	84,000	
- Gasoline (L)	560	42.5	23,800	1,367.44
Subtotal			**107,800**	**1,367.44**
• **Pyrolysis**				
- Furnace	2		10,000	
- Maintenances(days)	8	1,000	8,000	
- Fuel Use (kg)	72,000			10,007
- Labor (man-day)	14	2,000	28,000	
Subtotal			**46,000**	**10,007**
• **Transportation**				
- Duration (km)	90			
- Hiring pickup 4 wheels	1	300	300	
- Diesel Use (L)	12	30	360	
- Pickup 4 wheels, full load 7 ton, 0 % loading for depart	1			28
- Pickup 4 wheels, full load 7 ton, 100 % loading for return	1			12.62
Subtotal			**660**	**40.62**
• **Biochar application to soil**				
- Labor for application (man-day)	1	300	300	
- Hiring tractor + Diesel Use	1	375	375	
- Diesel Use (L)	12.5			37.19
- Crusher		300	300	
Subtotal			**975**	**37.19**
Total			**222,275**	**11,862.48**

Table A-1 Estimating costs and greenhouse gas emissions from biochar production from 5 feedstocks (con't)

Process	Amounts	Cost (THB/unit)	Total Cost THB/year	Total GHG kgCO2eq/year
2. Rice husk				
• Land preparation				
- Area (Rais)	8			
- Tractor (Tillage 3 times)		1,900	1,900	
- Maintenances	1	80	80	
- Diesel Use (L)	40	25	1,000	116.04
- Labor (man-day)	6	200	1,200	
Subtotal			**4,180**	**116.04**
• **Paddy cultivation**				
- Area (Rais)	8			1,923.04
- Seeds (kg)	32	30	960	
- Compost-fertilize (kg)	4,000			757.6
- Labor (man-day)	1	200	200	
Subtotal			**1,160**	**2,680.64**
• **Harvesting**				
1) Rice Harvest Machine		1,850	1,850	
2) Gasoline Use (L)	15.66	30	470	38.24
3) Labor (man-day)	2	200	400	
Subtotal			**2,720**	**38.24**
• **Transportation**				
- Duration (km)	0.06			
- Gasoline Use (L)	1	30	30	2.44
Subtotal			**30**	**2.44**
• **Rice Production**				
- Rice huller machine	1	6,400	6,400	
- Electricity Use (hr.)	74	8.378	620	92.91
- Labor (man-day)	9.25	200	1,850	
Subtotal			**8,870**	**92.91**
• **Pyrolysis**				
- Stoves	1	300	300	
- Fuel Use (kg)	750			104.24
- Labor (man-day)	4.16	200	832	
Subtotal			**1,132**	**104.24**
• **Biochar application to soil**				
- Labor (man-rai)	6.25	50	312.5	
Subtotal			**312.5**	
Total			**18,404.5**	**3,034.51**

Table A-1 Estimating costs and greenhouse gas emissions from biochar production from 5 feedstocks (con't)

Process	Amounts	Cost (THB/unit)	Total Cost THB/year	Total GHG kgCO2eq/year
3. Bamboo				
• **Land preparation**				
- Labor (Digging)	17	5	85	
Subtotal			**85**	
• **Cultivation**				
- Seeds (tree)	17	30	510	
Subtotal			**510**	
• **Harvesting**				
- Labor (man-day)	1	300	300	
Subtotal			**300**	
• **Pyrolysis**				
- Stoves	1	300	300	
- Fuel Use (kg)	750			104.24
- Labor (man-day)	6.25	200	1,250	
Subtotal			**1,550**	**104.24**
• **Transportation**				
- Duration (km)	46			
- Diesel Use (L)	2.7	30	81	
- Pickup 4 wheels, full load 7 ton, 0 % loading for depart	1			7.16
- Pickup 4 wheels, full load 7 ton, 100 % loading for return	1			3.22
- Labor (man-day)	1	200	200	
Subtotal			**281**	**10.38**
• **Biochar application to soil**				
- Labor (man-rai)	6.25	37.5	234.4	
Subtotal			**234.4**	
Total			**2,960**	**114.62**

Table A-1 Estimating costs and greenhouse gas emissions from biochar production from 5 feedstocks (con't)

Process	Amounts	Cost (THB/unit)	Total Cost THB/year	Total GHG kgCO2eq/year
4. Corn cob				
• **Land preparation**				
- Area (Rai)	1			
- Hiring Tractor (Tillage 2 times)	2	300	600	
- Diesel Use (L)	4			11.90
Subtotal			**600**	**11.90**
• **Cultivation**				
- Seeds (kg/rai)	15	30	675	
- Chemical fertilizer (N-P-K)16-16-16 (kg/rai)	8	14	112	9.29
- Compost-fertilize (kg/rai)	4,000			757.6
- Labor (man-day)	1	300	300	
Subtotal			**1,087**	**766.89**
• **Harvesting**				
-Labor (man-day)	1	300	300	
Subtotal			**300**	
• **Production**				
- Corn sorter machine	1	825	825	
- Gasoline Use (L)	2.5	40	100	6.10
- Labor (man-day)	1	200	200	
Subtotal			**1,125**	**6.10**
• **Transportation**				
- Duration (km)	140			
- Diesel Use (L)	8.235	30	247	
- Pickup 4 wheels, full load 7 ton, 0 % loading for depart	1			26.08
- Pickup 4 wheels, full load 7 ton, 100 % loading for return	1			11.31
- Labor (man-day)	1	300	300	
Subtotal			**547**	**37.39**
• **Pyrolysis**				
- Stoves	1	200	200	
- Fuel Use (kg)	750			104.24
- Labor (man-day)	8.33		1,000	
Subtotal			**1,200**	**104.24**
• **Biochar application to soil**				
- Hiring Tractor	1	700	700	
- Diesel Use (L)	12.5			37.19
- Labor (man-rai)	1	300	300	
Subtotal			**1,000**	**37.19**
Total			**5,859**	**963.71**

Table A-1 Estimating costs and greenhouse gas emissions from biochar production from 5 feedstocks (con't)

Process	Amounts	Cost (THB/unit)	Total Cost THB/year	Total GHG kgCO2eq/year
5. Mixed softwoods				
• **Pruning**				
- Labor (man-day)	4	300	1,200	
Subtotal			**1,200**	
• **Transportation**				
- Duration (km)	1			
- Diesel Use (L)	0.067	30	2	
- Pickup 4 wheels, full load 7 ton, 0 % loading for depart				0.31
- Pickup 4 wheels, full load 7 ton, 50 % loading for return				0.27
- Labor (man-day)	1	100	100	
Subtotal			**102**	**0.58**
• Pyrolysis				
- Stoves	1	200	200	
- Fuel Use (kg)	750			104.24
- Labor (man-day)	6.25		1,000	
Subtotal			**1,200**	**104.24**
• **Biochar application to soil**				
- Hiring Tractor	1	700	700	
- Diesel Use (L)	12.5			37.19
- Labor (man-rai)	1	300	300	
Subtotal			**1,000**	**37.19**
Total			**3,502**	**142.01**

APPENDIX B

(Summary costs, GHG emissions and mitigation costs from 5 feedstocks)

Table B-1 Summary costs**,** GHG emissions and mitigation costs from 5 feedstocks

Type of feedstock	Items	THB /ton biomass	THB / ton biochar	THB/ha	NOTE
Mangrove	1. Biomass production	27.29*	81.87*	-	Mangrove : biochar = 3:1
	2. Biochar production	136.90*	410.70*	-	
	3. Biochar application	-	492.57	1,635	(1) + (2) = (THB/ton biochar)
	4. Application rate (10 ton/ha)	-	4,925.70	-	
	5. Total cost (THB/ha)	-	-	6,560.70	(3) + (4) = Total cost (THB/ha)
	6. GHG emission (ton CO2e/ha)	-	-	0.18	Sequestration 1.9 tonCO2e/ha
	7. Mitigation cost (THB/ton CO2e)	-	-	381.44	Total cost (THB/ha) / Net sequestration(tonCO2e/ha)
Rice husk	1. Biomass production	1,927.22*	4,818.05*	-	Rice husk : biochar = 2.5
	2. Biochar production	1,132.00*	2,830.00*	-	
	3. Biochar application	-	7,648.05	312.50	(1) + (2) = (THB/ton biochar)
	4. Application rate (10 ton/ha)	-	76,480.50	-	
	5. Total cost (THB/ha)	-	-	76,793.00	(3) + (4) = Total cost (THB/ha)
	6. GHG emission (ton CO2e/ha)	-	-	1.09	Sequestration 1.87 tonCO2e/ha
	7. Mitigation cost (THB/ton CO2e)	-	-	9,845.26	Total cost (THB/ha) / Net sequestration(tonCO2e/ha)
Bamboo	1. Biomass production	895*	1,492*	-	Bamboo : biochar = 1.67 : 1
	2. Biochar production	1,550*	2,583*	-	
	3. Biochar application	-	4,075	515	(1) + (2) = (THB/ton biochar)
	4. Application rate (10 ton/ha)	-	40,750	-	
	5. Total cost (THB/ha)	-	-	41,265	(3) + (4) = Total cost (THB/ha)
	6. GHG emission (ton CO2e/ha)	-	-	0.18	Sequestration 2.64 tonCO2e/ha
	7. Mitigation cost (THB/ton CO2e)	-	-	1,677	Total cost (THB/ha) / Net sequestration(tonCO2e/ha)
Corn cob	1. Biomass production	1,244.80*	6,224*	-	Corn cob : biochar = 5:1
	2. Biochar production	1,747*	8,735*	-	
	3. Biochar application	-	14,959	1,000	(1) + (2) = (THB/ton biochar)
	4. Application rate (10 ton/ha)	-	149,590	-	
	5. Total cost (THB/ha)	-	-	150,590	(3) + (4) = Total cost (THB/ha)
	6. GHG emission (ton CO2e/ha)	-	-	2.32	Sequestration 2.85 tonCO2e/ha
	7. Mitigation cost (THB/ton CO2e)	-	-	28,413.2	Total cost (THB/ha) / Net sequestration(tonCO2e/ha)
Mixed softwoods	1. Biomass production	1,200*	3,600*	-	Mixed softwoods : biochar = 3:1
	2. Biochar production	1,302*	3,906*	-	
	3. Biochar application	-	7,506	1,000	(1) + (2) = (THB/ton biochar)
	4. Application rate (10 ton/ha)	-	75,060	-	
	5. Total cost (THB/ha)	-	-	76,060	(3) + (4) = Total cost (THB/ha)
	6. GHG emission (ton CO2e/ha)	-	-	0.35	Sequestration 2.53 tonCO2e/ha
	7. Mitigation cost (THB/ton CO2e)	-	-	3,488.99	Total cost (THB/ha) / Net sequestration(tonCO2e/ha)

Remark: * Can estimating costof biochar by biomass production cost multiply by the ratio of biochar

APPENDIX C

(Economic return rates)

Table C-1 Economic return rates of sweet sorghum crop

Item	Without adding biochar	Mangrove biochar application rate (ton/225m^2) 0.225
1. Production cost of sweet sorghum (THB)	773*	773*
2. Application cost (THB/ton biochar)	0	492.57
3. Total application cost (THB) = (2) × (Application rate)	0	110.83
4. Total expenditure (THB) = (1) + (3)	773	883.83
5. Cane yield (ton/225m^2)	0.52	0.68
6. Sale price of sweet sorghum (THB/ton cane)	700	700
7. Total income from yield (THB) = (5) × (6)	364	476
8. Net income (THB) = (7) – (4)	-409	-183.83
9. C sequested (tonCO_{2eq}/ton biochar)	0	1.72
10. Total C sequester (tonCO_{2eq}) = (9) × (Application rate)	0	0.15
11. Carbon credit price (THB/tonCO_{2eq})	0	2.405
12. Total carbon credit price (THB) = (10) × (11)	0	0.31
13. Net benefit (THB) = (8) + (12)	-409	-183.52

Remark: THB based on the carbon credit price (CERs) of 0.065 EU/ton CO_2e with the exchange rate of 37 THB/1 EU
So carbon credit (CERs) = 0.065EU/ton CO_2e × 37 THB/1 EU = 2.405 THB/tonCO_{2eq}
* Cost from seeds 100 THB/rai + labor 5,400 THB/rai (Soil prepared 1,400 THB/rai, cultivated 700 THB/rai, manage 2,100 THB/rai, harvested 1,200 THB/rai) = 773 THB/225m^2

The benefits of selling products without mangrove biochar application to soil in the sweet sorghum crops at King Mongkut's University of Technology Thonburi Rajchaburi Campuswas -409 THB.

When adding mangrove biochartothe sweet sorghum crops with the application rate 0.225 ton per 225m^2 can mitigate GHG 0.15 tonCO_{2eq} by the benefits gains associated with the net income for these application rates after selling caneyield was -183.83 THB. However, if estimate the net benefit from product sells plus that of carbon credit was-183.52 THB(Table C-1).

Table C-2 Economic return rates of rice crop

Item	Without adding biochar	Rice husk biochar application rate (ton/8 rai) 0.144
1. Production cost of rice (THB)	21,760*	8,060**
2. Application cost (THB/ton biochar)	0	7,648.05
3. Total application cost (THB) = (2) × (Application rate)	0	1,101.32
4. Total expenditure (THB) = (1) + (3)	21,760	9,161.32
5. Rice yield (ton/8 rai)	4.4	8.8
6. Sale price of rice (THB/ton rice)	8,000	8,000
7. Total income from yield (THB) = (5) × (6)	35,200	70,400
8. Net income (THB) = (7) – (4)	13,440	61,238.68
9. C sequested (tonCO_{2eq}/ton biochar)	0	0.78
10. Total C sequester (tonCO_{2eq}) = (9) × (Application rate)	0	0.112
11. Carbon credit price (THB/tonCO_{2eq})	0	2.405
12. Total carbon credit price (THB) = (10) × (11)	0	0.27
13. Net benefit (THB) = (8) + (12)	13,440	61,238.94

Remark: THB based on the carbon credit price (CERs) of 0.065 EU/ton CO_2e with the exchange rate of 37 THB/1 EU
So carbon credit (CERs) = 0.065 EU/ton CO_2e × 37 THB/1 EU = 2.405 THB/tonCO_{2eq}
* Cost from seeds 120 THB/rai + manure 50 THB/rai + chemical fertilizer 1,400 THB/rai + fuel 150 THB/rai + labor 1,000 THB/rai (prepared 300 THB, cultivated 200 THB, manage 200 THB, harvested 300 THB) = 21,760 THB/8rai
** Organic agriculture, cost from seeds 120 THB/rai + machinery 468.75 THB/rai, maintenance 10 THB/rai, fuel 183.75 THB/rai + labor 225 THB/rai (prepared 150 THB, cultivated 25 THB, harvested 50 THB) = 8,060 THB/8rai

The benefits of selling products without adding rice husk biochar to soil in rice field near the New Theory Farming Center, Mae Taeng District ChiangmaiProvince was 21,760 THB. However, compared with the New Theory Farming Center that adding rice husk biochar in the rice field with the application rate 0.144 ton/8 rai at and the site can mitigate GHG 0.112 tonCO_{2eq}/year and the benefits gains associated the net income for these application rates after selling ricefrom rice yield was 61,238.68 THB. Furthermore, if estimate the net benefit from product sells plus that of carbon credit was 61,238.94 THB (Table C-2).

Table C-3 Economic return rates into lettuce plot

Item	Without adding biochar	Bamboo biochar application rate (ton/m^2)		
		0.5×10^{-3}	1×10^{-3}	1.25×10^{-3}
1. Production cost of lettuce (THB)	11.63*	11.63*	11.63*	11.63*
2. Application cost (THB/ton biochar)	0	4,075	4,075	4,075
3. Total application cost (THB) = (2) × (Application rate)	0	2.04	4.08	5.09
4. Total expenditure (THB) = (1) + (3)	11.63	13.67	15.71	16.72
5. Lettuce yield (ton/m^2)	0.067	0.060	0.063	0.063
6. Sale price of lettuce (THB/ton)	25,000	25,000	25,000	25,000
7. Total income from yield (THB) = (5) × (6)	1,667.5	1,500	1,575	1,575
8. Net income (THB) = (7) – (4)	1,655.87	1,486.07	1,570.41	1,569.26
9. C sequested (tonCO_{2eq}/ton biochar)	0	2.46	2.46	2.46
10. Total C sequester (tonCO_{2eq}) = (9) × (Application rate)	0	0.0123	0.0246	0.0308
11. Carbon credit price (THB/tonCO_{2eq})	0	2.405	2.405	2.405
12. Total carbon credit price (THB) = (10) × (11)	0	0.03	0.06	0.07
13. Net benefit (THB) = (8) + (12)	1,655.87	1,486.10	1,570.47	1,569.33

Remark: THB based on the carbon credit price (CERs) of 0.065 EU/ton CO_2e with the exchange rate of 37 THB/1 EU
So carbon credit (CERs) = 0.065 EU/ton CO_2e × 37 THB/1 EU = 2.405 THB/tonCO_{2eq}
*Cost from seeds 160 THB/rai + manure 50 THB/rai + chemical fertilizer 50 THB/rai + Labor 18,600 THB/rai (prepared 30 days 9,000 THB, cultivated 1 day 300 THB, manage 30 day 900 THB, harvested 1 day 300 THB) = 11.63 THB/m^2

The benefits of selling products without bamboo biochar application to soil in the lettuce plot at the Office of Land Development Region 6 (Chiangmai province) was 1,655.87 THB.

When adding bamboo biochar in lettuce plots with the biochar application rate of 0.5×10^{-3}, 1×10^{-3} and 1.25×10^{-3} ton per m^2 can mitigate GHG were 0.0123, 0.0246 and 0.0308 tonCO_{2eq}/year respectively by the benefits gains associated with the net income for these application rates after selling lettuce was 1,500, 1,575 and 1,575 THB.

However, if estimate the net benefit from product sells plus that of carbon credit was 1,486.10, 1,570.47 and 1,569.33 THB respectively (Table C-3).

Table C-4 Economic return rates of corn crop

Item	Without adding biochar	Corn cob biochar application rate (ton/4m^2)			
		1×10^{-3}	2×10^{-3}	3×10^{-3}	4×10^{-3}
1. Production cost of corn (THB)	4.97*	4.97*	4.97*	4.97*	4.97*
2. Application cost (THB/ton biochar)	0	14,959	14,959	14,959	14,959
3. Total application cost (THB) = (2) × (Application rate)	0	14.96	29.92	44.88	59.84
4. Total expenditure (THB) = (1) + (3)	4.97	19.93	34.89	49.85	64.81
5. Corn yield (ton/4m^2)	6×10^{-3}	7.6×10^{-3}	8×10^{-3}	9.2×10^{-3}	10.8×10^{-3}
6. Sale price of corn (THB/ton cane)	10,000	10,000	10,000	10,000	10,000
7. Total income from yield (THB) = (5) × (6)	60	76	80	92	108
8. Net income (THB) = (7) – (4)	55.03	56.07	45.11	42.15	43.19
9. C sequested (tonCO_{2eq}/ton biochar)	0	0.53	0.53	0.53	0.53
10. Total C sequester(tonCO_{2eq}) = (9) × (Application rate)	0	0.00053	0.00106	0.00159	0.00212
11. Carbon credit price (THB/tonCO_{2eq})	0	2.405	2.405	2.405	2.405
12. Total carbon credit price (THB) = (10) × (11)	0	0.001	0.003	0.004	0.005
13. Net benefit (THB) = (8) + (12)	55.03	56.071	45.113	42.154	43.195

Remark: THB based on the carbon credit price (CERs) of 0.065 EU/ton CO_2e with the exchange rate of 37 THB/1 EU
So carbon credit (CERs) = 0.065 EU/ton CO_2e × 37 THB/1 EU = 2.405 THB/tonCO_{2eq}
*Cost from seeds 675 THB/rai + chemical fertilizer 112 THB/rai + Labor 1,200 THB/rai (Land prepared 600 THB, cultivated 300 THB, harvested 300 THB) = 4.97 THB/4m^2

The benefits of selling products without corn cob biochar application to soil in corn crop at the Huay Sai Royal Development Study Center was55.03 THB.

When adding corn cob biochar in corn crop with the biochar application rate of 0.001, 0.002, 0.003 and 0.004 ton per 4 m^2 can mitigate GHG 0.00053, 0.00106, 0.00159 and 0.00212 tonCO_{2eq} respectivelyby the benefits gains associated with the net income for these application rates after selling corn yield was 56.07, 45.11, 42.15 and 43.19 THB.

However, if estimate the net benefit from product sells plus that of carbon credit the result was56.071, 45.113, 42.154 and 43.195 respectively (Table C-4).

Table C-5 Economic return rates of corn crop

Item	Without adding biochar	Mixed softwoodsbiochar application rate (ton/4m^2)			
		2×10^{-3}	4×10^{-3}	6×10^{-3}	8×10^{-3}
1. Production cost of corn (THB)	4.97*	4.97*	4.97*	4.97*	4.97*
2. Application cost (THB/ton biochar)	0	7,506	7,506	7,506	7,506
3. Total application cost (THB) = (2) × (Application rate)	0	15.01	30.02	45.03	60.04
4. Total expenditure (THB) = (1) + (3)	4.97	26.95	34.99	50.00	65.01
5. Corn yield (ton/4m^2)	4.31×10^{-3}	5.75×10^{-3}	7.19×10^{-3}	10.06×10^{-3}	11.50×10^{-3}
6. Sale price of corn (THB/ton cane)	10,000	10,000	10,000	10,000	10,000
7. Total income from yield (THB) = (5) × (6)	41.3	57.5	71.9	100.6	115.0
8. Net income (THB) = (7) – (4)	36.33	30.55	36.91	50.60	49.99
9. C sequested (tonCO_{2eq}/ton biochar)	0	2.18	2.18	2.18	2.18
10. Total C sequester(tonCO_{2eq}) = (9) × (Application rate)	0	0.00436	0.00872	0.01308	0.01744
11. Carbon credit price (THB/tonCO_{2eq})	0	2.405	2.405	2.405	2.405
12. Total carbon credit price (THB) = (10) × (11)	0	0.01	0.02	0.03	0.04
13. Net benefit (THB) = (8) + (12)	36.33	30.56	36.93	50.63	50.03

Remark: THB based on the carbon credit price (CERs) of 0.065 EU/ton CO_2e with the exchange rate of 37 THB/1 EU
So carbon credit (CERs) = 0.065 EU/ton CO_2e × 37 THB/1 EU = 2.405 THB/tonCO_{2eq}
*Cost from seeds 675 THB/rai + chemical fertilizer 112 THB/rai + Labor 1,200 THB/rai (Land prepared 600 THB, cultivated 300 THB, harvested 300 THB) = 4.97 THB/4m^2

The benefits of selling products without mixed softwoods biochar application to soil in corn crop at the Huay Sai Royal Development Study Center was 36.33THB.

When adding mixed softwoods biochar in corn crop with the application rate of 0.002, 0.004, 0.006 and 0.008 ton per 4m^2 can mitigate GHG 0.00436, 0.00872, 0.01308 and 0.01744 tonCO_{2eq} respectivelyby the benefits gains associated with the net income for these application rates after selling corn yield was 30.55, 36.91, 50.60 and 49.99 THB.

However, if estimate the net benefit from product sells plus that of carbon credit was30.56, 36.93, 50.63 and 50.03 respectively (Table C-5).

The differences in net benefits given varying prices of each biochar and carbon offset are further illustrated in Table C-6.

Table C-6 Comparison of economic return rates

Type of biochar	Crop	Application rate (ton/ha)	Net income from yield (THB/ha)	Carbon credit price (THB/ha)	Net benefit (THB/ha)
Mangrove	Sweet sorghum crop	Without adding biochar	-409	0	-409
		10	-183.83	0.31	-183.52
Rice husk	Rice field	Without adding biochar	13,440	0	13,440
		0.1125	61,238.68	0.27	61,238.94
Bamboo	Lettuce plot	Without adding biochar	1,655.87	0	1,655.87
		5	1,486.07	0.03	1,486.10
		10	1,570.41	0.06	1,570.47
		20	1,569.26	0.07	1,569.33
Corn cob	Corn crop	Without adding biochar	55.03	0	55.03
		2.5	56.07	0.001	56.071
		5	45.11	0.003	45.113
		7.5	42.15	0.004	42.154
		10	43.19	0.005	43.195
Mixed softwood	Corn crop	Without adding biochar	36.33	0	36.33
		5	30.55	0.01	30.56
		10	36.91	0.02	36.93
		15	50.60	0.03	50.63
		20	49.99	0.04	50.03

Table C-6 shows that the net benefits from mangrove biochar application to soil increase by adding carbon offset from -183.83 THB/ha to -183.52 THB/ha. However, the net benefit from mangrove biochar seems to be loss because of the net income loss from selling product.

The result of the net benefits from rice husk biochar application to soil show hardly gets the carbon offset from 61,238.68 THB/ha to 61,238.94 THB/ha due to the farmer applies a low quantity of biochar. However, the farmer was getting the profit from selling product.

The net benefits of bamboo biochar application to soil show that cost increase depend on biochar application rate 5 ton/ha from 1,486.07 THB/ha to 1,486.10 THB/ha, application rate 10 ton/ha from1,570.41 THB/ha to 1,570.47 THB/ha and application rate 20 ton/ha from 1,569.26 to 1,569.33THB/ha respectively.

The net benefits of corn cob biochar slightly increased due to the cost from carbon offset was low increased by the application rate 2.5 ton/ha from 56.07 THB/ha to 56.071 THB/ha, application rate 5 ton/ha from 45.11 THB/ha to 45.113 THB/ha, application rate 7.5 ton/ha from 42.15THB/ha to 42.154 THB/ha and application rate 10 ton/ha from 43.19to43.195 THB/ha respectively.

Application mixed softwood biochar to soil shows that the net benefits increase depending on biochar application rate 5 ton/ha from 30.55 THB/ha to 30.56 THB/ha, application rate 10 ton/ha from 36.91 THB/ha to 36.93 THB/ha, application rate 15 ton/ha from 50.60 THB/ha to 50.63 THB/ha and application rate 20 ton/ha from 49.99 to 50.03 respectively which the net benefit increase as the price of carbon offset increases.