COMPARISON OF COST AND GREENHOUSE GAS EMISSION FROM RICE FIELDS BETWEEN CONVENTIONAL AND ALTERNATE WETTING AND DRYING TECHNIQUES

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A THESIS SUBMITTED AS A PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING IN ENVIRONMENTAL TECHNOLOGY AND MANAGEMENT

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ABSTRACT

Alternate wetting and drying (AWD) technique has been recently recommended for mitigating the emissions of greenhouse gases from rice fields. However, the cost associated with implementing AWD under the field condition is largely unknown. The aim of this study is to estimate cost of greenhouse gas emission mitigation when AWD is implemented in farmer's rice field, compared to that with the conventional field (continuous flooding). The case studies were carried out in Nakhon Sawan, Chai Nat, and Prachin Buri provinces where several farmers have recently adopted the AWD technique for rice cultivation. It was found that under AWD conditions in these three provinces, the average cultivation costs were 27,841 THB/ha, 33,317 THB/ha, and 27,355 THB/ha, respectively. The cost-savings under AWD condition were 8,672 THB/ha in Nakhon Sawan, 9,915 THB/ha in Chai Nat, and 5,139 THB/ha in Prachin Buri. The average costs per the unit of greenhouse gas emissions were 5,124 THB/tonCO_2e in Nakhon Sawan, 2,526 THB/tonCO_2e in Chai Nat, and 1,371 THB/tonCO_2e in Prachin Buri. The reduced cost under AWD was mainly resulted from less use of seed, fertilizer, pesticide, labor and water. Applying AWD also help increased rice yield (from 5.28 to 6.07 ton/ha) and reduced the amount of greenhouse gases emission per unit grain yield (from 1.38-2.91tonCO_2e/ton grain yield to 0.71-1 tonCO_2e/ton grain yield). Thus, when water management is possible (i.e. under irrigation), applying AWD in rice fields can provide benefits to farmer in terms of income increase and to the environment in terms of reducing greenhouse gas emissions.

Keyword: Alternate wetting and drying, Greenhouse gas, Cost-saving, Rice cultivation, Rice field

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LIST OF ABBREVIATIONS

GHG	Greenhouse Gases
CO_2	Carbon Dioxide
CH_4	Methane
N_2O	Nitrous Oxide
O_3	Ozone
CFC	Chlorofluorocarbon.
SF_6	Sulfur Hexafluoride
NO_x	Nitrogen Oxide
GWP	Global Warming Potential
EF	Emission Factors
AWD	Alternate Wetting and Drying
CF	Continuous Flooding
SII	Shallow Intermittent Irrigation
SCD	Semi-Dry Cultivation
SWD	Shallow Water Depth with Wetting and Drying
˚C	Degree Celsius
ppm	Parts-per-million, 10^{-6}
ppb	Parts-per-billion, 10^{-9}
CO_2e	Carbon Dioxide Equivalent
Ha	Hectare
THB	Thai Baht
WHO	World Health Organization
IPCC	Intergovernmental Panel on Climate Change
UNFCCC	United Nations Framework Convention on Climate Change
ONEP	Office of Natural Resources and Environmental Policy and Planning
FAO	Food and Agriculture Organization of the United Nations
TGO	Thailand Greenhouse Gas Management Organization (Public Organization)
IRRI	International Rice Research Institute

CHAPTER 1

INTRODUCTION

1.1 Rationales

Currently, climate change induced by global warming is a major concern because it contributes to many problems such as droughts, floods, and other hazards. The Intergovernmental Panel on Climate Change (IPCC) reported that the average global temperature due to greenhouse gas (GHG) emission will rise by up to 5.8 ˚C by 2100 (Abdullah, 2005). NASA's data show that between 2002 to 2006 in Greenland the mass of ice sheet has been lost about 150-250 km^3 (36–60 cubic miles), while between 2002 to 2005 the Antarctica lost about 152 km^3 (36 cubic miles) (VijayaVenkataRaman et al., 2010). Climate change also causes the sea level to rise by 8–23 cm in 2030 (Cicerone, 2012).

The major greenhouse gases that cause global warming include 53% carbon dioxide (CO_2), 17% methane (CH_4), 13% ozone (O_3), and 12% nitrous oxide (N_2O). These greenhouse gases concentrations have increased by approximately 0.5% per year since the Industrial Revolution. For example, the concentration of carbon dioxide in the atmosphere is approximately 280 ppm in 1750 but current this is around 370 ppm (WMO, 2010; Ahmad et al., 2009). Methane concentrations have increased from 715 ppb during the pre-industrial revolution period to 1,732 ppb. Methane is emitted into the atmosphere naturally but 80% of total methane emissions come from human activity; for example, the consumption of energy, industrial processes, waste disposal, deforestation, and agricultural activities (Lantin et al., 2002; WMO, 2010).

Thailand is one of main rice producing nations and its economy is highly dependent on rice cultivation and exports. Rice is also an important food source. Rice planting area accounted for 6% of the world and 52% of the area in Thailand (Maneesuwan, 2002), with the rice cultivation areas of about 10 million ha (Chimparee, 2014). Normally, rice cultivation requires the flooding water during plant growth. This flooded condition can promote methane production and emission as the decomposition of organic carbon occurs under the anaerobic condition. The flooded rice field therefore becomes one of the important methane sources (IPCC, 1995; Bronson et al., 2002). Methane emissions in rice field are controlled by various factors. These factors include type of soil, rice varieties, climate, the way to prepare the soil and grow the rice, and water management. In conventional irrigation, soil in rice field is submerged for a long period of time; as result, this condition stimulates anaerobic bacteria to produce a large amount of methane and emit into the atmosphere.

According to the Second National Communications to the United Nations Framework Convention on Climate Change (UNFCCC), methane emissions from rice cultivation in Thailand is the largest contributor (70%) to the total emissions from the agricultural sector (ONEP, 2011). Because of this large contribution, attentions have been paid to finding out the measures to mitigate methane and other greenhouse gases in rice field. Water management technology including alternate wetting and drying (AWD) is one of the promising technologies that are effectively applied to reduce methane emission (Towprayoon et al., 2005). AWD in principle keeps water to the level that is sufficient for plant growth but would negatively affect methane production and emission. AWD have been shown to reduce methane emission from rice field by 30-40% compared to the conventional water management scheme and therefore recommended as one of the techniques adopted by farmers (Doi and Pitiwut, 2014).

In Thailand, however, there has been no study to evaluate the unit cost of methane emission reduction in rice field soil when AWD is applied. This may be due to the fact that AWD is only recently applied in field trials in Thailand. Since evaluating the cost of greenhouse gas emission and mitigation is one of the important parameters determining its feasibility and effectiveness, the cost associated with AWD needs to be evaluated. In addition each methodology for reducing methane emissions from rice fields has different cost of management. For example, conventional irrigation has average cost at about 30,063-43,188 THB/ha (Prachathai, 2012). It is therefore important to compare the cost of mitigation technology with such tradition practices. Accordingly, the objective of this study is to estimate the cost when AWD is applied under the field conditions, compared to that of the conventional rice cultivation.

1.2 Literature reviews

Towprayoon et al. (2005) analyzed how much and how long water should be drained and how such practices affect methane emissions. They reported that multiple drainage and mid-season drainage can reduce methane by 11.4 and 6.9% respectively. These two systems significantly decrease rice yields. Fewer draining days also contribute to the reduction in nitrous oxide. Therefore, the best possible drainage system to reduce methane while keeping acceptable quantity of rice yields is to adopt mid-season drainage during the rice flowering stage, with only about 3 drain days.

Tyagi et al. (2010) also revealed consistent findings with that of Towprayoon et al. The study compared the reduction of methane emissions by four different drainage systems including continuous flooding, tillering drainage, mid-season drainage, and multiples drainage. It was found that continuous flooding system emitted the highest amount of methane at 346.6 mg/m^2/day. This was followed by tillering stage drainage, mid-season drainage, and multiples drainage at 315.1, 219.3, and 204.7 mg/m^2/day, respectively. While multiples drainage and mid-season drainage can reduce methane by 36.7 % and 41% respectively, these systems significantly decrease rice yields. Fewer drainage days also contribute to the reduction in nitrous oxide. Moreover, in all systems, redox potential of the soil was inversely proportional to methane emissions.

Yang et al. (2011) found that controlled irrigation could help mitigate the emissions of greenhouse gases from rice fields. They conducted field experiments in China where water-saving practices were adopted to deal with water shortage. They used closed chambers to monitor methane and nitrous oxide emissions from rice field under controlled irrigation and continuous flooding irrigation, compared with flooding irrigation during rice-growing period. There was a significant decrease in the amount of methane emissions by 79.1% from 2006 to 2007, while nitrous emission increased by 10.6% over the same period. As a result, controlled irrigation can help to reduce carbon dioxide equivalents of methane and nitrous oxide efflux, with a considerable fall by 61.4% compared to those from continuous flooding irrigation.

Sujono et al. (2011) attempted to find the most effective water saving irrigation technique that increased both water productivity and rice yield. They studied eight irrigation practices for rice-growing in plot experiments. Shallow intermittent irrigation (SII) was used as a control method compared to other irrigation treatments. Water was saved under semi-dry cultivation (SCD), followed by the alternate wetting and drying (AWD), and the shallow water depth with wetting and drying (SWD), with 18.4%, 13.1%, and 5.4% reduction of water use respectively compare to control method. However, the rice yields increased more under AWD (22.9%) and SWD (17.9%) than SCD (14%). Likewise, water productivity improved when AWD and SWD were used, with a significant increase of 41.6% and 24.2% improvement of water productivity.

Nalley et al. (2014) studied the AWD irrigation method for reducing methane emissions and water usage from rice cultivation. AWD methods were irrigation in form of dry intermittently during rice growing. The study focused on three types of the AWD irrigation methods in Arkansas to indicate water usage, methane emission, and cost of the rice production. This water irrigation method could reduce water usage up to 20-70% and more than 50% of methane emissions compare to continuous flooding. The cost of rice production under continuous flooding condition was 250,000 THB/ha, while AWD condition could reduce up to 48% (131,000 THB/ha).

1.3 Objectives

1. To compare the costs of rice cultivation between conventional irrigation and AWD techniques.
2. To study the potential of AWD techniques to reduce greenhouse gas emissions from rice fields.

1.4 Scope of the study

The study focuses on the costs of rice cultivation between conventional and AWD techniques from land preparing until the harvesting. These costs consist of fertilizer, pesticide, herbicide, labor, pumping and rented land. This study interviewed farmers in Nakhon Sawan, Chai Nat, and Prachin Buri provinces that farmers always plant rice of photoperiod insensitive varieties in wet and dry season. Greenhouse gas emissions from rice fields were calculated as those described in the IPCC Guideline for national greenhouse gas inventories in 2006: Volume 4 Agriculture, forestry and other land.

CHAPTER 2

THEORIES

2.1 Greenhouse gases

The Earth obtains energy from the Sun in the form of light energy. Some energy is reflected back out of the Earth. Greenhouse gases have the ability to absorb heat radiation in the atmosphere, so the world can maintain temperature, which is suitable for living organisms. Since the Industrial Revolution, the concentrations of greenhouse gases have increased significantly. The increase has been attributed to the emissions of greenhouse gases from human activities. The major greenhouse gases are carbon dioxide, methane and nitrous oxide (Figure 2.1).

Carbon dioxide is emitted from natural process and human activities, such as breathing of human and animals, wildfires, volcanic eruptions, fossil fuel burning, and clearing the land in forest for residential or agricultural land. As carbon dioxide emission is caused by so many factors, the amount of carbon dioxide accumulation in the atmosphere is higher than any other greenhouse gas.

Sources of methane emissions include rice fields, livestock, landfills, wastewater treatment plants, burning fossil fuels, and industry. Methane has a higher potential to cause global warming than carbon dioxide. Although the average life time of methane is shorter than carbon dioxide, the impact of methane on world's temperature is significant.

Nitrous oxide is released from many industries, such as the nylon fiber industry, chemical industry, and some types of plastic industry.

Chlorofluorocarbons (CFCs) are caused by human activities directly, as they do not exist in nature. The sources of chlorofluorocarbons are industrial plants and many electrical appliances. This gas is harmful because it absorbs high heat energy and can also be combined with ozone. This chemical reaction results in a decrease in the ozone level and a leak in the ozone layer, allowing harmful radiation into the Earth.

Sulfur hexafluoride (SF_6) comes from the industries producing electrical equipment. Although the level of sulfur hexafluoride in the atmosphere is quite low, it has a high ability to absorb heat energy. Therefore, it can contribute to global warming (Greenpeace, 2010; Keereerom, 2011; ONEP, 2011).

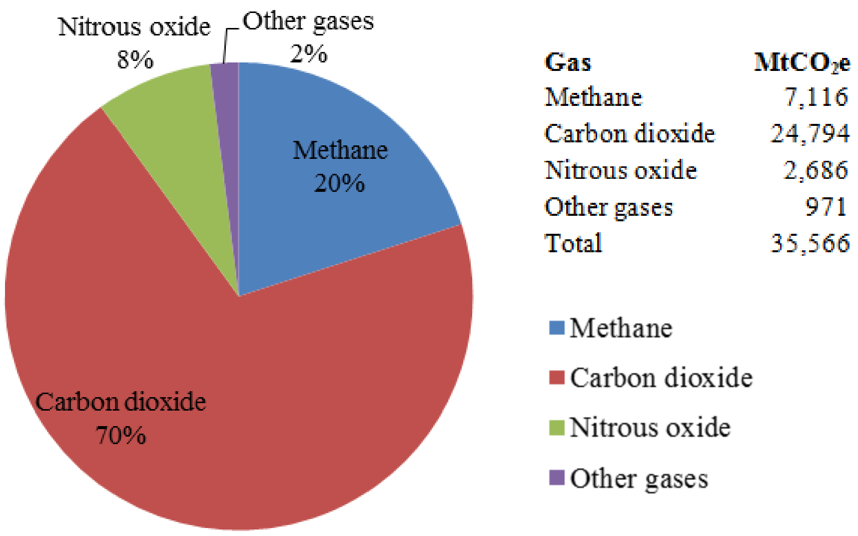


Figure 2.1 World greenhouse gas emissions in 2010 (Mt CO_2e) (Kahraman et al., 2011)

Each type of greenhouse gas has a different Global Warming Potential (GWP). Global warming potential indicates the ability of greenhouse gases to warm up the atmosphere when compared to carbon dioxide in equal weight (Table 2.1). Therefore, these greenhouse gases are the main reason for global warming.

Table 2.1 Global warming potentials of greenhouse gases (IPCC, 2007)

Greenhouse gases	Global Warming Potentials (GWP)			
	SAR‡ 100 yr.	20 yr.	100 yr.	500 yr.
1. Carbon dioxide (CO_2)	1	1	1	1
2. Methane (CH_4)	21	72	25	7.6
3. Nitrous oxide (N_2O)	310	289	298	153

2.1.1 Chemical property of greenhouse gases

a) Carbon dioxide

Carbon dioxide is considered the most well–known greenhouse gas. The chemical formula is CO_2. Consisting of one carbon atom and two oxygen atoms in one molecule, carbon dioxide is a compound of carbon gas that is floating in the Earth's atmosphere. Carbon dioxide is colorless, flammable and non-reactive. The density of carbon dioxide is 1.98 kg/m^3, which are about 1.5 times of air molecules. The solid state of carbon dioxide is called solid carbon dioxide. When carbon dioxide is dissolved in water, it becomes carbonic acid, which turns into bicarbonate and carbonate (IPCC, 2006).

b) Methane

The chemical formula of methane is CH_4, which is flammable, colorless, and low water-soluble at approximately 12-40 mg/L. The other properties are the ease of combustion, leading to carbon dioxide emissions. Methane gas has global warming potential at about 25 times of the carbon dioxide (Table 2.1) (IPCC, 2007). Methane gas can absorb more infrared radiation than carbon dioxide with the same volume. Methane is the major element of natural gas and is a result of organic digestion process under anaerobic condition in swamps, lakes, and rice fields (Keereerom, 2011). Methane gas in the troposphere is oxidized with hydroxyls (OH^-), releasing other gases including ozone (O_3), water vapor, carbon monoxide (CO) and hydrogen (H_2)

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

Methane gas completely reacts with oxygen by combustion

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

Methane gas incompletely reacts with oxygen by combustion

$$2CH_4 + O_2 \rightarrow 2CO + 4H_2$$

The reaction changes water into water vapor and creates carbon dioxide

$$CO + H_2O \rightarrow CO_2 + H_2$$

The end product of the reaction is methane and water that will return to the substrate.

$$CO + 3H_2 \rightarrow CH_4 + H_2O$$

2.1.2 Anthropogenic greenhouse gas emission sources

Human activities affect carbon dioxide emissions into the atmosphere. The effects from human activities have been increasing significantly. Burning of fossil fuels are the main sources of emission. Among these, electricity and heat are the largest sources of carbon dioxide emissions accounting for 42%, followed by transportation (23%), industry (20%), residential emission (6%), and others (9%, Figure 2.2). Fossil fuels uses in agriculture such as during land preparation can also release carbon dioxide to add into the atmosphere.

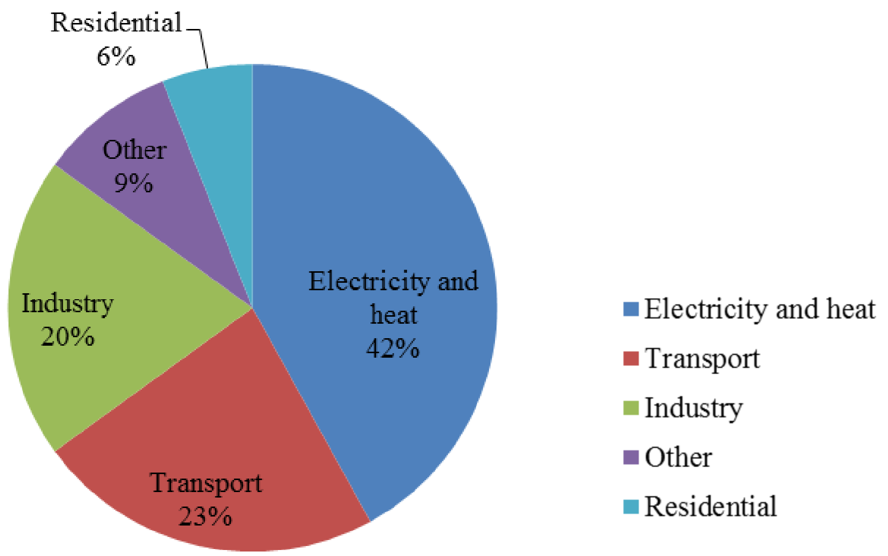


Figure 2.2 World carbon dioxide emissions by sector in 2012 (IEA, 2014)

Methane is also emitted from various anthropogenic sources. Out of the global total, 70% of methane is emitted from human activities (Figure 2.3). Most methane comes from biological origin produced by methanogen bacteria in submerged soil, but agriculture sector account for 10-15% of total methane emission (Mer and Rober, 2001). According to the IPCC, submerged soils emit the largest amount of methane (115 Tg/year) followed by rice fields (60 Tg/year), with 1 kg of rice produce emitting about 100 g of methane. This is followed by other natural sources which causes 50 Tg/year of methane emission (Table 2.2). Methane often occurs under anaerobic conditions by micro-organisms activity. About 55% of methane is emitted from submerged soil and 5% from upland.

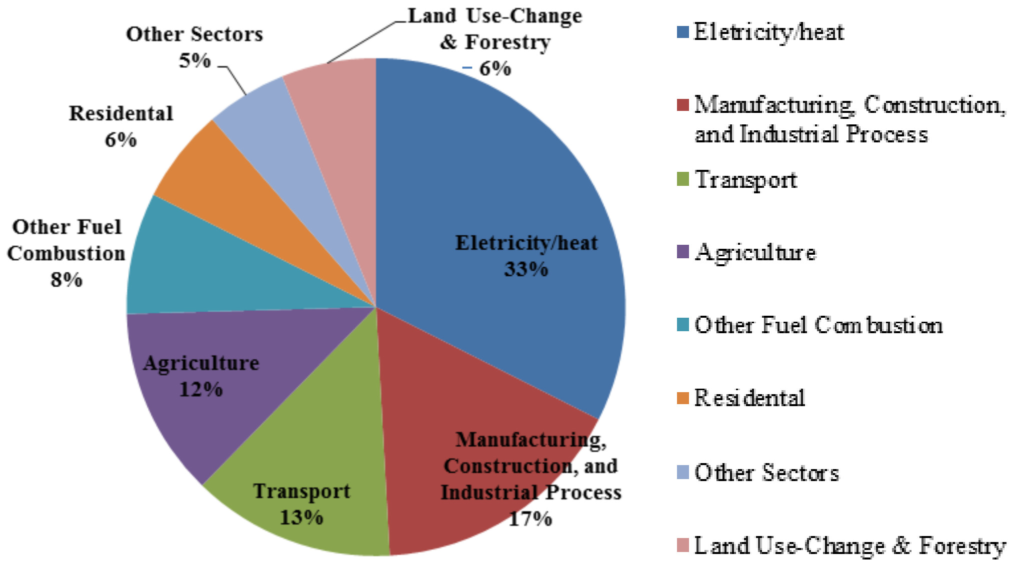


Figure 2.3 Greenhouse gas emissions by sector (Kahraman et al, 2011)

Table 2.2 Sources and sinks of atmospheric methane (Mer and Roger, 2001).

	Estimate (Tg/yr)	Uncertainly
Source		
Submerged soils	115	55-150
Other natural sources	50	25-140
Rice fields	60	20-100
Enteric fermentation and animal waste	105	85-130
Energy production and use	100	70-120
Landfills	30	20-70
Biomass burning	40	20-80
Domestic sewage	25	
Total of source	525	
Sink		
Consumption in atmosphere	470	420-520
Oxidation in upland soils	30	15-45
Total of sinks	559	

2.2 Methane production processes in rice field

Methane source from rice fields relates to methanogenesis and methanotrophy (Mer and Roger, 2001). Methane is produced by methanogenesis and is oxidized by methanotrophy in the soil. Methane productions depend on organic carbon substrates and environmental factor (IPCC, 2006). The production process of methane is described below and shown in Figure 2.5.

2.2.1 Hydrolysis

Methane gas in rice fields occurs from the decomposition of organic compounds that rely on hydrolytic bacteria under aerobic, or facultative, and anaerobic conditions (Mer and Roger, 2001; Norina, 2007). Bacteria release substances and enzymes outside of the cell. These enzymes stimulate and allow faster reaction. They are called "Hydrolytic enzyme". The reaction depends on the concentration of enzyme, temperature, surface area between the enzyme and organic matter. Hydrolysis is the chemical reaction by water molecules are broken into hydrogen ions (H^+) and hydroxyl ions (OH^-). This reaction transforms large molecules of organic matter (cellulose, protein, carbohydrate, etc.) into small molecules (Figure 2.4).

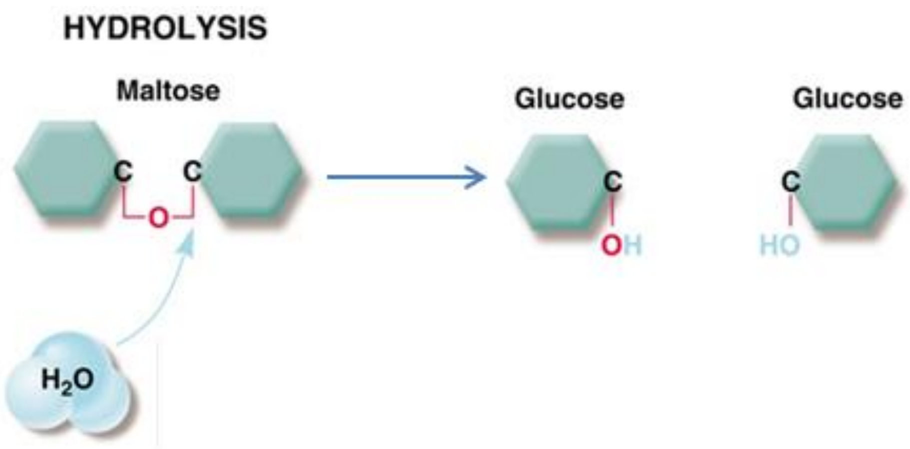


Figure 2.4 Hydrolysis reaction (Wiley, 2006)

2.2.2 Acidogenesis

Small molecules from the hydrolysis reaction are changed into volatile fatty acids (VFA) by the process of the fermentation by acidogenic bacteria. The products of this reaction are acetic acid, propionic acid, lactic acid, and other acids. Usually the highest amount acetic acid is produced under facultative and anaerobic condition.

2.2.3 Acetogenesis

Volatile fatty acids derived from the acidogenesis become the substrate for bacterial growth. However, many bacteria cannot use VFA that have more than two carbon atoms such as butyric acid and propionic acid. Consequently, acetogenic bacteria degrade VFA to become acetic acid for their growth.

2.2.4 Methanogenesis

The acetogenesis reaction produces acetic acid and hydrogen, which are used by methanogenic bacteria to produce methane. Most methanogens are in the methophilic bacteria group. The optimum temperature range is 20 to 40^{o}C. The pH that is suitable for the growth of bacteria and the production of methane is in the range of 6.5-7.8

$$CH_3COOH \rightarrow CO_2 + CH_4$$

Methanotrophs are gram-negative bacteria that use carbon dioxide and hydrogen (energy source) to produce methane.

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$$

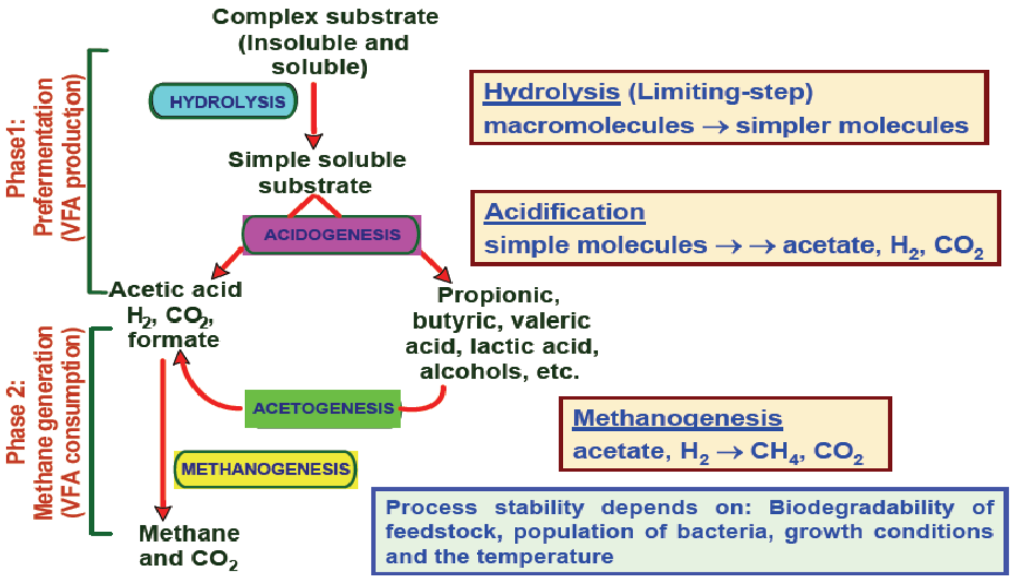


Figure 2.5 Methane productions (Jintana, 2004)

2.3 The pathway of methane emissions in rice field

The pathway of methane emissions from rice fields is shown in Figure 2.6. Methane is produced by micro-organisms in the soil. There are three main pathways mediating the release of methane from the soil into the atmosphere, including the transportation of methane through rice plants, ebullition and gas diffusion (Macintyre, 1984; Mudge and Adger, 1994).

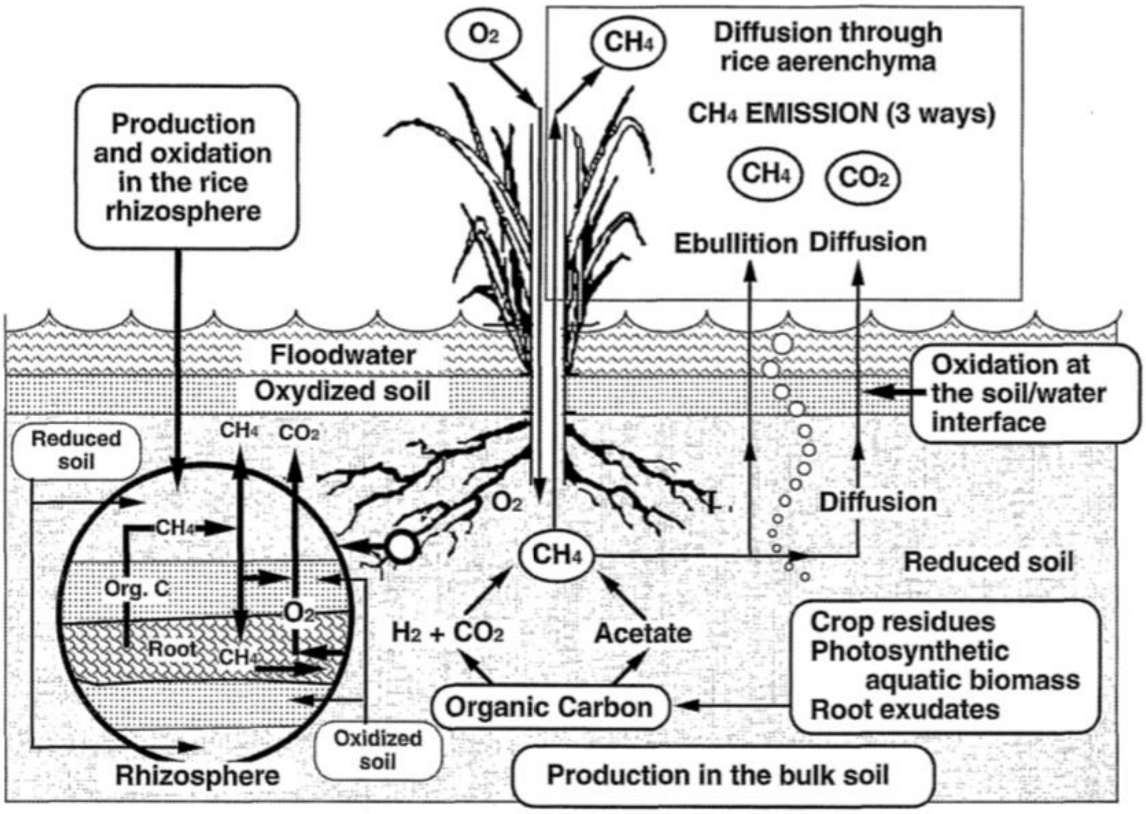


Figure 2.6 The pathways of methane emission (Mer and Roger, 2001)

2.3.1 The transportation of gas by rice plants

Up to 90% of methane is emitted from rice fields though the aerenchyma of rice plants, which is similar to the release of methane in natural wetlands (Whiting and Chanton, 1992; Chanton et al., 1992). The gas moves through a hollow stem and root which connect to the root (Schutz et al., 1991). From a study reported by IPCC (1992), the aerenchyma of rice plant not only transports methane to the atmosphere but also transfers oxygen into the rhizosphere through root respiration and thus supports methane oxidation. Methane emissions depend on photosynthesis of plants and the plants stoma. In other words, methane emission is controlled by stoma of plants (Morrissey et al., 1993). The size and volume of the air channels in the root and aerenchyma is larger in accordance with rice's age. Methane is oxidized more than 50% in the vegetation period and 90% of methane is consumed during the rice maturation (IPCC, 2000). The density of the plants per square meter (m^2) also influences the methane flux.

2.3.2 The transportation of gas by diffusion

The diffusion of methane gas can spread through the soil, water, and atmosphere (Chanton, 2005). In the water, methane gas diffuses slower than in the air by 10^4 times (Jain, 2004). The transportation of air in daytime is higher than in the night by molecule diffusion only (Grosse and Mevi-Schutz, 1987). In the rice fields, when the water levels decrease, diffusion of gas will increase (Chanton et al., 1992). But the diffusion of methane usually accounts for less than 1% of total methane emission in rice field (Jain, 2004).

2.3.3 The transportation of gas by ebullition

Methane emission by ebullition depends on many factors, including wind speed, water temperature, water table, solar radiation, and pressure of the air (Jain, 2004). In the dry season when air temperature is usually high, there is more ebullition that is less soluble than wet season. In addition, the soil with low density usually occur the bubbles easier than the high density (Mudge and Adger, 1994; Chanton, 1992; Chanton, 2004).

2.4 Factor affecting methane emissions

2.4.1 Rice structure

Methane in soil is emitted through plants (50-90% of total emitted amount) to the atmosphere (Knapp, 1991). The factors affecting methane emissions involve the morphology of leaves, the plant’s structure, the plant’s age, the plants respiration and the temperature of the plants. Large size of leave and roots can emit more gas. Although, the stomata closed at night, the plants can gather methane during the night and emit methane into the atmosphere after the opening of stomata (Knapp, 1991). Microspore at the base of leaf sheath also plays the important role on releasing methane into the atmosphere, regardless of opening and closing of stomata. The mass of rice plant related to methane emissions from rice fields. Heavy mass of plants would emit less methane emission, as more carbon is fixed by mass of heavy plant (Xiaohong et al., 2011). According to a study conducted by Xiaohong et al. (2011), conventional rice released methane more than hybrid rice because hybrid rice’s yields lower plant mass than conventional rice. Therefore, hybrid rice can reduce methane emissions while increasing rice yield.

2.4.2 Water level

Rice can grow well in five conditions, including upland, lowland, flood recession, lowland irrigation and deep water. The main difference in these conditions is water level, which affects the quantity of methane emission (Watcharee et al., 2002; Saulter, 2013). Figure 2.7 illustrates different water level in five conditions.

1. Upland: Rice is grown in the low-water area, or drought-prone area, which releases fewer methane emissions.

2. Lowland rainfed: Rice is grown in low flooding conditions. Rice planting relies mainly on rainfall and groundwater.

3. Flood recession: Rice is usually grown in Africa near the river. Sometimes, rice crops depend on rainfall in the wet season.

4. Irrigated: Rice cultivation depends heavily on irrigated water in the rice fields.

5. Deep water: Rice is grown in deep water conditions at more than 50 cm in depth.

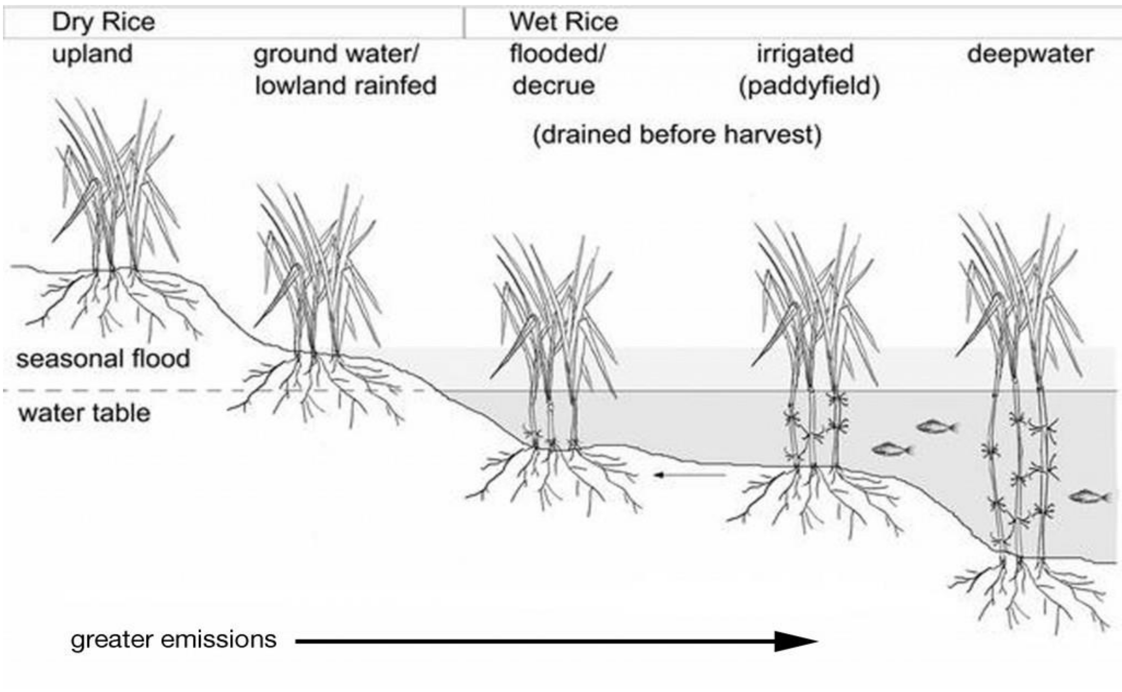


Figure 2.7 Water table conditions (Saulter, 2013)

2.4.3 Soil temperature

The soil temperature affects methane emissions. The optimum temperature for methanogens is approximately 30-40°C. The low soil temperature can reduce methane production not only from the methanogen activity but also from other bacterial activities. The variations of temperature during the day can affect the release of methane in the rice fields, as the rate of methane production is high in the afternoon and low in the morning (Jain, 2004). Methane emissions usually occur during the daytime 12.00-14.00 p.m. because of the maximum temperature of the day (Pheeyaboon, 1993; Tapon et al., 2008).

2.4.4 Soil pH

Soil in different areas has a different level of alkalinity and acidity. Most of methane production is pH 6.5-7.5. Normally, methane is produced under the pH range from 6.9 to 7.1 in the soil by methanogens. The methanogen activities are usually sensitive to the soil pH (Jain, 2004). However, methanogens are also susceptible to acidification (Mer and Roger, 2001). When pH is lower than 5.8 and higher than 8.8, methane production is suspended (Tapon et al., 2008).

2.4.5 Soil properties

In submerged soils, the ability to absorb nutrients affects the bacterial growth in the soil. Submerged soil has more moisture and less oxygen. Methane production relies on bacteria growth, soil temperature, the amount of organic matter in soil, and depth of soil oxidation. The clay soil can emit higher amount of methane than other types of soil as it keeps the mineral for methanogens. When the density of soil increases, it affects pH, redox potential variations, and organic matter decomposition after flooded. Methane production in accordance to different soil types is shown in Table 2.3

Table 2.3 Methane emissions in different soils (g CH_4/ha/d) (Mer and Roger, 2001)

Environments	Minimum	Maximum	Median
Upland soil temporarily submerged	0	216	3
Freshwater environments without plants	0	10×10^3	3×10^3
Swamps	0	17×10^3	720
Peat lands	6	2×10^3	433
Rice fields	1	29×10^3	10^3

2.4.6 Organic matter

Organic matter is a group of carbon compounds, derived from living things including plants, animals, and their remains. Soil usually consists of an organic matter at approximately 2-8%. Soils contain less than 2% of organic matter are sandy soils and acid soils (Pettit, 2004). In submerged soil, the ability to decompose organic matter depends on the fertility of the soil. The application of organic matters such as rice straw and green manure in the rice fields usually increases the methane emission (Yagi, 2006). Naturally, the organic matter is electron acceptor. Therefore, the organic matter is major source of electrons from which methanogen can produce methane in rice fields. The soil with abundance of organic matter will increase methane production and emissions (Mer and Roger, 2001). Therefore, methane emission could be mitigated by reducing the amount of organic matter. The composted organic matter affects methane efflux less than the fresh organic matter because compost has the ability of decomposition carbon easier than fresh organic matter (Yagi, 2006).

2.4.7 Redox potential

The redox potential of the soil (Eh) is the indicator of a flooded soil's status of the difference between the ability of receiving and donating electrons. In general, Eh value has an impact on both methane production and emission though the plant (Jain, 2004). Normally, Eh value is gentle increased when rice field is drained and decreased when rice field is flooded (Tyagi et al., 2010). Low Eh value results in increasing methane production and emission. Higher Eh indicates that an oxidation reaction occurs in the soil (Mer and Roger, 2001). Eh value is also indicative of the activity of methanogen bacteria. When Eh of the soil is -200 to -280 mV, methane is produced (Table 2.4).

Table 2.4 Redox potential of the soil (Eh) and corresponding biogeochemical processes (Komkrit, 2011)

Reduction	**Redox potential (mV)**	
$O_2 \rightarrow H_2O$	+380 to +320	
$NO_3 \rightarrow N_2Mn^{+4} \rightarrow Mn^{+2}$	+280 to +220	Denitrification, Manganese
$Fe \rightarrow Fe^{+2}$	+180 to +150	Iron reduction
$SO_4^{-2} \rightarrow S^{-2}$	-120 to -180	Sulfate reduction
$CO_2 \rightarrow CH_4$	-200 to -280	Methane reduction

2.4.8 Fertilization

Plants need nutrients for growth. The use of fertilizers is one of the factors to increase plants productivity. However, fertilization also influences the activity of methanogens. The inorganic fertilizer application will increase electron acceptors and therefore the competition between methanogens and other reducers. For example, ammonium chloride and ammonium sulfate can reduce methane emission up to 50-70% in rice field by suppressing methanogen activity through increasing competition of nitrate reducers (Table 2.5) (Jain et al., 2004). The nitrate–N application can reduce dissolve oxygen concentration as well as low methane emission (Mer and Roger, 2001). On the other hand, organic fertilizer application will result in more methane production and emissions as the substrates for methanogens increase (Xiaohong et al., 2011).

Table 2.5 Methane emission rate of early and late rice as affected by fertilization (Xiaohong et al., 2011)

Fertilizer types	**Emission of early rice ($mg/m^2/h$)**	**emission of late rice ($mg/m^2/h$)**
Normal fertilizer	2.88	5.50
Organic fertilizer	4.54	13.62
Mineral fertilizer	5.20	12.12
Biogas residues fertilizer	2.94	15.82

2.5 Water management and methane emission mitigation

Water management is very important for rice production and also for mitigating methane emissions from rice fields (Sass, 2006; Tyagi et al., 2010). Methane emissions are sensitive to soil when soil aeration is controlled by water management (Sass, 2006). Rice production of 1 kg use water 2,300 liter (McGegor et al., 2014). Rice production needs water all the time during transplanting until before harvest (Tyagi et al., 2010). Usually, water can be supplied through field irrigation. There are several types of irrigation including:

2.5.1 Continuous flooding (CF)

Continuous flooding during rice cultivation in Asia usually consumes water around 700-1500 mm/reason that consists 150-250 mm for land preparing, 55 mm for transplanting, and 500-1200 mm for rice growth (Chumwong and Kwanyuen, 2009). Rice is grown in rice fields that are continuously flooded which water level should be 3 cm after transplanting which is gradually increased to 5-10 cm until 7-10 days before harvest for weed control and support of plants growth. Rice plants should be large enough to grow in rice fields under flooded condition (3-4 leaf stage). Lowland rice is not only used a lot of water but sensitive to water shortage at flowering period. When water is not enough, rice yield will be significantly decreased (IRRI, 2009).

2.5.2 Shallow water depth (SWD)

This shallow water depth with wetting and drying maintains the water level at around 1-4 cm on the soil surface. About 60% of saturated moisture content (SMC) is controlled by water level. The water level is limited around 4-7 cm for rainfall and drainage (Figure.2.9) (Sujono et al., 2011).

2.5.3 Mid-season drainage (MSD)

Mid-season drainage is the practice of adding oxygen in the rice fields for reduction of methane production and increasing oxidation in the soil. In short term, water drainage can reduce methane from cultivation by 42-45%, when is compared with continuous flooding. It can mitigate methane emission from rice fields. In Philippines, water is drained during 2 week of mid-season that can reduce methane by up to 60%. Methane emission from rice fields can reduce with mid-season method by up to 50% in the United State (Sass, 2006). The system of mid-season drainage is shown in Figure 2.9 (Fower, 2011).

2.5.4 Alternate wetting and drying (AWD)

AWD is a technique to reduce irrigation water use and methane emissions. Irrigation can put water in rice fields after transplanting 1-2 weeks. After that, the water drops to 15 cm below the soil surface. When the water drops to 15 cm below the soil surface, the field is re-flooded again to maintain the water level at 5 cm above the soil surface. To reduce water stress flooded condition should be maintained during flowering stage. After the flowering, the water level can drop to 15 cm below the soil surface in grain filling and ripening period and re-flood again (Figure 2.8) (IRRI, 2009).

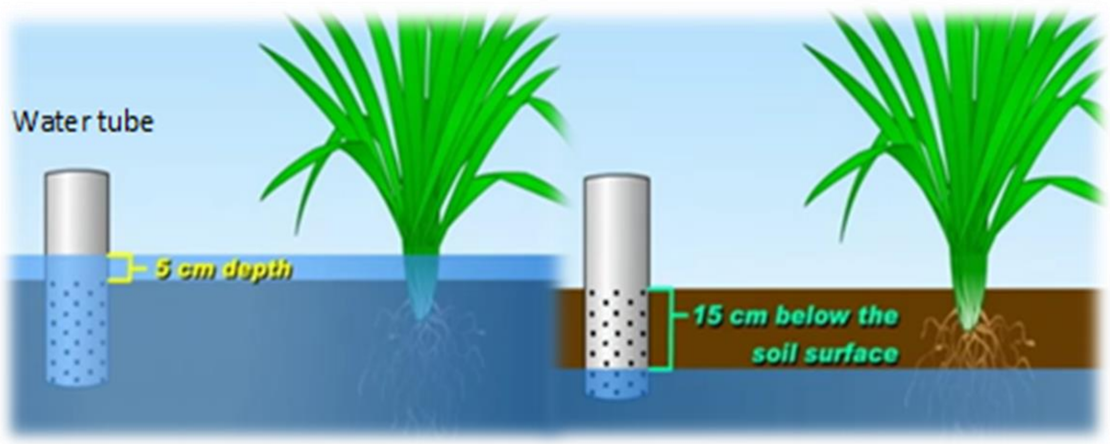


Figure 2.8 Water management by AWD technique (IRRI, 2009)

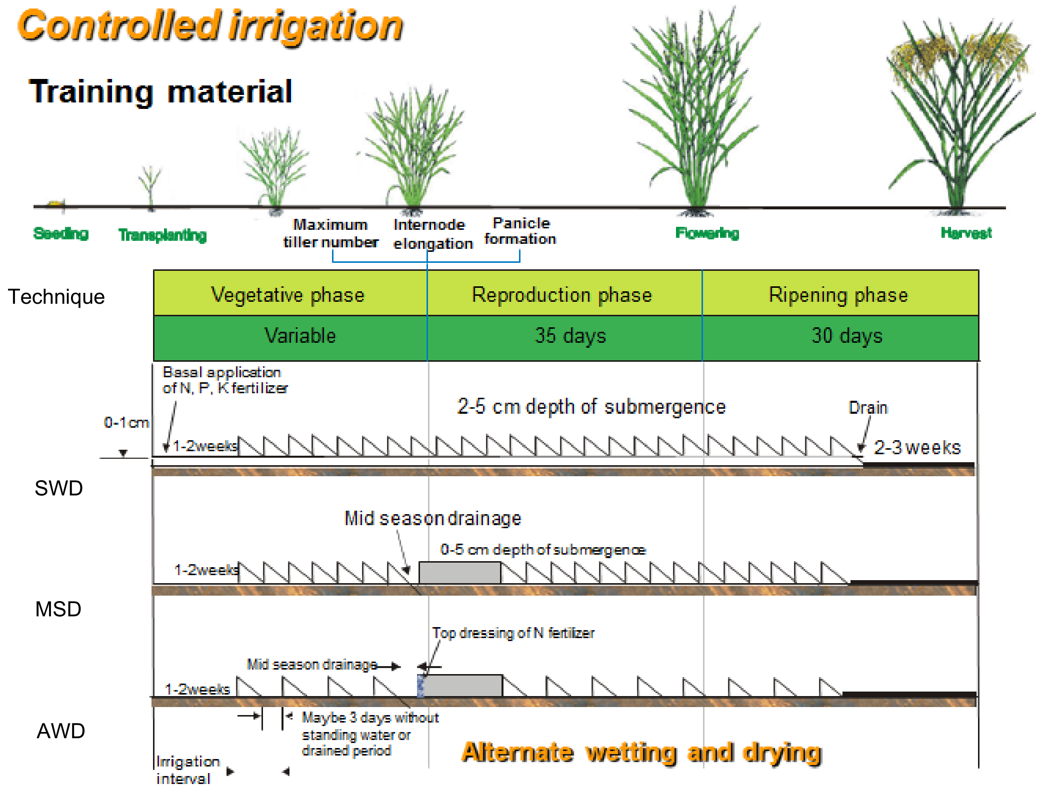


Figure 2.9 Controlled irrigation in rice field (IRRI, 2009)

2.6 Costs of rice cultivation

Rice cultivation is scattered throughout Thailand. In the years 2012-2013, the cultivation areas were 12 million ha, while the cultivation areas were 1.4 million ha in year 2007-2008. The cultivation areas increased up to 12.7%. Cultivation areas are divided by rainfed (or in-season) and 2nd rice (off-season) rice. Rainfed rice was 66.4 million ha in the north and north-east region and 2nd rice was 10.6 million ha in the central regions where irrigation is available (Chimparee, 2014) (shown in Figure. 2.10).

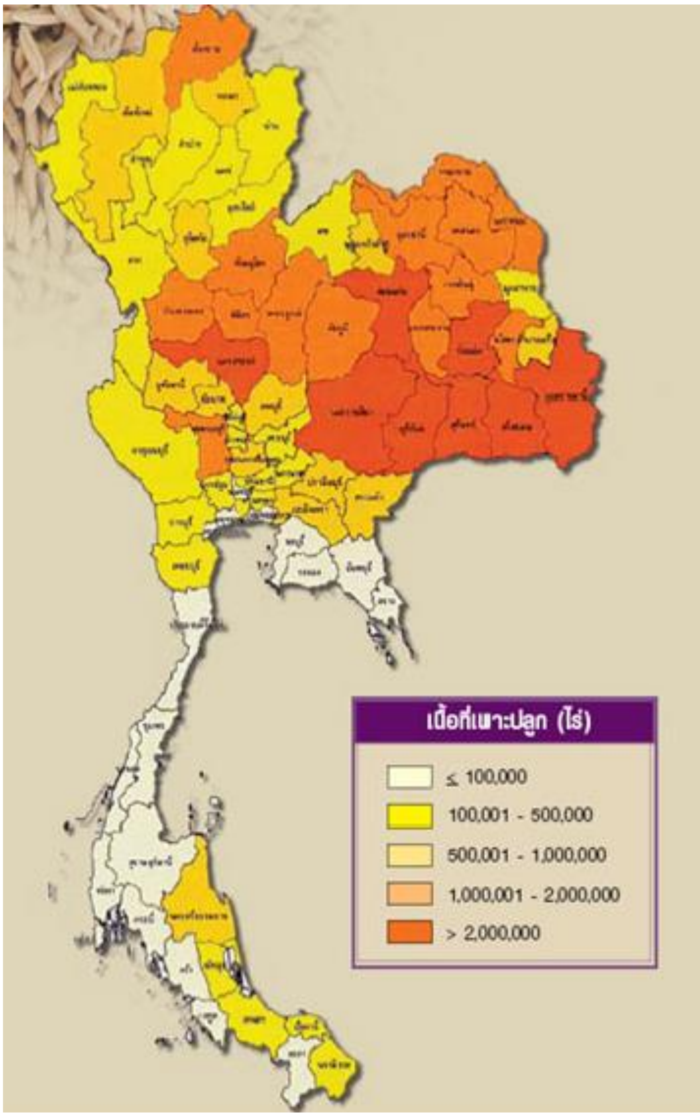


Figure 2.10 Distribution of rice cultivation areas in Thailand (AFTC, 2007)

The important rice cultivars contain both photoperiod sensitive and photoperiod insensitive varieties. Photoperiod insensitive varieties are often planted for in-season rice while photoperiod insensitive varieties are often planted for off-season rice.

There are a number of factors affecting rice production costs (in-season rice). Labor costs (human and machinary) are the largest cost of rice production, accounting for 66%. This is followed by input costs (19%), which are largely the costs of fertilizers. The two main costs include land rental (12%), and opporturity costs (3%) (shown in Figure 2.11) (AFTC, 2007).

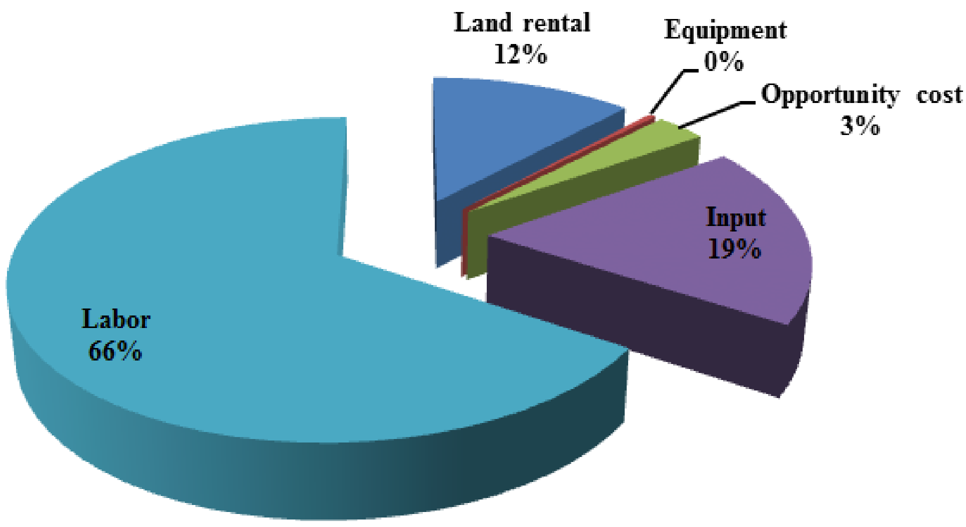


Figure 2.11 Costs of rice cultivation in 2003 (in-season rice) (AFTC, 2007).

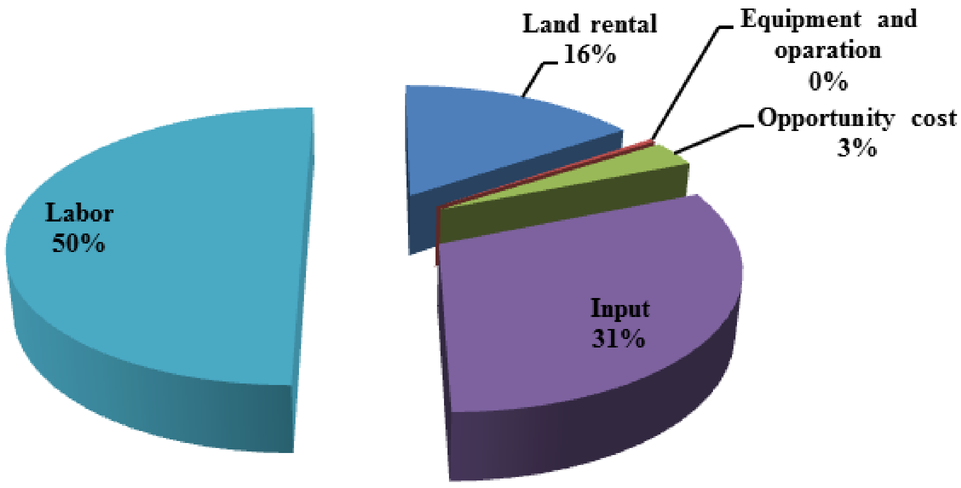


Figure 2.12 Costs of rice cutivation in 2003 (off-season rice) (AFTC, 2007)

The average costs of rice production is 3.3 THB/kg or 14,261 THB/ha under off-season rice cultivation. The cost of off-season rice production is higher than that of in-season rice production. This is because off-season rice can only be planted in irrigated areas to produce high yields. Other main costs of rice production during off-season are labor cost (50%), input cost (31%), land rental (16%), and opportunity cost (3%) (shown in Figure 2.12) (AFTC, 2007).

Gaytancioilu and Surek (2001) studied about input use and production cost of rice cultivation in Turkey. They found that costs varied according to different techniques for fertilizers used by farmers in different regions. The major costs were fertilizer, seed, water and labor. Normally, farmers applied excessive fertilizer and herbicide. This led to a significant increase in the cost of rice production and environmental problems. In addition, the study revealed that rice cultivation in Turkey is labor-intensive. Every stage of rice cultivation from soil preparation to harvesting required labor rather than machinery. Thus, the average cost of rice production was 37,346-63,503 THB/ha.

Nirmala and Muthuraman (2009) studied the economic constraints for rice cultivation in 2007-2008. They collected data by interviewing the farmers. The expenses of rice cultivation included the cost of seed (1.9%), manure (7.3%), fertilizer (18.9%), pesticide (11.6%), irrigation (5.2%), transportation (4.6%), labor (19.7%), machine (25.3%), and interest on working capital (5.4%). This study found that the main constraints of rice cultivation were pests and disease incidence, labor shortage, and lack of profit. This is especially true for labor, pests, and disease without an effective management. The cost of investment tended to increased, while the productivity decreased. In this study, the average cost investment was about 18,306 THB/ha and the average yield was 4.99 ton/ha.

Devi and Ponnarasi (2009) also revealed consistent findings. They studied about the expense of rice cultivation between system of rice intensification (SRI) and conventional method. The technique of rice cultivation affected the cost of investment. Rice investment would increase or decrease depending on seeds, human labor, irrigation and weed management. SRI method could reduce the cost of seed (from 978 to 73 THB/ha), human labor (from 5,857 to 5,098 THB/ha), irrigation (from 2,699 to 1,150 THB/ha), and herbicide (from 617 to 324 THB/ha). They reported that cost with SRI implementation was about 2,125 THB/ha, compared with 3,996 THB/ha under conventional method. On the other hand, rice yields under SRI method was more than conventional method (5.4 from SRI vs. 3.5 ton/ha for conventional method). Thus, the benefits of SRI method were increasing productivity, high profit, and water-saving. However, the limitation is that sufficient knowledge to implement it is needed.

Tonpanya (2011) reported about the rice production costs in Phichit Province. The average cost of rice production was 31,770 THB/ha. This included input costs of 4,094 THB/ha (13%), labor of 7,770 THB/ha (24%), and equipment operation of

19,907 THB/ha (63%). Along the process of rice cultivation, farmer tended to do most of the job by themselves, which contributed to 79% of all labor costs. Other than that, workers were hired for the application of fertilizer (10%) as well as pesticide and herbicide (6%), rice planting (3%), and drainage channel (2%).

Jayapalreddy and Shenoy (2013) compared the costs of rice production under SRI and conventional method. It is stated that the decreasing rice production depended on the use of fertilizer, pesticide, and water. Normally, under conventional method rice plantation used a great deal of labor and herbicide. On the other hand, SRI can reduce the costs of labor and herbicide by using weeder machinery for weed management instead of labor. In addition, the use of more organic pesticide rather than chemical pesticide was used which led to the reduction of the cost investment.

According to a study conducted by Ketpirune (2013), the expenses of rice production with the use of both chemical and organic inputs combined were 29,375 THB/ha. If farmers used organic fertilizers instead of chemical fertilizers, the costs were reduced to 20,250 THB/ha. By contrast the average yields under chemical condition was lower than organic condition (2.56 vs. 3.18 ton/ha). Thus, the cost of rice cultivation under chemical condition was higher than that under organic condition by about 52.9%. The largest part of cultivation cost was input cost (78%) including seed, herbicide, and fertilizer. The second largest part of cost cultivation was workers' wage including transportation, soil preparation, and harvest. Lastly, the cost of fuel used come from water pumping in rice fields.

Noomueang (2014) reported that rice production costs can vary depending on the method of planting, using fertilizer, water management and environmental factors. The costs for rice production was 29,438-35,688 THB/ha. Without rice fields rent, the cost was reduced to was 23,188-28,188 THB/ha.

CHAPTER 3

METHODOLOGY

This research is divided into two main sections: (1) collection of the data on cultivation and investment costs through the interview with farmers; and (2) estimation of the data about greenhouse gas emissions based on IPCC methodology.

3.1 Study sites

Currently, in Thailand there are several rice planting sites that applied conventional and AWD techniques. From the preliminary surveys, the following sites were selected:

1. Nakhon Sawan is located at 15° 41’ 0” North latitude/100° 7’ 0” East longitude
2. Chai Nat is located at 15° 10’ 60” North latitude/100° 7’ 60” East longitude
3. Prachin Buri is located at 14°4’59.99” North latitude/101°40’0.02”East longitude

In Nakhon Sawan, Chai Nat, and Prachin Buri, farmers always plant the photoperiod insensitive lowland rice variety from May to March. Rice is cultivated 2-3 times/year. The soil in study sites is characterized as slightly acidic to neutral soil. The soil fertility is medium that drain quite low to medium for rice cultivation. Soil in Nakhon Sawan and Chia Nat was clay soil, while in Prachin Buri was heavy clay soil. Under AWD, all these three provinces adopt similar water management approach (adding water to the field when water level decreased to below -15 cm).

Figure 3.1 Locations of the study sites

3.2 Data Collection

The data were collected to estimate the costs associated with AWD technology by in-depth interviews with individual farmers. It contained the following information:

1. Variable costs include labor costs (land preparation, planting, maintenance, and harvesting), material costs (rice cultivar, fertilizer, pesticide, fuel bills, and the other material), and opportunity costs.

2. Fixed costs include land rental and equipment depreciation costs.

3.3 Calculation of greenhouse gas emissions

The calculations of greenhouse gas emissions were based on the protocols described in the IPCC guidelines for national greenhouse gas inventories in 2006: Volume 4 agriculture, forestry and other land uses.

3.3.1 Greenhouse gas emissions from residue burning

$$L_{fire} = A \cdot M_B \cdot C_f \cdot G_{ef} \cdot 10^{-3} \quad (1)$$

Where:

L_{fire} = amount of greenhouse gas emissions from burning, tons

A = area burnt, ha

M_B = mass of fuel combustion, ton/ha (Table 3.1.A)

C_f = combustion factor, dimensionless (Table 3.1.B)

G_{ef} = emission factor, g/kg dry matter burnt (Table 3.1.C)

Table 3.1 Biomass consumption, combustion factor of residue type, and emission factor of type burning (IPCC, 2006)

A. Biomass consumption (dead organic matter and live biomass) (tons dry matter/ha)		
Residue	**Type**	**Value**
Agricultural residues	Wheat residues	4
	Maize residues	10
	Rice residues	5.5
	Sugarcane	6.5

B. Combustion factor of residue type (proportion of fuel biomass consumed before field burning)		
Residue	**Type**	**Value**
Agricultural residues (post-harvest field burning)	Wheat residues	0.9
	Maize residues	0.8
	Rice residues	0.8
	Sugarcane	0.8

C. Emission factor (g/kg dry matter burnt) of type burning				
Residue	**CO_2**	**CO**	**CH_4**	**NO_x**
Agricultural residues	1515±177	92±84	2.7	2.5±1.0

3.3.2 Greenhouse gas emissions from fuel combustion

$$\text{GHG emissions}_{fuel} = \text{Fuel consumption} \bullet \text{Emission factor}_{fuel} \qquad (2)$$

Where:

$\text{GHG emissions}_{fuel}$ = greenhouse gas emissions under fuel types, kg CO_2e

$\text{Fuel consumption}_{fuel}$ = annual of fuel combusted, TJ

$\text{Emission Factor}_{fuel}$ = default greenhouse gas emission factor depending on fuel types, kg/TJ

3.3.3 Methane emission from rice cultivation

$$CH_{4\,rice} = \sum_{i,j,k} (EF_{i,j,k} \bullet t_{i,j,k} \bullet A_{i,j,k} \bullet 10^{-6}) \qquad (3)$$

Where:

$CH_{4\,Rice}$ = annual methane emissions from rice cultivation, kg CH_4/year

EF_{ijk} = emission factor under i, j, and k conditions, in kg CH_4/ha/day

t_{ijk} = period of rice cultivation under i, j, and k conditions, in day

A_{ijk} = annual rice harvested area under i, j, and k conditions, in ha/year

i, j, and k = different conditions depending on ecosystems, water regimes, types and amounts of organic amendments

Default of methane emission from rice fields
1) Emission factor

$$EF_i = EF_c \bullet SF_w \bullet SF_p \bullet SF_o \bullet SF_{s,r} \qquad (4)$$

Where:

EF_i = emission factor of harvested area

EF_c = emission factor of continuous flooding fields without organic amendments (Table 3.2)

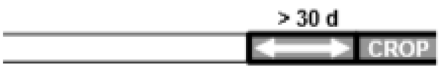
SF_w = scaling factor of water regime during the rice cultivation period (Table 3.2)

SF_p = scaling factor of water regime before the rice cultivation period (Table 3.2)

SF_o = scaling factor of type and amount of organic amendment applied (from Equation 5 and Table 3.3)

$SF_{s,r}$ = scaling factor of soil type under rice cultivation, etc., if available

Table 3.2 Default methane emission factor during rice planting (IPCC, 2006)

Methane Emissions (kg CH_4/ha/d)		**Emission factor**
		1.30
Default methane emission scaling factors of water regimes		
Water regimes during the rice cultivation period		**Scaling Factor (SF_w)**
Upland		0
Irrigation	Continuously flooded	1
	Intermittently flooded – single aeration	0.60
	Intermittently flooded – multiple aeration	0.52
Rainfed and deep water	Regular rainfed	0.28
	Drought prone	0.25
	Deep water	0.31
Water regime pre-rice planting		**Scaling Factor (SF_p)**
	Non-flooded pre-season < 180 d 	1
	Non-flooded pre-season < 180 d 	0.68
	Flooded pre-season (>30)[a,b] 	1.90

2) Adjusted methane emission scaling factors for organic amendments

$$SF_0 = (1+\sum_i ROA_i \bullet CFOA_i)^{0.59} \quad (5)$$

Where

SF_o = scaling factor of type and amount of organic amendment applied

ROA_i = rate of organic amendment i application (in dry straw and fresh weight), ton/ha

$CFOA_i$ = conversion factor of organic amendment applied before cultivation (Table 3.3)

Table 3.3 Default conversion factor of organic amendment by different types (IPCC, 2006)

Organic amendment	Conversion factor (CFOA)
Straw incorporated shortly (<30 days) before cultivation[a]	1
Straw incorporated shortly (>30 days) before cultivation[a]	0.29
Compost	0.05
Farm yard manure	0.14
Green manure	0.05

a: Straw incorporated into the soil, it does not include case that straw just placed on the soil surface, nor that straw was burned on the field.

3.3.4 Greenhouse gas emissions per unit rice yields

$$\text{GHG emissions} = \frac{\text{Total gases emission during rice production (ton } CO_2e)}{\text{Rice yields (ton yields)}} \quad (6)$$

Where:

GHG emissions = annual greenhouse gas emissions per yield, ton CO_2e/ton yields

Total gases = total gases of rice production, ton CO_2e

Rice yield = annual of rice harvested, ton yields

3.3.5 Cost-savings per greenhouse gas emissions of rice cultivation

$$\text{Cost-savings} = \frac{\text{(costs of AWD tech. (THB/ha)) - (costs of conventional tech. (THB/ha))}}{\text{(emissions of AWD tech.(ton}CO_2\text{e/ha) - (emissions of conventional tech. (ton}CO_2\text{e/ha)}} \quad (7)$$

Where:

Cost-savings	= cost-savings of rice cultivation, THB/ton CO_2e
Costs of conventional technique	= expenses of conventional cultivation, THB/ha
Costs of AWD technique	= expenses of alternate wetting and drying cultivation, THB/ha
Emissions of conventional technique	= annual of methane emission by conventional technique, ton CO_2e/ha
Emissions of AWD technique	= annual of methane emission by alternate wetting and drying technique, ton CO_2e /ha

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Collected data

In this study, the data were collected by interviewing 180 farmers. Farmers in each province were separated into two groups; CF and AWD conditions. Thus, each group consisted of 30 farmers/province. The calculation of rice production costs contained many processes (pre-planting, planting, fertilizer, pesticide, herbicide, water management, harvesting). The data regarding the use of input (seed, fertilizer, herbicide, and pesticide) and expense of rice production from each group was averaged. Then, the average costs (THB/ha) of rice cultivation under CF and AWD was compared and analyzed for these three provinces.

4.2 Local cultivation practice and cost management

The detailed cultivation practices of rice plantation vary from area to area and also depend on the farmer's preference, which led to the difference rice expenses. Nakhon Sawan, Chai Nat, and Prachin Buri were selected in study because farmers there adopted AWD along with the existence of conventional practices in the adjacent areas. Farmers in these areas have linked to each other through the Weekend Farmers' Holiday Network. Sharing the rice cultivation knowledge and information is the most prominent features of this network. However, in Prachin Buri, most farmers just have adopted AWD technique, but there was network. Certain characteristics of farmers and their cultivation practices are given in Table 4.1 and 4.2. Moreover, water controlled by farmers adopted under conventional and AWD condition is shown in Figure 4.1.

Table 4.1 Summary of information obtained from farmers' interview

Aspect	Subaspect	Explanation
Province		Nakhon Sawan, Chai Nat, and Prachin Buri
Farmers' age range		25-70
Cultivation area (ha)	Owned	397 ha (47.83% of samples)
	Rented	433 ha (52.17% of samples)
Number of crop (times /year)		1 - 3
Irrigation systems		River, canal, and groundwater
Rice variety	RD 31, RD 41 Hom Pathomtani Khao Bahn Nah 432	

Table 4.2 Rice cultivation practices

Filed management	Rice cultivation practices	
	Conventional	**Alternate wetting and drying**
Pre-planting	Residue burning	Residue burning / straw management
Planting	Direct seeding	Transplanting
Fertilizer	Chemical >> organic	Organic > chemical • Bio-extract • Green manure (*Crotalaria juncea* L.)
Pesticide	Chemical >> organic	Organic > chemical • *Beauveria bassiasna* • Beneficial insects
Weed	Herbicide	Bio-technique method • Azolla • Rotary weeder
Water management	Continuously flooding	Multiple drained following AWD principle

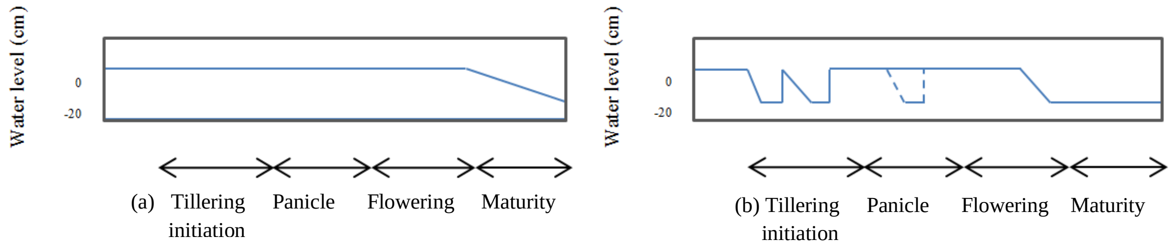


Figure 4.1 Water controlled by farmers adopted under (a) Conventional (b) AWD conditions. The frequeny of broken line occurences which represent water level drops depends on farmers and cultivation areas (Doi and Pitiwut, 2014).

The expenses of planting depend on many factors including land preparation, water management, types of material and equipment, and labor. The expenses of planting rice under conventional and AWD technique are different, especially the expenses of irrigation, fertilizer consumption, and labor. These are described according cultivation stage as shown below.

4.2.1 Land preparation

a) Local cultivation practices of land preparation

Land preparation is mostly done before rice cultivation. From the survey, generally, the process of land preparation for planting rice consists of chiseling, plowing, discing, land leveling, and rolling. In Thailand, buffalos were used for tilling rice fields; however, over the past decades, tractors have become popular as it is more effective and cost-savings. Under conventional and AWD techniques, chiseling is the process of opening up and drying the surface soils. In terms of discing, a stubble disc is used to break up a large clod to soften and dry the surface soil (Figure 4.2).

Additionally, discing helps destroy weeds and some plant diseases as well as remove the residue from the surface. Then, as water drainage and management are a significant process of rice field plantation, the triplane is used to level and smooth rice fields to help manage and adjust the water level in the rice fields. After that, soil is rolled before planting and flooding. Farmers used agricultural tractor or motor gasoline including 2 strokes and 4 stroke petrol engine. The type and cost of fuel varied depending on what kind of tractor farmers used.

Figure 4.2 Land preparations steps; discing and land leveling (Tang-sub, 2015)

b) The expense of land preparation

In this study, most farmers usually plow the soil, depending on the type and amount of weeds by farm tractor. The cost estimated during land preparation steps are shown in Table 4.3.

Under conventional technique

- The duration of land preparation is approximately 3 days

- The workers were hired to work for 6 hr/day by 3 workers and about 1-2 times/crop.

- The use of fuel (diesel) for the farm tractor was 3-25 L/ha. The costs of fuel used and labor were combined with farm tractors.

- The total costs were 3,125 THB/ha and 6,250-12,500 THB/year.

Under AWD technique

- The duration of land preparation was approximately 7 days.

- The workers were hired to work for 6 hr/day by 1-2 workers and about 3 times/crop. As straw and stubble were fermented in rice fields to reduce the use of fertilizer under AWD technique, there was more residue crop in the rice field to manage. Therefore, rice field is needed to be plowed more often under AWD technique when compared with that of the conventional one.

- The use of fuel (diesel) was 3-25 L/ha. The costs of fuel used and labor were combined with farm tractors.

- The total costs were 3,125 THB/ha and 6,250-18,750 THB/year.

The investment cost of a farm tractor is 250,000-470,000 THB. The lifetime of a farm tractor is approximately 7-16 years. The maintenance costs were 1,000-3,000 THB/year.

Table 4.3 Cost estimated during land preparation steps

Provinces	**Nakhon Sawan**		**Chai Nat**		**Prachin Buri**	
Technique	**CF (n=30)**	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**
Period of land preparation (days)	3	7	5	7	2	5
The number of plows (times/crop)	2	3	1	1	1	2
Labor (person)	2	1	3	1	2	1
Working time (hr/day)	6	6	8	6	7	7
Use of fuel from machine (L/ha)	6	6	13	13	16	16
Land preparation costs (THB/ha)	3,125	3,125	3,125	3,125	3,125	3,125

CF= continuous flooding (conventional technique), AWD = alternate wetting and drying

c) Greenhouse gas emissions during land preparation

Greenhouse gas emissions came from fuel used (diesel) by farm tractor combustion. This process was 25-61 kg CO_2e/ha under conventional and 34-89 kg CO_2e/ha under AWD technique (Table 4.4). Greenhouse gas emission depended on type of fuel used and type of farm tractor.

Table 4.4 Greenhouse gas emissions from land preparation

Parameters	Nakhon Sawan		Chai Nat		Prachin Buri	
	CF (n=30)	AWD (n=30)	CF (n=30)	AWD (n=30)	CF (n=30)	AWD (n=30)
Tillage by machine (kg CO_2e/ha)	33.78	33.70	25.38	37.04	61.47	89.10

CF= continuous flooding (conventional technique), AWD = alternate wetting and drying

4.2.2 Planting

a) Local cultivation practices of planting

There are two main rice planting methods, including direct seeding and indirect seeding. Direct seeding comprises of dry-seeding and pre-germinated seed in initial phrase of conventional rice planting. It is true that transplanting technique consumes more effort as it takes about 15-18 days to raise seedling in seedbeds before being planted in the rice fields. However, this technique is more cost-effective.

For direct seeding, about 150-180 kg/ha of rice seeds are used, while transplanting requires only 80-156 kg/ha (Table 4.5). After seeding and planting, the soil becomes flooded. The periods of rice planting depend on the quantity of water and seasons in each area. In Nakhon Sawan and Chai Nat, rice is planted between May and March in double-crop fields. In Prachin Burin, rice is usually planted once a year from May to September.

Figure 4.3 Rice seedling and transplantation by rice planting machine in Chai Nat (Ruenpakdan, 2015)

b) The expenses during rice planting

The cost difference between CF and AWD therefore came from the difference in labor used for seeding. By contrast, in AWD approach indirect seeding is more popular than direct seeding because it is easier to manage the rice fields. Rice plantation under AWD technique is usually planted by rice planting machine. AWD technique can reduce the use of seed up to 54% in Nakhon Sawan and 39% in Chai Nat. In Prachin buri used seed more than other provinces; this is because some farmers selected rice cultivation by direct seed under AWD technique. AWD technique in Prachin Buri can reduce the use of seed about 6%. Therefore, farmers under conventional technique have to pay labor cost more than machinery and equipment costs because rice was planted manually (Table 4.5). Below are summaries of planting and cost under both conventional and AWD conditions.

Under conventional technique

- The duration of rice plantation was 1 day.
- The expense of the seeds was 2,172-2,467 THB/ha.
- 3-5 workers spent 6-8 hr/day. The expense of workers were about 5,625-9,375 THB/ha. Conventional technique used the labor to plant rice rather than using rice planting machine.

Under AWD technique

- The duration of rice plantation was 1 day.
- The expense of the seeds were 1,367-1,729 THB/ha.
- 1-2 workers were hired to work for 8 hr/day and rice planting machines were preferred to manual planting.
- The use of fuel (diesel and gasoline) was 6 L/ha. The expenses of fuel and labor are combined with rice planting machines.
- The expenses of rice planting machines were 3,125 THB/ha

Thus, the investment costs of rice planting machines were 175,000-200,000 THB under AWD approach. The lifetime of rice planting machines were approximately 5-10 year. The maintenance costs of rice planting machines were 1,000-2,000 THB/year.

Table 4.5 Rice seeds requirements and costs under CF and AWD conditions

Parameter	Nakhon Sawan		Chai Nat		Prachin Buri	
	CF (n=30)	AWD (n=30)	CF (n=30)	AWD (n=30)	CF (n=30)	AWD (n=30)
Period of rice planting (days)	1	1	1	1	1	1
Labor (person)	3	1	4	2	5	4
Time working (hr./day)	6	6	7	6	5	5
The amount of seed (kg/ ha)	179	82	153	94	169	156
Fuel of rice plantation (L/ha)	6	6	19-44	19-44	19	19
Costs of seed (THB/ha)	2,467	1,367	2,231	1,378	2,172	1,729
Cost of labor/ rice plantation machine (THB/ha)	5,625	3,125	7,500	3,125	9,375	3,125

CF= continuous flooding (conventional technique), AWD = alternate wetting and drying

Figure 4.4 Soil surface conditions in rice field under AWD technique

c) Greenhouse gas emissions during rice planting

Greenhouse gas emissions are caused by fuel used (diesel) by rice planting machines. The amount of greenhouse gas emission from rice cultivation under conventional is lower than that under AWD technique (5 kg CO_2e/ha compared to 17-35 kg CO_2e/ha). Greenhouse gas emission depended on the type of fuel used and type of rice planting machine. Under conventional technique rice was planted by labor rather than using rice planting machine only. Labor was used for rice planting instead of rice planting machine in Prachin Buri under both CF and AWD condition and Nakhon Sawan under CF condition. Therefore, Greenhouse gas emission of rice planting in this province was 0 kg CO_2e (Table 4.6).

Table 4.6 Greenhouse gas emissions during rice planting

Parameters	**Nakhon Sawan**		**Chai Nat**		**Prachin Buri**	
	CF (n=30)	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**
Rice plantation (kg CO_2e/ha)	0.00	17.44	4.88	35.08	0.00	0.00

CF= continuous flooding (conventional technique), AWD = alternate wetting and drying

4.2.3 Fertilizer application

a) Local cultivation practices

In this study, farmers under conventional and AWD techniques used fertilizers with different proportions of nitrogen (N): phosphorus (P): potassium (K). Farmers in Nakhon Sawan and Chai Nat always use fertilizer 46-0-0, 16-20-0, and 15-15-15. In Prachin Buri, farmers use fertilizer 46-0-0 and 16-20-0 (Figure 4.5). Fertilizer is used two to three times/crop.

Figure 4.5 Chemical fertilizer used by farmer in Nakorn Sawan, Chai Nat, and Prachin Buri

First, fertilizer was applied when rice plants were 5-7 days, which is called “basal fertilization”. Then, fertilizer was used again during tillering which was usually about 25-30 days. The last fertilizer application in the planting cycle was applied at panicle initiation stage (55-60 days).

Farmers under the conventional technique usually used chemical fertilizers rather than organic fertilizers. Approximately 120-188 kg/ha of granular fertilizer is applied into the soil (Table 4.7). During the period of land preparation, farmers under AWD technique applied organic fertilizer about 156 kg/ha of compost (from pig and cow manure) into the rice filed to improve soil fertility.

Figure 4.6 Granular fertilizers from pig manure

In addition, the bio-extract fertilizers used in the rice fields by some farmers were produced from leftovers of daily life (fish, golden apple snail, vegetable, and fruit) by fermenting with molasses and biocatalyst Super LDD.1, with water in the tank at 6.25: 20 L/ha (Figure 4.7).

Figure 4.7 Bio-extract fertilizers prepared by local farmers

Crotalaria juncea L. is an important plant for green manure. It improves the soil and soil fertility because it adds nutrients and organic matters in the soils. *Crotalaria juncea* L. is usually planted before rice planting once a year or once every four years. The quantity of *Crotalaria juncea* L. seed used was 31 kg/ha (5 kg/rai). Farmers can plant *Crotalaria juncea* L. under conventional and AWD techniques (shown in Figure 4.8).

Figure 4.8 Planting and incorporating *Crotalaria juncea* L. into rice field soil before cultivation in Nakorn Sawan (Tang-sub, 2015)

b) The expenses of fertilizers

The use of fertilizers can be varied depending on the farmer's technique and cash availability. For AWD technique, farmers often used organic manure combined with chemical fertilizer to reduce the cost of chemical fertilizers. The amount, rate, and labor requirements and cost for fertilizer applications under CF and AWD condition shown in Table 4.7.

Under conventional technique

- The application of fertilizer was usually 1 day and about 2-3 times/crop.

- The expense of chemical fertilizer was 4,818-5,664 THB/ha.

- The labor was used for 6 hr/day by 3-5 workers. The labor cost for fertilizer application was 1,000-1,250 THB/ha, while the number of labor depended on each area.

Under AWD technique

- The application of fertilizer was 1 day and this was applied about 2-3 times/crop.

- The expense on compost, bio-extract fertilizer, and *Crotalaria juncea* L. was 750 THB/ha, 188 THB/ha, and 125 THB/ha, respectively. *Crotalaria juncea* L. was plowed at the time with land preparation (Figure 4.8).

- The expense of chemical fertilizer was 2,490-4,010 THB/ha. Thus, AWD condition can reduce the expense of chemical fertilizer by 16.8-52.2%

- The labor was used for 6 hr/day by 1-2 workers. The labor for fertilizer application was 500 THB/ha.

Table 4.7 The amount, rate, and labor requirements and costs for fertilizer applications under CF and AWD conditions

Parameters	**Nakhon Sawan**		**Chai Nat**		**Prachin Buri**	
	CF (n=30)	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**
The amount of chemical fertilizer (kg/ ha)	179	82	153	94	169	156
Costs of chemical fertilizer (THB/ha)	5,664	2,709	5,016	2,490	4,818	4,010
Labor (person)	2	2	2	2	2	2
The amount of organic fertilizer (kg/ ha)	0	156	0	156	0	0
Costs of organic fertilizer (THB/ha)	0	750	0	750	0	0
Labor (person)	2	2	2	2	2	2
The amount of green manure (kg/ ha)	0	31	0	31	0	0
Costs of green manure (THB/ha)	0	125	0	125	0	0
Labor (person)	2	2	2	2	2	2
Cost of labor (THB/ha)	1,000	500	1,250	500	1,000	500

CF= continuous flooding (conventional technique), AWD = alternate wetting and drying

c) Greenhouse gas emissions from fertilizer

Fertilizer was an important factor leading to greenhouse gas emissions. The use of fertilizer in Nakhon Sawan, Chai Nat, and Prachin Buri emitted 10,472, 9,386, and 6,408 kg CO_2e/ha under conventional technique and 2,182, 5,207, and 4,157 kg CO_2e/ha under

AWD technique, respectively (Table 4.8). Thus, AWD technique could reduce greenhouse gas emission up to 35-79%.

Table 4.8 Greenhouse gas emissions from the use of fertilizer

Parameters	Nakhon Sawan		Chai Nat		Prachin Buri	
	CF (n=30)	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**
Rice growth (kg CO_2e/ha)	10,472.40	2,181.79	9,386.00	5,206.93	6,407.60	4,156.83

CF= continuous flooding (conventional technique), AWD = alternate wetting and drying

4.2.4 Weed and pest management

In all rice fields, there are many problems about pests, weeds, and diseases that subsequently reduce rice yields. Farmers need to know how to manage rice fields effectively. They have to know about type of pests in their rice fields, pesticide availability in the market, pest monitoring, and pest management.

1) Weed management

a) Local cultivation practices

Air and soil ground composition influences the amount of grass weeds and broadleaf in rice fields. Farmers use herbicide to control weeds in the rice fields. The use of herbicide depends on cultivation management. Herbicide was always used in conventional fields in which farmer applied two to three times/crop. Farmers mixed herbicide with water in the tank at 200: 1000 mL and spray on rice plants and weeds.

However, under AWD technique, some farmers used Azolla in rice fields in Nakhon Sawan and Chai Nat to cover the soil for weed control (Figure 4.9). This Azolla also provides the habitats of blue-green algae that can fix atmospheric nitrogen and transform to the form rice plant can use (ammonium). When water dropped in rice fields, Azolla thus is decomposed and provided nitrogen nutrient to rice plant. It could also reduce the use of fertilizer and costs.

Figure 4.9 Azolla in rice fields

One of the main problems for farmers is “weedy rice”. In Nakhon Sawan, Chai Nat, and Prachin Buri, famers under conventional and AWD techniques are concerned about weedy rice because it leads to low yields and loss of income. Weedy rice is caused by cross pollinations between wild rice commonly found in nature and planted rice. This hybrid rice, rapidly spread in the rice filed is resulted in damaged kernels production and rice will fall before harvest (Figure 4.10). As a result farmers have to deal with the problem by weeding, which increase expense for investment.

Figure 4.10 Damaged kernels and undeveloped kernels by weedy rice (IRRI, 2009).

b) The expenses of weed management

Under conventional technique

- The duration of weed control was 1 day and about 2-3 times/crop.
- The expense of herbicide was 905-1,409 THB/ha.
- The labor was used for 6 hr/day by 2-5 workers with costs of 455-1,646 THB/ha (shown in Table 4.9).

Under AWD technique

- The duration of weed control was 1 day and about 2-3 times/crop.
- The expense of herbicide was 568-913 THB/ha.
- The labor was used for 6 hr/day by 1-3 workers with costs of 375-912 THB/ha.
- The expense associated with the use of Azolla was 28,125 THB/ha, based on the fact that 1 kg of Azolla was 180 THB. The rotary weeder is an important tool to manage weed. The investment cost was 1,500 THB/piece. AWD technique used rotary weeder to reduce the use of herbicide.

Table 4.9 Use and costs of herbicide

Parameters	**Nakhon Sawan**		**Chai Nat**		**Prachin Buri**	
	CF (n=30)	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**
Herbicide (L/ha)	63	32	63	32	63	38
*Costs of herbicide (THB/ha)	918	568	905	839	1,409	913
Labor (person)	2	1	2	1	2	1
Cost of labor (THB/ha)	1,008	375	1,646	912	455	375

CF= continuous flooding (conventional technique), AWD = alternate wetting and drying

2) Insect

a) Local cultivation practices

Species of insects in the rice fields vary in each area due to weather conditions, soils, and pest management techniques that are used. Insect consists of rice insect pests, insect pests, and beneficial insects. Rice insect pests include rice stem borer, leafhopper, plant hopper, rice black bug, rice mealy bug, army worm and rice grasshopper. Generally, insecticide is used one to three times/crop. Farmers used insecticide by mixing with water at the proportion of 200:1000 mL in a tank. The use of insecticide was 80% of the number of farmers interviewed. This can be said that insecticide use is common among farmers.

Figure 4.11 Beauveria bassiasna used for insect control in rice fields

Under the AWD technique, farmers in Nakhon Sawan and Chai Nat often used biotechnology (such as *Trichogramma confusum*) to kill and control insects and pests. As the temperature of rice stubble varies depending on water dropped, the rice receives more oxygen. Rice plants have strong head rice and insects cannot live in rice fields.

In addition, some farmers used *Beauveria bassiasna* to protect insect pests by mixing with 20 L of water per 1 kg of *Beauveria bassiasna* (Figure 4.11). Farmers often spray *Beauveria bassiasna* in rice fields at high moisture because insects and pests favor the high humidity (Figure 4.12). The biotechnolygy and *Beauveria bassiasna* under AWD technique can reduce insecticide costs more than the conventional technique.

Figure 4.12 Farmers spraying pesticide and herbicide in rice fields in Chai Nat (Ruenpakdan, 2015)

b) The expenses of pest management

Under conventional technique

- The duration of pest management was 1 day and about 2-3 times/crop.
- The expense of pesticide was 1,093-2,490 THB/ha.
- The labor was used for 6 hr/day by 2-4 workers with the cost of 625-1,250 THB/ha.

Under AWD technique

- The duration of pest management was 1 day and about 2-3 times/crop.
- The expense of pesticide was 567-791 THB/ha.
- The labor was used for 6 hr/day by 1-2 workers with the cost of 625 THB/ha.
- The maintenance of equipment was 500-1,000 THB/year.
- The expense of *Beauveria bassiasna* was 28,125 THB/ha.

Table 4.10 Use and costs of pesticide

Parameters	Nakhon Sawan		Chai Nat		Prachin Buri	
	CF (n=30)	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**
Pesticide (L/ha)	94	50	75	38	63	38
Labor (person)	2	2	4	2	3	2
*Costs of pesticide (THB/ha)	1,093	681	2,399	791	2,490	567
Costs of organic pesticide (THB/ha)	0	180	0	180	0	0
Costs of labor (THB/ha)	625	625	1,250	625	1,250	625

CF= continuous flooding (conventional technique), AWD = alternate wetting and drying

*According to Table 4.9 and 4.10, although average farmers in all three provinces used the amount of pesticide and herbicides, the costs in each province were different. The cost depended on farmers' preference. Some farmer used relatively costly chemical pesticide and applied excess amount of them, while others adapted for more affordable organic pesticide or useful insect. In terms of labor cost in all three provinces the costs of pesticide application under AWD condition were similar to CF condition that depended on farmers.

4.2.5 Irrigation

a) Local cultivation practices

Irrigation is a major step of rice planting. Each location requires a different amount of water, which depends on the type of soil. Ineffective soil management can significantly increase cost of production. Compared to irrigated rice fields, non-irrigated fields requires cost as farmers have to pay high water and electricity bills from pumping water into the rice field. On average, water expense on rice plantation under AWD is lower than that under conventional technique (1,012 THB/ha compared with 1,718 THB/ha).

Figure 4.13 Pumping water into rice field in Chai Nat (Ruenpakdan, 2015)

According to the field surveys in Nakhon Sawan, it was found that rice cultivation under AWD consumed 15,625 m^3/ha of water, whereas under the conventional technique, the water consumption was 20,250 m^3/ha. Thus applying AWD was resulted in water consumption reduction by 22.8%. In Chai Nat under AWD, water consumption was 15,523 m^3/ha, while under the conventional technique it was 20,625 m^3/ha. Water consumption is reduced by 24.7%. In addition, Prachin Buri, water consumption under AWD was 12,084 m^3/ha and 8,525 m^3/ha under conventional technique. Water consumption was decreased by 29.5% in this case. Thus, AWD requires less water, compared to conventional cultivation method (Table 4.11).

b) The expenses of irrigation

Under conventional technique

- The duration of irrigation was 1-4 days. When the water level dropped, farmers put water in rice fields. So, farmers put water in rice fields several times/crop. It depends on rice field area.

- The expense of irrigation was 2,113-2,718 THB/ha.

- In the irrigation process, farmers did not hire the labor because the farmers controlled the water by themselves.

- The use of fuel (diesel and gasoline) was 6-44 L/ha. The type and cost of fuel varied depending on what kind of tractors the farmers used. For the total cost of irrigation process, some farmer paid electricity bills about 1,250 THB/ha.

Under AWD technique

- The duration of irrigation was 1-4 days and about 2-3 times/crop.

- The expense of irrigation was 1,250-1,600 THB/ha.

- In the irrigation process, farmers did not hire labor because the farmers controlled the water by themselves.

- The use of fuel (diesel and gasoline) was 6-44 L/ha. The type and cost of fuel varied depending on what kind of tractors the farmers used. For the total cost of irrigation process, some farmer paid electricity bills about 1,250 THB/ha.

Thus, the investment cost of pumping machines under conventional and AWD technique was 8,800-20,000 THB. The lifetime of pumping machine was approximately 10-20 years. The maintenance costs were 1,000-2,000 THB/year.

Table 4.11 Water consumption under CF and AWD technique

Parameter	Nakhon Sawan		Chai Nat		Prachin Buri	
	CF (n=30)	AWD (n=30)	CF (n=30)	AWD (n=30)	CF (n=30)	AWD (n=30)
Period of rice planting (days)	1-4	1-4	1-4	1-4	1-4	1-4
Labor (person)	1	1	1	1	1	1
Water consumption (m^3/ha)	20,250	15,625	20,625	15,523	12,085	8,525
Fuel of pumping (L/ha)	6	6	19-44	19-44	19	19
Irrigation (THB/ha)	2,400	1,250	2,113	1,600	2,718	1,250

CF= continuous flooding (conventional technique), AWD = alternate wetting and drying

c) Greenhouse gas emissions of irrigation

Greenhouse gas emissions came from fuel used (diesel and gasoline) by pumping. This process was 10.56-127.24 kg CO_2e/ha under conventional technique and 0.98-102.46 kg CO_2e/ha under AWD technique (Table 4.12). Greenhouse gas emissions depended on type of fuel used, amount of fuel, and type of pumping. Some farmers put water into rice fields by direct water flowing from river/canal, so greenhouse gas from pumping is emitted less. On the other hand, some area was upland area, farmer needed to put water by pumping, which led to higher greenhouse gas emissions from fuel used.

Table 4.12 Greenhouse gas emissions from irrigation

Parameters	Nakhon Sawan		Chai Nat		Prachin Buri	
	CF (n=30)	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**
Irrigation (kg CO_2e/ha)	127.24	0.98	10.56	102.46	25.65	14.62

CF= continuous flooding (conventional technique), AWD = alternate wetting and drying

4.2.6 Rice harvest

a) Local cultivation practices

The harvest day of rice is different depending on the rice varieties. In Nakhon Sawan and Chai Nat, there are many types of rice varieties used by farmers including RD29, RD31, RD41, RD49 and Pathum Thani 1. All of these have the harvest time of 95-120 days. Farmers in Prachin Buri usually plant RD29, RD41, RD49, RD51, and Khao Bahn Nah 432, with the harvest time of 95-120 days. This is with exception for a rice variety Khao Bahn Nah 432 (deep water rice) that has a growing period of 240 days. Most farmers often harvest rice crop at 25-30% of kernel moisture by a combine harvester. Then, the farmers combine the grain into the cart, which is transported dry before selling.

Figure 4.14 Rice harvesting in Nakhon Sawan (Tang-sub, 2015)

Transportation, drying and storage

Normally, most farmers under AWD condition can sell rice grain after harvesting promptly. Kernels that are well-developed are kept for seeding because of the high quality of rice grain. After harvest, the grains were dried to decrease the moisture content, because moisture affects the quality of rice grain. Rice grains should be dried within 24 hrs or as soon as possible to reduce moisture. As a result, completely dry grain can be stored for a period of time. Although some farmers have to pay more for transportation and the drying process, this practice can help improve the quality of rice grain, and consequently increase selling price. In this study, most farmers sold green rice kernel after harvesting.

b) The expense of harvesting

Under conventional and AWD techniques

- The duration was 1 day.
- The expense of harvesting machinery was 3,125 THB/ha.
- The labor was used for 6 hr/day by 2 workers.
- The use of fuel (diesel) was 13-31 L/ha (Table 4.13). The type and cost of fuel varied depending on what kind of tractor farmers used. The costs of fuel used and labor were combined with harvesting machinery.
- The total costs were 3,125 THB/ha and 6,250-18,750 THB/year.

Thus, the investment cost of harvesting machinery was 350,000-750,000 THB. The lifetime of farm tractor was approximately 5-10 years. The maintenance costs were 1,000-10,000 THB/year.

Table 4.13 Machinery and equipment costs for rice plantation

Parameter	**Nakhon Sawan**		**Chai Nat**		**Prachin Buri**	
	CF (n=30)	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**
Labor (person)	2	2	2	2	2	2
Fuel consumption (L/ha)	25	25	13-31	13-31	19	19
Harvesting (THB/ha)	3,125	3,125	3,113	3,394	3,125	3,125

CF= continuous flooding (conventional technique), AWD = alternate wetting and drying

c) Greenhouse gas emissions during harvesting

Greenhouse gas emissions came from fuel used (diesel) by farm tractor combustion. This process was 17-81 kg CO_2e/ha under conventional technique and 48-68 kg CO_2e/ha under AWD technique (Table 4.14). Greenhouse gas emission depended on type of fuel used and amount of fuel used.

Table 4.14 Greenhouse gas emission during harvest

Parameters	**Nakhon Sawan**		**Chai Nat**		**Prachin Buri**	
	CF (n=30)	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**
Harvesting (kg CO_2e/ha)	16.89	67.56	80.91	48.13	49.16	51.87

CF= continuous flooding (conventional technique), AWD = alternate wetting and drying

4.2.7 Grain yield

a) Local cultivation practices

In all three provinces, AWD technique helped enhance rice yield with an average amount of 5.2-6 ton/ha. By contrast, farmers who adopted conventional technique, the yields were somehow lower than that of to the AWD technique, average yields 3.8-5.2 ton/ha (Table 4.15). However, conventional technique was invested more than AWD technique. Additionally, the moisture in green rice kernels harvested in rice fields with AWD was significantly lower than those kernels with conventional method (18-20% compared to 24-28%) (Figure 4.15). AWD reduces the moisture in green rice kernels, as water dropped below the surface soils. This usually led to higher selling price and more profit.

Figure 4.15 Mature rice ready for harvest (Tang-sub, 2015)

Table 4.15 Rice yields

Parameter	Nakhon Sawan		Chai Nat		Prachin Buri	
	CF (n=30)	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**
Yield (ton/ha)	3.76±1.10	6.07±0.98	5.19±0.51	5.74±0.41	4.96±0.45	5.28±0.96

CF= continuous flooding (conventional technique), AWD = alternate wetting and drying

b) Grain selling price

The average income of yields was sold by 6,000-6,300 THB/ton. The revenue of yields depended on the demand market. Although farmers used a different technique, but farmers faced the selling price as same. Therefore, AWD technique could help to reduce production costs as mentioned above.

4.2.8 Land rental fee

From the interviews, it was found that the majority (52.2%) of rice cultivated land was rented. The average rental fees are in the range of 6,250-12,500 THB/ha. The different costs of conventional and AWD technique depended on each area of rice plantation such as water resource availability, transportation mode, upland and lowland conditions.

4.2.9 Straw management

a) Local cultivation practices

Generally, after harvest, there are many options to manage straw and stubble, including (1) straw burning, (2) chopping and removing, and (3) fallowing. In this study, it was found that all straw in rice fields was burned in conventional rice fields, because farmers can prepare the land for the next planting in a timely manner.

However, this resulted in soil degradation, and therefore, a large amount of fertilizer was required. In this study, farmers who used AWD technique adopted different straw management. About 50-75% of straw together with stubble was burned in the field (Figure 4.16) and the rest were removed to sell to animal food manufacture, others fallow all straw.

Figure 4.16 Burning straw in rice field (Dailynew, 2014)

During the straw fermentation process, straw and stubble were chopped and disked. Water was baled for straw fermentation. Farmers also used bio-extract to help straw decomposition, which reduced the time to decompose straw (Figure 4.17). The benefits of straw fallowing are that it increases organic matters in the soils and reduces the use of fertilizer and herbicides. In addition, when water dries up, it causes more weeds. Weeds are destroyed during disking and rolling straw and stubble. AWD can help reduce straw burning, which is a main cause of pollutant and greenhouse gas emissions. However, in this study, the cost of straw management was so low that it was not included in an investment cost.

Figure 4.17 Straw fermentation in the rice field by using bio-extract (Ruenpakdan, 2015)

b) The expense of straw fermentation

The expense of straw fermentation was combined with land preparation

c) Greenhouse gas emissions of straw management

Greenhouse gas emissions came from residue burning. This process was 232-297 kg CO_2e/ha under conventional technique and 261-289 kg CO_2e/ha under AWD technique (Table 4.16). Greenhouse gas emission depended on size of area.

Table 4.16 Greenhouse gas emissions of straw management

Parameters	**Nakhon Sawan**		**Chai Nat**		**Prachin Buri**	
	CF (n=30)	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**
Residue burning (kg CO_2e/ha)	297.00	260.60	231.93	289.09	280.35	275.20

CF= continuous flooding (conventional technique), AWD = alternate wetting and drying

4.3 Mitigation of greenhouse gas emissions and cost-savings

There were several important processes during rice production that affected both the emissions of greenhouse gases and cost as illustrated in Figure 4.18. The main rice production contained land preparation, rice plantation, use of fertilizer, water pumping, rice harvesting, and straw management. All processes had input and the expense of rice production different depending on the technique used. Normally, labor and fuel used were the basic input of rice production. The first cultivation process as land preparation costs were about 3,125 THB/ha under CF and AWD condition. This process led to greenhouse gas emissions about 25-61 kg CO_2e/ha and 32-89 kg CO_2e/ha under CF and AWD conditions, respectively. Although more greenhouse gas was emitted under AWD condition, but the expenses of AWD was lower than CF condition. Additionally, both uses of fertilizer and water pumping under CF condition, the expense were higher as well as greenhouse gas emission (from 11-127 to 0.98-102 kg CO_2e/ha). Rice was always harvested by combine harvester; the average expense was 3,125 THB/ha under CF and AWD condition. In term of greenhouse gas emissions during harvest, it depended on fuel used and harvested areas. AWD could emit greenhouse gas more because of high yields and large harvested area. Lastly, straw management could release greenhouse gas by straw burning. Under CF and AWD condition, most farmers still burned straw in rice filed, as it required shorter period for soil preparation. Greenhouse gas emission was about 260-289 kg CO_2e/ha. AWD technique also reduced cost of rice production and greenhouse gas emission.

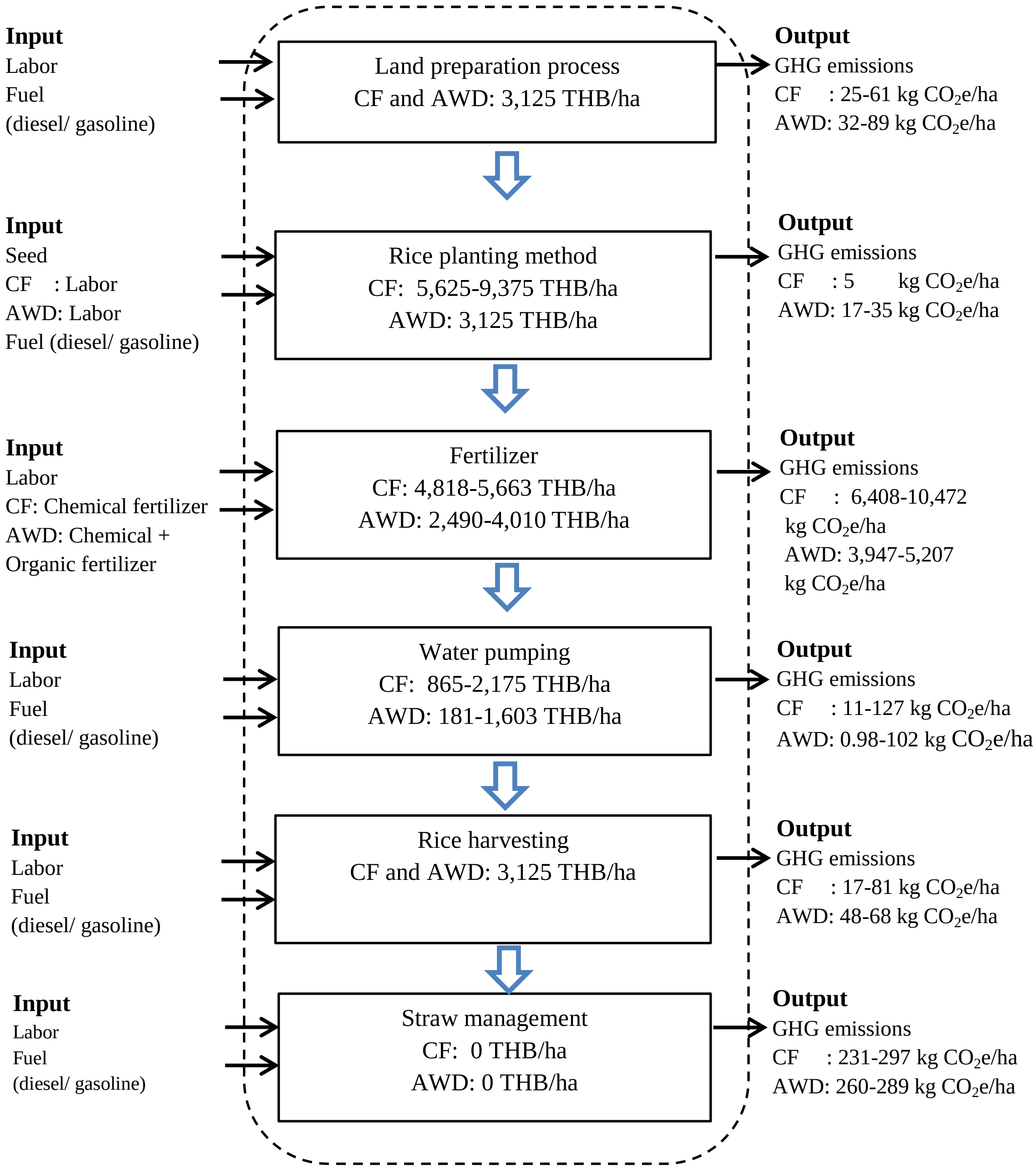


Figure 4.18 The process of rice cultivation

4.3.1 Rice cultivation cost-savings

From the results described above, the mitigation cost when AWD was applied was estimated. Under the conventional cultivation, the main variable costs came from machinery, fertilizer, irrigation and labor. These accounted for 33.71%, 15.69%, 14.85%, and 14.25% of total investment respectively. Under the AWD condition, the main variable costs consisted of machinery (45.35%), fertilizer (13.57%), labor (11.99%), irrigation

(11.01%), seed (6.59%), land rent (4.47%), herbicide (3.42%), pesticide (3.01%) and manure (0.59%) (Table 4.17).

The average costs associated with rice cultivation were estimated as 32,495-43,232 THB/ha and 27,355-33,317 THB/ha for conventional and AWD conditions, respectively. Thus, greenhouse gas emission reduction as mentioned above, the application of AWD could also reduce the overall costs of rice cultivation. The main cost reduction was a result of factors associated with water management, namely, fuel, electricity costs for water pumping and irrigation. Based on the data presented in Table 4.19, the cost for greenhouse gas mitigation by using AWD was then estimated as 1,371-5,124 THB/tonCO_2e.

Under the conventional technique, the expense of rice cultivation was 36,513THB/ha in Nakhon Sawan, 43,232 THB/ha in Chai Nat, and 32,495 THB/ha in Prachin Buri. On the other hand, the expense of rice cultivation under AWD technique was 27,841 THB/ha in Nakhon Sawan, 33,317 THB/ha in Chai Nat, and 27,355 THB/ha in Prachin Buri. AWD technique which can reduce cost up to 16-23%, cost-savings in Nakhon Sawan, Chai Nat and Prachin Buri were -8,672 THB/ha, -9,915 THB/ha, and -5,139 THB/ha respectively. The negative costs indicate that AWD could spend less or save more money when compared to the conventional technique.

Table 4.17 Rice cultivation cost of CF and AWD techniques

Cost item	**Averaged variable costs (THB/ha)**					
	Nakhon Sawan		**Chai Nat**		**Prachin Buri**	
	CF (n=30)	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**
Seed	2,466.73	1,365.71	2,231.25	1,378.38	2,171.88	1,729.17
Manures	0.00	142.56	0.00	109.82	0.00	149.01
Fertilizers	5,663.89	2,708.69	5,015.63	2,490.42	4,817.94	4,009.72
Pesticides	1,092.94	681.43	2,398.54	791.39	2,490.34	566.67
Herbicides	917.54	567.50	905.00	839.02	1,409.09	912.7
Irrigation	2,175.00	1,250.00	2,114.58	1,603.38	865.06	181.25
Labor	4,556.45	1,689.29	7,118.75	4,668.92	2,404.21	1,778.97
Machinery	10,265.32	10,060.71	14,072.92	12,060.81	8,961.16	8,652.78
Land rental	9,375.00	9,375.00	9,375.00	9,375.00	9,375.00	9,375.00
Total	36,512.87	27,840.89	43,231.67	33,317.14	32,494.68	27,355.27

CF= continuous flooding (conventional technique), AWD = alternate wetting and drying

4.3.2 Mitigation of greenhouse gas emissions

Water management is an important factor that influences methane emissions from rice fields. Each province has local cultivation practice and the similar water management approach. In three provinces, under conventional technique, water was continuously flooded without drainage, while under AWD technique, water drainage was applied during flowering period. Water drainage led to decrease methane emission. The data surveyed were used to calculate by the default factor of IPCC 2006 (such as water regimes during the cultivation period, water regimes before the cultivation period, and different types of organic amendment) that the default factor was used to followed by farmers' technique (such as organic fertilizer inputs). Therefore, methane emission from calculation in three provinces did not affect the values when the data were compared with others area.

The study found that under conventional cultivation, the amount of average greenhouse gas emissions in Nakhon Sawan, Chai Nat, and Prachin Buri were 10.95, 9.74 and 6.82 tonCO_2e/ha respectively. On the other hand, under the AWD condition, the emission was reduced to 4.33, 5.72, and 4.59 tonCO_2e/ha, or a reduction of 60.5 %, 41.3 % and 32.7 % respectively (Table 4.19).

Table 4.18 Greenhouse gas emissions by processes

Parameters (kg CO_2e/ha)	**Nakhon Sawan**		**Chai Nat**		**Prachin Buri**	
	CF (n=30)	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**
Tillage by machine	33.78	33.70	25.38	37.04	61.47	89.1
Rice plantation	0.00	17.44	4.88	35.08	0.00	0.00
Rice growth	10,472.40	3,947.40	9,386.00	5,206.93	6,407.60	4,156.83
Irrigation	127.24	0.98	10.56	102.46	25.65	14.62
Harvest	16.89	67.56	80.91	48.13	49.16	51.87
Residue burning	297.00	260.60	231.93	289.09	280.35	275.2
Total emission	10,947.31	4,327.67	9,739.67	5,718.72	6,824.22	4,587.63

CF= continuous flooding (conventional technique), AWD = alternate wetting and drying

Greenhouse gas was also emitted from various steps of rice cultivation, including greenhouse gas emissions during rice growing (94.50%), fossil fuel used during land preparation and harvest (0.02%), and rice straw burning (5.48%) (Table 4.18). The reduction of greenhouse gas emissions was mainly a result of AWD implementation. When estimated based on grain yield, greenhouse gas emissions were 2.91, 1.87, and 1.38

$tonCO_2e$/ton grain yields in Nakhon Sawan, Chai Nat, and Prachin Buri under conventional technique and 0.71, 1.00, and 0.87 $tonCO_2e$/ton grain yield for AWD conditions respectively.

Table 4.19 Summary data of CF and AWD techniques

Parameters	Nakhon Sawan		Chai Nat		Prachin Buri	
	CF (n=30)	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**	**CF (n=30)**	**AWD (n=30)**
Yield (ton/ha)	3.76±1.10	6.07±0.98	5.19±0.51	5.74±0.41	4.96±0.45	5.28±0.96
GHG emissions ($tonCO_2e$/ ha)	10.95±0.79	4.33±0.77	9.74±1.16	5.72±0.44	6.82±1.77	4.59±1.09
GHG emissions per unit yield ($tonCO_2e$/ ton grain yields)	2.91±1.24	0.71±0.32	1.87±0.31	1.00±0.12	1.38±0.84	0.87±0.25
Rice cultivation costs (THB/ha)	36,513±9,395	27,841±4,493	43,232±9,408	33,317±9,707	32,495±5,463	27,355±3,275
Costs per unit yield (THB/ton grain)	9,711±4,718	4,587±4,190	8,330±2,070	5,804±750	6,551±1,330	5,181.±564
Cost-saving (THB/ha)	-	-8,672	-	-9,915	-	-5,139
Cost-saving per unit greenhouse gas (THB/ $tonCO_2e$)	-	-5,124	-	-2,526	-	-1,371

CF= continuous flooding (conventional technique), AWD = alternate wetting and drying

The results mentioned above show that the application of AWD offered benefits to farmers in terms of reducing cultivation costs, increasing rice yield, and at the same time, it also contributed to greenhouse gas mitigation. From field surveys and the interviews of the farmers who adopted this technique, it is clear that the farmers themselves recognize these benefits (except for greenhouse gas emission reduction). They mentioned that AWD can reduce the use of rice seeds, water use, fertilizer, pesticide, and labor. For the effects on plant performance, they claimed that AWD could increase rice yields, rice growth, and profits. In the study conducted by Nalley et al. (2014), AWD technique can reduce fuel and cost of irrigation when compared with that continuous flooding. AWD also saves water usage up to 70%, and increases rice yield up to 8.2-30%.

The largest benefit of AWD can be reached if farmers are able to adopt this technique effectively in their planting. From the interviews, it was also found that farmers who adopted AWD have special characteristics with regards to field managements as follows; 1) farmers need not to go their fields more often because the precise control of water level is required and managed in rice fields, 2) farmers can transplant rice seedlings using machines instead of labor, 3) farmer can reduce the amount of seed for planting, fertilizer and water consumptions, and 4) lastly, while water is dropped below the surface soil, farmers could walk into their fields, rendering it easy and convenient to access work, and deal with problems in rice fields immediately.

Providing education to farmers through farmer network groups is one way farmers can exchange knowledge about rice planting. The Weekend Farmers' holiday including farmer in Nakhon Sawan and Chai Nat is a good example of successful network. Apparently, farmers in Nakhon Sawan have cooperated in the exchange of experiences among each farmer that led to a group of farmers to manage their rice fields. Farmer could reduce the rice cultivation costs and increase productivity. AWD technique also helps reduce the use of chemicals on health, reduce the cost of farming, and can also reduce emissions of methane from rice fields as well. It is a good choice for farmers.

CHAPTER 5

CONCLUSION

Globally, one of the major concerns today is increasing concentrations of atmospheric greenhouse gases and the impact on environment and climate change. Methane is the second most important greenhouse gas after carbon dioxide. Human activities can cause methane emissions through various activities including rice plantation. AWD technique is used to reduce methane emission from rice fields but the cost associated with adopting AWD and the cost-saving is largely unknown in Thailand.

This study focuses on comparisons of costs and greenhouse gas emissions between conventional and AWD techniques from rice fields. The main objectives include evaluating the potential of AWD techniques to reduce greenhouse gas emission from rice fields and the cost-saving. To fulfill these objectives, necessary data were collected through field surveys and farmers interviews in Nakorn Sawan, Chai Nat and Prachin Buri in 2014. Totally, 180 farmers were interviewed. Methane emissions were not measured in the fields directly but estimated according to Tier 2 IPCC 2006 guideline methodology.

5.1 Cost of conventional and AWD technique

Choosing an effective mitigation technique is very important because each technique is different in its potential to reduce greenhouse gas emissions from rice fields. Increasing yields and low rice cultivation costs are the keys to the adoption of mitigation techniques by farmers. This study found that in conventional conditions, rice yields was lower compared to AWD condition. The rice yields in conventional condition were 3.76-5.19 ton/ha, while AWD of rice yields were 5.28-6.07 ton/ha. Both conventional technique and AWD technique require similar processes including land preparation, planting, water management (pumping), harvesting, straw management, use of fertilizer, pesticide, herbicide, labor and equipment maintenance.

Estimating costs of rice cultivation included:

- Use of seed under conventional conditions was 2,172-2,467 THB/ha, while AWD conditions was 1,366-1,729 THB/ha. AWD can reduce 20-45% of use of seed.

- Use of fertilizer under conventional conditions was 4,818-5,664 THB/ha, while AWD conditions was 2,490-4,010 THB/ha. AWD can reduce 17-52% of use of fertilizer.

- Use of pesticide under conventional conditions was 1,093-2,490 THB/ha, while AWD conditions was 567-791 THB/ha. AWD can reduce 38-77% of use of pesticide.

- Use of herbicide under conventional conditions was 905-1,409 THB/ha, while AWD conditions was 568-913 THB/ha. AWD can reduce 7-38% of use of herbicide.

- Use of irrigation under conventional conditions was 865-2,175 THB/ha but AWD conditions was 182-1,603 THB/ha. AWD can reduce 24-43% of use of irrigation.

- Use of labor under conventional conditions was 2,404-7,119 THB/ha but AWD conditions was 1,689-4,669 THB/ha. AWD can reduce 26-63% of use of labor.

In term of cost per unit yield under conventional and AWD technique were 6,551-9,711 THB/ton grain and 4,587-5,181 THB/ton grain, respectively. AWD can reduce cost per unit yield by about 53% in Nakhon Sawan, 30% in Chai Nat, and 21% in Prachin Buri.

Under conventional conditions, the expense of rice cultivation was 36,513 THB/ha in Nakhon Sawan, 43,232 THB/ha in Chai Nat, and 32,495 THB/ha in Prachin Buri. On the other hand, the expense of rice cultivation under AWD technique was 27,841 THB/ha in Nakhon Sawan, 33,317 THB/ha in Chai Nat, and 27,355 THB/ha in Prachin Buri. AWD technique which can reduce cost up to 16-23%, cost-savings in Nakhon Sawan, Chai Nat and Prachin Buri were -8,672 THB/ha, -9,915 THB/ha, and -5,139 THB/ha respectively. The negative costs indicate that AWD invests less when compared to the conventional technique.

The potential cost-saving was a significant factor depending on the use of seeds, fertilizers, herbicides, pesticides, water consumption, and labor. Together with other benefits such as more rice yield and less water consumption, therefore AWD has the potential to mitigate methane emission in rice field without negative effects on rice production in general.

5.2 Greenhouse gas emissions from rice fields

Farmers in Nakhon Sawan, Chai Nat, and Prachin Buri planted photoperiod insensitive varieties that consist of RD31, RD41, RD49, RD51, Pathum Thani 1, and Khao Bahn Nah 432. The period of rice growing cycles varies depending on varieties, and in this case this was between 95 and 240 days. This study found that greenhouse gases are emitted from rice fields under the conventional technique more than the AWD technique. The amount of greenhouse gas from rice field under conventional technique in Nakhon Sawan, Chai Nat and Prachin Buri were 10.95, 9.74 and 6.82 tonCO_2e/ha, respectively. The amount of greenhouse gas from rice field under AWD technique was 4.33, 5.72, and 4.59 tonCO_2e/ha in Nakhon Sawan, Chai Nat and Prachin Buri, respectively. It can be seen that AWD technique can reduce methane emissions in rice fields by 32-60%.

In addition, greenhouse gas emissions per unit yields under conventional and AWD techniques were 1.38-2.91 tonCO_2e/ton grain yields and 0.71-1 tonCO_2e/ton grain yields, respectively. Thus, AWD can reduce greenhouse gas emission per unit yields in Nakhon Sawan, Chai Nat, and Prachin Buri by 75%, 47% and 36%, respectively. Therefore, cost-saving per greenhouse gas emission, AWD can reduce -5,124 THB/tonCO_2e in Nakhon Sawan, -2,526 THB/tonCO_2e in Chai Nat, and -1,371 THB/ tonCO_2e in Prachin Buri.

In summary, this study estimated the cost-savings of greenhouse gas emissions under AWD technique at farmer's farm level and compared that cost with that of the conventional cultivation method. The study areas were in Nakhon Sawan, Chai Nat, Prachin Buri Provinces in Thailand. The results indicate that the use of AWD technique can create benefits to farmers by reducing cultivation costs, reducing greenhouse gas emissions and increasing grain yield when compared to the conventional ways of rice cultivation. This study clearly represents economic and environmental benefits of AWD.

5.3 Recommendations

The costs of rice cultivation vary from area to area depending on geographical features of each area. So, to further investigate the contributing factors to cost variation, it is recommended that study about the expenses of rice cultivation under AWD in other provinces in Thailand should be conducted. The information regarding AWD technique in different areas will be a great benefit to cost reduction.

According to the results found in this study, it can be said that in Thailand, farmers had to deal with many problems such as expensive fertilizers, pesticides and herbicides, as well as high labor wages. Although they applied the same amounts of those chemicals, but the prices in each province were different. It led to cost variation in rice production under conventional technique and even increased cost of rice production in some areas. On the other hand, under AWD technique, famers used inexpensive organic substances which can be produced by themselves from materials available in their rice fields. Therefore, the government should encourage farmers to adopt AWD to reduce the use of chemical substances and the cost of rice production. This is because AWD technique help reduce the use of chemical fertilizers, herbicides, and pesticides that have been applied excessively. This is also because AWD technique is more environmentally friendly as it reduces greenhouse gas emissions from rice cultivation.

However, AWD technique has not gained popularity, as compared to conventional technique as most farmers in Thailand lack true understanding of the genuine benefits of AWD. They also have limited water sources to manage their rice field. However, even in the irrigated rice field, AWD has not yet widely adopted since most farmers still believe that conventional technique is better than AWD. Besides, more studies on socio-economic aspects under different conditions may be needed to further push towards more adoption of this technique. In addition, promotion and support of the AWD technique by educating farmers as well as providing knowledge technical assistance to farmers may be also useful.

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APPENDIX

APPENDIX A: Cultivation Questionnaire for interviewer

Comparison of cost and greenhouse gas emission from rice fields between conventional and alternate wetting and drying techniques in Thailand

วันที่สัมภาษณ์:____

ผู้สัมภาษณ์:____

A. **ข้อมูลทั่วไป**

A1	ชื่อเกษตรกร:	A2	☐ ชาย ☐ หญิง
A3	อายุ:	A4	เบอร์ติดต่อ:
A5	ที่อยู่/ ที่ตั้งของนาข้าว:		

B. ข้อมูลการปลูกข้าว

B1. รายละเอียดของนาข้าว	
1) พื้นที่การปลูกข้าวทั้งหมด: ☐ เป็นเจ้าของที่ดิน_________ ไร่__________ งาน ☐ เช่าที่ดิน_________ไร่__________ งาน ค่าเช่าที่นา_________บาท/ไร่/ปี	
2) ที่ตั้งของนาข้าว: ☐นอกเขตชลประทาน ☐ เขตชลประทาน ลักษณะภูมิประเทศ ☐นาดอน ☐นาลุ่ม ☐นาน้ำลึก ☐อื่นๆ _________	
3) ลักษณะของดิน: ☐ ดินเหนียว ☐ดินร่วน ☐ ดินทราย ☐อื่นๆ _________	
4) จำนวนรอบของการปลูกข้าว _________ ครั้ง/ปี ช่วงระยะการปลูก: นาปี เริ่มเดือน_________ถึง_________ นาปรัง เริ่มเดือน_________ถึง_________	
B2. ขั้นตอนการเตรียมพื้นที่	
1) ระยะเวลาการเตรียมดิน_________วัน	2) เวลาในการทำงาน_________ ชม./วัน
3) จำนวนการไถ_________ครั้ง	4) จำนวนแรงงาน_________คน ค่าแรงงาน _________บาท/คน/วัน
5) เครื่องมือในการเตรียมพื้นที่ ☐ แรงงานสัตว์ ชนิด _________จำนวน_________ อายุของสัตว์_________ปี ☐ เครื่องจักร ☐ อื่นๆ______________________	

หมายเหตุ:

B3. รายละเอียดการปลูก						
1) พันธุ์ข้าว						
รอบที่	ชื่อชนิดพันธุ์	ชนิดข้าว N= ไวแสง/ P= ไม่ไวแสง	ราคาเมล็ดพันธุ์ (บาท/กก.)	ปริมาณที่ใช้ (กก./ไร่)	ปริมาณที่ใช้ (กก./ไร่)	ระยะเวลาการปลูก (วัน)
1						
2						
3						
4						

2) การปลูก

วิธีการปลูก:

☐ ย้ายกล้าปลูก (ดำนา) ☐ หว่าเมล็ด (เมล็ดแช่)

☐ หว่านเมล็ด (ข้าวเปลือก) ☐โยนกล้า

☐ อื่นๆ__________________

จำนวนวันในการปลูก__________วัน เวลาในการทำงาน ___________ ชม./วัน

จำนวนแรงงาน __________คน ค่าแรงงาน ___________ บาท/คน/วัน

ค่าเช่าเครื่องจักร ___________ บาท/ครั้ง

การเพาะกล้า:

จำนวนวันที่ใช้ในการเพาะกล้า __________ วัน

จำนวนแรงงาน __________ คน ค่าแรงงาน ___________ บาท/คน/วัน

อุปกรณ์ในการเพาะกล้า:

☐ เครื่องจักร ☐ อุปกรณ์อื่นๆ _______________

B4. การจัดการน้ำ

1) แหล่งน้ำที่ใช้ในการทำนา

☐ น้ำฝน ☐ ระบบชลประทาน ☐ บ่อขุด

☐ น้ำบาดาล ☐ แม่น้ำหรือคลองธรรมชาติ ☐ อื่นๆ ____________________

2) จำนวนครั้งที่มีการขังน้ำต่อรอบการผลิต_____________ครั้ง

การปล่อยน้ำเข้าที่นา	การปล่อยน้ำเข้า (จำนวนวันหลังเพาะปลูก)	ความลึก (ซม.)	การสูบน้ำออก (จำนวนวันหลังเพาะปลูก)
ครั้งที่ 1			
ครั้งที่ 2			
ครั้งที่ 3			
ครั้งที่ 4			

3) การใช้ปั๊มน้ำสำหรับการระบายน้ำ ท่านมีการใช้ปั๊มน้ำหรือไม่ ? ☐ ไม่ใช่ ☐ ใช่	
ชนิดของปั๊ม: ________________	ชนิดเชื้อเพลิง: ________________
ยี่ห้อ: ________________	อัตราการใช้เชื้อเพลิง(ลิตร/ไร่): ________________
รุ่น: ________________	ราคาเชื้อเพลิงต่อไร่(บาท): ________________
แรงม้า: ________________	จำนวนชั่วโมงสูบน้ำ(ชม): ________________
ราคาปั๊ม (บาท): ________________	อัตราการสูบ(ลิตร/นาที): ________________

B5. การใช้ปุ๋ยเคมี

1) ท่านมีการใช้ปุ๋ยเคมีในนาข้าวหรือไม่? ☐ ไม่ใช่ ☐ ใช่

2) ความถี่ในการใช้ปุ๋ยเคมีต่อรอบการปลูก ________________ ครั้ง

ครั้งที่ใช้	ชนิด	ชื่อปุ๋ยเคมี	สัดส่วน N:P:K	ราคา	วันที่ใส่ปุ๋ย (หลังปลูก)	ปริมาณที่ใช้ (กก./ไร่)	จำนวนแรงงาน	ค่าจ้างแรงงาน
1			__:__:__					
2			__:__:__					
3			__:__:__					
4			__:__:__					

B6. การใช้ปุ๋ยอินทรีย์/วัสดุปรับปรุงดิน

1) ท่านมีการใช้ปุ๋ยอินทรีย์/วัสดุปรับปรุงดินในนาข้าวหรือไม่? ☐ ไม่ใช่ ☐ ใช่

2) ความถี่ในการใช้ปุ๋ยอินทรีย์/วัสดุปรับปรุงดินต่อรอบการปลูก ________________ ครั้ง

ครั้งที่ใช้	ชนิดอินทรียวัตถุ S= ฟาง M= มูลสัตว์, C= ปุ๋ยหมัก G= ปุ๋ยพืชสด, EM= จุลินทรีย์ O =อื่นๆ	ราคา (บาท)	วันที่ใส่ปุ๋ย (หลังปลูก)	ปริมาณที่ใช้ (กก./ไร่)	จำนวนแรงงาน	ค่าจ้างแรงงาน (บาท)
1						
2						
3						
4						

B7. การใช้ปูนขาว						
1) ท่านมีการใช้ปูนขาวในนาข้าวหรือไม่? ☐ ไม่ใช่ ☐ ใช่ 2) ความถี่ในการใช้ปูนขาวต่อรอบการปลูก ________________ ครั้ง						
ครั้งที่ใช้	ปูนขาว	ราคา (บาท)	วันที่ใส่ปูนขาว (หลังปลูก)	ปริมาณที่ใช้ (กก./ไร่)	จำนวนแรงงาน (คน)	ค่าจ้างแรงงาน (บาท)
1						
2						
3						
4						

B8. การใช้ยาฆ่าแมลง							
1) ท่านมีการใช้ยาฆ่าแมลงในนาข้าวหรือไม่? ☐ ไม่ใช่ ☐ ใช่ 2) ความถี่ในการใช้ยาฆ่าแมลงต่อรอบการปลูก ________________ ครั้ง							
ครั้งที่ใช้	ชนิด	ราคา (บาท)	วันที่ใส่ยา (หลังปลูก)	การเจือจาง (1 กรัม/20 ลิตร)	ปริมาณที่ใช้ (ลิตร/ไร่)	จำนวนแรงงาน	ค่าจ้างแรงงาน
1							
2							
3							
4							

B9. การใช้ยากำจัดวัชพืช							
1) ท่านมีการใช้ยากำจัดวัชพืชในนาข้าวหรือไม่? ☐ ไม่ใช่ ☐ ใช่ 2) ความถี่ในการใช้ยากำจัดวัชพืชต่อรอบการปลูก ________________ ครั้ง							
ครั้งที่ใช้	ชนิด	ราคา (บาท)	วันที่ใส่ยา (หลังปลูก)	การเจือจาง (1 กรัม/20 ลิตร)	ปริมาณที่ใช้ (ลิตร/ไร่)	จำนวนแรงงาน	ค่าจ้างแรงงาน
1							
2							
3							
4							

B10. การเก็บเกี่ยว
1) วิธีการเก็บเกี่ยว ☐ แรงงาน ค่าจ้างแรงงาน: ______________ บาท/คน/วัน ☐ เครื่องจักร ค่าเครื่องจักร: ______________ บาท

B11. ผลผลิต									
รอบที่	ชนิดพันธุ์	ปริมาณ (ตัน/ไร่)	% ความชื้น	ผลผลิตรวม (ตัน)	ผลผลิตที่ขาย (ตัน)	ราคาขาย	ปริมาณเก็บไว้บริโภค (ตัน)	ปริมาณเก็บไว้ปลูก(ตัน)	ปริมาณเก็บไว้ใช้ส่วนอื่นๆ
1									
2									
3									
4									

B12. ข้อมูลการใช้เครื่องจักรในขั้นตอนต่างๆ										
ขั้นตอนการปลูก	ชนิดเครื่องจักร	เช่า/ หรือเป็นเจ้าของ	ผู้ผลิต/ รุ่น	ราคา (เช่า/ซื้อ)	ระยะเวลาทำงาน (วัน,ชม./วัน)	ชนิดเชื้อเพลิง	อัตราสิ้นเปลือง (ลิตร/ไร่)	อายุการใช้งาน (ปี)	อายุของเครื่อง (ปี)	ค่าซ่อมแซม (บาท/ปี)
การเตรียมพื้นที่										
การเพาะกล้า										
การปลูก										
การจัดการน้ำ/การสูบน้ำ										
การใส่ปุ๋ย										
การใช้ยาฆ่าแมลง/กำจัดศัตรูพืช										
การเก็บเกี่ยว										

B13. การจัดการเศษวัสดุหลังการเก็บเกี่ยว

1) วิธีการจัดการ ☐ กำจัดออก ❍100% ❍>50% ❍ <50% ❍0% ☐ เผา ❍100% ❍>50% ❍ <50% ❍0% ☐ ปล่อยทิ้งไว้ (ไม่เผา) ❍100% ❍>50% ❍ <50% ❍0%	2) การใช้ประโยชน์ ☐ ฟาง ❍100% ❍>50% ❍ <50% ❍0% ☐ ตอซัง: ❍100% ❍>50% ❍ <50% ❍0%
3)การใช้ประโยชน์จากฟางข้าว (ตอบได้มากกว่า1 ข้อ) ☐ อาหารสัตว์ _______% ☐ คลุมดิน _______% ☐ ปรับปรุงดิน _______% ☐ วัสดุปลูกเห็ด _______% ☐ อื่นๆ __________________	4) การใช้ประโยชน์จากตอซัง (ตอบได้มากกว่า1 ข้อ) ☐ อาหารสัตว์ _______% ☐ คลุมดิน _______% ☐ ปรับปรุงดิน _______% ☐ วัสดุปลูกเห็ด _______% ☐ อื่นๆ ___________________
5) เหตุผลในการเผา ☐ เตรียมพื้นที่ปลูก ☐ กำจัดแมลงศัตรูพืช ☐ กำจัดวัชพืช ☐ อื่นๆ ระบุ:	6) สัดส่วนในการเผา ☐ ฟางข้าว ❍100% ❍>50% ❍ <50% ❍0% ☐ ตอซัง ❍100% ❍>50% ❍ <50% ❍0%
7) ช่วงเวลาที่ทำการเผา? ☐ เช้า (6:01-12:00) ☐ บ่าย (12:01-18:00) ☐ กลางคืน (18:01-6:00)	8) ระยะเวลาในการเผาแต่ละครั้ง? ☐ < 1 ชม. ☐ 1-2 ชม. ☐ 1 วัน ☐ อื่นๆ ___________________

APPENDIX B1: Costs of rice cultivation in Nakhon Sawan province

QN No.	Nakhon Sawan (CF)			Nakhon Sawan (AWD)		
	Unit area		Cost (THB/ha)	Unit area		Cost (THB/ha)
	rai	ha		rai	ha	
Q1	16	2.56	CF	35	5.60	22,000
Q2	55	8.80	38,438	7	1.12	20,625
Q3	47	7.52	35,631	29	4.64	18,800
Q4	100	16.00	38,213	50	8.00	21,813
Q5	50	8.00	49,550	39	6.24	22,000
Q6	20	3.20	42,328	68	10.88	28,188
Q7	40	6.40	38,156	20	3.20	25,000
Q8	15	2.40	39,150	18	2.88	15,169
Q9	52	8.32	24,950	13	2.08	24,637
Q10	15	2.40	48,950	13	2.08	19,950
Q11	28	4.48	17,994	28	4.48	20,100
Q12	60	9.60	33,038	40	6.40	19,813
Q13	23	3.68	55,238	30	4.80	26,513
Q14	16	2.56	44,990	15	2.40	26,513
Q15	25	4.00	30,019	30	4.80	18,613
Q16	35	5.60	30,613	11	1.76	27,325
Q17	48	7.68	39,288	28	4.48	26,513
Q18	43	6.88	40,003	19	3.04	24,863
Q19	40	6.40	33,431	80	12.80	26,350
Q20	7	1.12	40,963	9	1.44	18,775
Q21	30	4.80	20,763	38	6.08	24,675
Q22	47	7.52	32,800	64	10.24	26,450
Q23	10	1.60	38,400	44	7.04	20,438
Q24	21	3.36	22,688	15	2.40	37,450
Q25	4	0.64	23,150	47	7.52	19,300
Q26	5	0.80	13,381	50	8.00	19,325
Q27	50	8.00	31,525	32	5.12	18,075
Q28	10	1.60	31,181	19	3.04	32,763
Q29	60	9.60	30,213	13	2.08	19,950
Q30	40	6.40	42,547	14	2.24	21,825
Q31	-	-	-	27	4.32	26,513
Q32	-	-	-	23	3.68	26,513
Q33	-	-	-	36	5.76	24,638
Q34	-	-	-	38	6.08	20,263
Q35	-	-	-	20	3.20	18,075

Note: QN= Questionnaire

APPENDIX B2: Costs of rice cultivation in Chai Nat province

QN No.	The total cost of rice production					
	Chai Nat (CF)			Chai Nat (AWD)		
	Unit area		Cost (THB/ha)	Unit area		Cost (THB/ha)
	rai	ha		rai	ha	
Q1	6	0.96	36,356	24	3.84	30,125
Q2	34.5	5.52	38,225	30	4.80	32,138
Q3	19	3.04	36,556	10	1.60	25,050
Q4	32	5.12	34,663	40	6.40	26,113
Q5	11	1.76	19,344	7	1.12	22,250
Q6	45	7.20	42,038	25	4.00	23,413
Q7	90	14.40	44,626	120	19.20	28,706
Q8	35	5.60	37,613	18	2.88	22,250
Q9	44	7.04	45,925	25	4.00	28,713
Q10	10	1.60	37,863	12	1.92	33,006
Q11	20	3.20	32,631	11	1.76	25,431
Q12	100	16.00	47,938	13	2.08	26,669
Q13	8	1.28	21,519	13	2.08	24,919
Q14	25	4.00	45,750	5	0.80	15,875
Q15	10	1.60	29,988	8	1.28	23,981
Q16	35	5.60	30,988	12	1.92	23,981
Q17	41	6.56	21,338	20	3.20	23,981
Q18	13	2.08	29,900	56	8.96	23,981
Q19	22	3.48	30,563	50	8.00	23,250
Q20	13	2.08	46,100	38	6.08	31,575
Q21	32	5.12	58,563	25	4.00	23,181
Q22	30	4.80	47,925	22	3.52	30,400
Q23	24	3.84	47,919	25	4.00	25,719
Q24	13	2.08	34,394	5	0.80	21,225
Q25	10	1.60	44,750	5	0.80	18,975
Q26	20	3.20	20,950	27	4.32	26,063
Q27	10	1.60	35,438	19	3.04	30,350
Q28	7	1.12	37,563	6	0.96	20,250
Q29	23	3.68	43,669	23	3.68	23,650
Q30	12	1.92	44,488	16	2.56	22,263
Q31	-	-	-	12	1.92	25,775
Q32	-	-	-	26	4.16	31,550
Q33	-	-	-	14	2.24	24,788
Q34	-	-	-	7	1.12	21,419
Q35	-	-	-	3	0.48	24,773
Q36	-	-	-	115	18.40	30,000
Q37	-	-	-	14	2.24	23,875

Note: QN= Questionnaire

APPENDIX B3. Costs of rice cultivation in Prachin Buri province

QN No.	The total cost of rice production					
	Prachin Buri (CF)			Prachin Buri (AWD)		
	Unit area		Cost (THB/ha)	Unit area		Cost (THB/ha)
	rai	Ha		rai	ha	
Q1	10	1.60	22,213	60	9.60	22,394
Q2	28	4.48	29,946	9	1.44	23,694
Q3	32	5.12	19,529	80	12.8	19,675
Q4	20	3.20	19,706	10	1.60	19,597
Q5	17	2.72	21,947	9	1.44	20,281
Q6	100	16.00	19,119	16	2.56	28,269
Q7	75	12.00	22,223	9	1.44	18,969
Q8	20	3.20	20,244	14	2.24	23,213
Q9	25	4.00	21,906	12	1.92	24,566
Q10	30	4.80	2,318	16	2.56	22,947
Q11	17	2.72	20,325	20	3.20	21,231
Q12	20	3.20	26,323	3	0.48	22,278
Q13	11	1.76	28,191	8	1.28	23,113
Q14	20	3.20	40,038	8	1.28	17,963
Q15	30	4.80	21,116	14	2.24	24,200
Q16	35	5.60	26,563	18	2.88	23,300
Q17	60	9.60	19,589	16	2.56	17,256
Q18	30	4.80	15,300	20	3.20	25,869
Q19	50	8.00	30,844	12	1.92	22,706
Q20	20	3.20	26,021	13	2.08	40,231
Q21	10	1.60	20,963	18	2.88	25,000
Q22	21	3.36	19,953	9	1.44	22,113
Q23	10	1.60	18,750	18	2.88	26,613
Q24	30	4.80	21,094	11	1.76	18,725
Q25	10	1.60	20,469	17	2.72	20,516
Q26	40	6.40	19,188	21	3.36	30,129
Q27	10	1.60	19,750	26	4.16	22,884
Q28	7	1.12	23,859	10	1.60	18,969
Q29	15	2.40	17,531	7	1.12	19,362
Q30	59	9.44	21,964	10	1.60	18,541

Note: QN= Questionnaire

APPENDIX C1: Greenhouse gas emissions from rice fields (ton CO_2e/ha)

QN No.	Greenhouse gas emission from rice fields (ton CO_2e/ha)					
	Nakhon Sawan		Chai Nat		Prachin Buri	
	CF	AWD	CF	AWD	CF	AWD
Q1	10.66	3.67	9.55	6.20	3.46	5.48
Q2	11.86	3.66	9.47	5.83	3.45	5.86
Q3	10.29	3.66	9.90	5.93	4.71	3.11
Q4	9.99	3.84	9.91	5.78	4.80	3.38
Q5	11.47	3.66	9.94	5.78	4.89	6.15
Q6	10.98	3.66	9.31	5.93	4.34	4.73
Q7	10.78	3.66	10.42	6.13	4.53	4.91
Q8	11.19	3.65	9.95	5.85	7.24	3.13
Q9	11.27	3.65	9.87	5.78	4.84	4.91
Q10	10.29	3.65	9.81	5.94	6.11	4.91
Q11	10.29	3.65	10.37	5.80	5.07	4.91
Q12	11.76	2.92	9.94	5.95	6.11	3.13
Q13	9.80	3.67	9.90	5.98	8.88	4.91
Q14	10.09	2.13	9.25	5.76	6.11	4.91
Q15	10.29	3.66	9.95	4.72	5.22	4.91
Q16	11.76	3.66	9.92	5.26	8.94	4.91
Q17	11.27	3.66	11.40	4.51	6.11	4.90
Q18	11.76	3.65	10.77	5.22	6.63	4.91
Q19	11.27	3.65	3.99	4.07	6.52	3.12
Q20	11.86	3.65	9.99	6.11	6.74	5.81
Q21	9.99	3.65	9.50	6.28	5.20	4.19
Q22	10.67	3.65	9.49	5.99	6.23	4.91
Q23	11.76	3.66	9.36	5.97	6.25	3.40
Q24	8.82	3.66	9.31	5.96	6.23	3.42
Q25	9.99	3.66	9.52	5.95	6.28	3.52
Q26	10.78	3.65	9.50	5.92	13.00	5.23
Q27	11.27	3.65	9.53	5.78	5.67	3.54
Q28	10.78	3.67	9.51	5.78	6.18	3.38
Q29	11.76	3.66	9.49	5.76	5.17	3.40
Q30	11.76	3.66	9.80	5.93	5.95	3.38
Q31	-	3.65	-	5.93	-	-
Q32	-	3.67	-	5.93	-	-
Q33	-	3.65	-	5.77	-	-
Q34	-	3.65	-	5.80	-	-
Q35	-	3.65	-	5.32	-	-
Q36	-	-	-	5.76	-	-
Q37	-	-	-	5.09	-	-

Note: QN= Questionnaire