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TECHNICAL, ECONOMIC AND ENVIRONMENTAL VIABILITY FOR ENERGY RECOVERY FROM RICE HUSK IN PERU

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“TECHNICAL, ECONOMIC AND ENVIRONMENTAL VIABILITY FOR ENERGY RECOVERY FROM RICE HUSK IN PERU”

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…dedicada a mis padres, Tomás y Felicia
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Summary and outline of this thesis

After the Paris agreement (United Nations, 2015), Governments reaffirmed its commitment to reduce greenhouse gas emissions to mitigate the contribution to global warming. Since the use of fossil fuels such as gasoline, diesel and coal, are one of the main causes of global warming (IPCC, 2007), one of the goals is to reduce their use in the combustion processes. To face this challenge, an alternative is using the available biomass, including agricultural solid residue, to obtain energy (Vitali et al., 2013; Shafie et al., 2012a,b). This presents some advantages for the mitigation of gaseous emissions of CO_2, SOx and N_2O, NO and N_2 (Saidur et al., 2011).

In developing countries, large amounts of biomass such as rice husks, straws, nutshells, fruit shells, fruit seeds, plant stems, green leaves and molasses are produced annually, but little is recover them as energy source (Okeh et al., 2014). Worldwide, the estimated amount of rice husk available reaches 134 million metric tons per year, with an energy potential of 2010 PJ (Quispe et al., 2017). Rice husk is a residue generated in paddy processing for commercial rice. Different techniques to obtain energy from rice husk are direct combustion, gasification and pyrolysis (Lim et al., 2012; Goyal et al., 2008; McKendry, 2002). Worldwide, the most studied and used technology is direct combustion, while fast pyrolysis is a promising new technology (Goyal et al., 2008; Caputo et al., 2005). However, due to economic viability and knowledge domain (Quispe et al., 2017), the simplest and most appropriate technology to adapt and use has been still direct combustion using a fluidized bed for drying processes. In order to select the most suitable technique to obtain energy, it is important to identify the physical properties and chemical composition of agricultural residue (McKendry, 2002a,b; Quispe et al., 2017). The common advantages of using agricultural residue as an energy source are: a reduced CO_2 net emissions and reduced gaseous emissions such as NOx, CH_4, SOx and CO compared to fossil fuels, due to very low S and N contents, which also increases agricultural waste's commercial value.

On the other hand, in Peru, up to 693,308 metric tons of rice husk is generated annually and 85% of it is burned in the open air or disposed in rivers, harming human health and contaminating our environment. In addition, official Peruvian energy policy is to incorporate the use of renewable energy sources, such as agricultural residue. Consequently, the aim of the study is to perform a technical, economic and environmental assessment for thermal energy recovery from rice husk (RH) and rice husk briquette (RHB) in Peru. The rice husk from Peru was characterized to identify its physical properties and chemical composition. The Life Cycle Assessment (LCA) methodology was employed to perform the environmental assessment. LCA is a standardized methodology to identify and quantify the environmental impact from the production, distribution, use and final disposal of the products, including the initial extraction of resources and material in the process (ISO 14040, 2006 and ISO 14044, 2006). The results show that the environmental impact to obtain 1 MJ from rice husk in the global warming, acidification and eutrophication environmental impact categories, are less than that of 1 MJ obtained from coal, 97%, 88% and 80% less, respectively. However, the use of coal to generate heat has a 98% better impact over rice husk, the opposite was found in the water depletion environmental impact category. If all rice husk available in Peru was used for drying processes, instead of coal, it could mitigate around 626,000 tons of CO_2-eq per year, approximately. On the other hand, these biofuels are significantly cheaper than coal, thus the mills can save up to 57% or 32% of the drying costs using RH or RHB, respectively and even protect the environment. Additionally, mills could diversify their products and sell RHB. Only 30% of the rice husk quantity generated in Peru would be used to dry the paddy production. Thus, there is enough rice husk to be used in other drying processes. Finally, energy recovery from RH is technically, economically and environmentally viable and it contributes to sustainability.

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CHAPTER I

1.1 Introduction

Current environmental problems have different causes, including global warming due to green-house gases emissions (GHGs), which are generated mainly from burning fossil fuels such as diesel, gasoline and coal (IPCC, 2007). On the other hand, all deposits of fossil fuels take millions of years to accumulate whereas the deposits are rapidly extracted and, if the extraction rate is faster than the replenishment rate, the resource will be finite in the sense that it will eventually be depleted (Höök and Pang, 2013; Capellán-Pérez et al., 2014). Facing this reality, governments have proposed policies to change their energy matrix in order to increase the share of renewable sources up to 15% and in some cases, 30% (Gabrielle et al., 2014). In this regard, research has aimed at obtaining energy from available biomass, including agricultural solid residues that can be generate energy trhough direct combustion.

Agricultural residues are generated in large amounts and are renewable energy resources that would provide about 10% of the total energy (Okeh et al., 2014), thus becoming an important alternative energy for the consumption of fossil fuels.

Using biomass offers numerous advantages such as hazardous emissions mitigation of CO_2, NOx, CH_4, SOx and CO, because agricultural residues have very low amount of S and N, and the amount of Cl is minimum. Another advantage is the diversification of fuel supply avoiding non-renewable resources depletion. In addition, agricultural residues have lower costs than fossil fuels. If using agricultural residues such as rice husk to obtain energy were to be promoted by governments, then it would be necessary to do an integral assessment considering all stages of its life cycle, and comparing it with the use of fossil fuels in order to identify which conditions and scenarios actually impact it less.

Peru is a country with a big biodiversity, ranging from rainforest in the east passing through the Andes Mountains to the Pacific coastal region with arid plains. Peru has 1,285,216 km^2 of territorial extension divided in three regions, traditionally: the coast, the highlands and the jungle; all these with different kind of soils and weather conditions.

Peru is an agro-industrial country where more than 16 million tons of agricultural residues are generated annually (Felix, E. and Rosell, C., 2010) and rice husk is one of the main residues. Rice husk has an important share in agricultural residues, reaching an amount of 693,308 tons per year, located chiefly in the Peruvian North Coast, where it concentrates 41% of the country's total production.

Peruvian energy policy has incorporated the use of renewable energy including agricultural residues, but there is not enough information regarding the current Peruvian situation in order to decide on what resource and technology should be used, and under which conditions.

The aim of the research is to perform a technical, economic and environmental assessment for obtaining energy from rice husk in Peru.

Thus, considering:

- Increasing energy demand for producing goods and services.
- Fossil fuels are the main source of energy.
- Agricultural residues are alternative sources to obtain energy through different technologies.
- In Peru, rice husk have an important share in agricultural residues reaching an amount of 693,308 tons per year, and 85% of rice husk is being burnt at open air or disposed in rivers, polluting the environment.
- Peruvian energy policy has incorporated the use of renewable energy, including agricultural residues.

- There is not enough information adapted to the current Peruvian situation in order to decide on what re-source should be used, and under which conditions.

The study proposes the following hypothesis:

The use of rice husk for obtaining thermal energy in furnaces has a lower environmental impact and cost compared with the use of solid fossil fuel.

1.2 Objectives

General Objective:

Perform a technical, economic and environmental assessment for thermal energy recovery from rice husk in Peru.

Specific Objectives:

Assess economic and environmental impacts for obtaining rice husk.

Assess economic and environmental impacts for obtaining rice husk briquette.

Compare the use of rice husk as solid fuel with the use of coal in furnaces, considering technical, economic and environmental aspects.

CHAPTER II

Methodology

2.1 Identifying the main producers of paddy in Peru

Databases from the National Institute of Statistics and Informatics (INEI, 2012) and the Peruvian Agriculture Ministry were used to identify the main producers of paddy as well as to estimate the amount produced and hectares cultivated per annum. Small farmers that cultivate between 7 and 10 ha, who are also leaders and technical professionals, were selected for the interviews. In total, five producers were interviewed; among them, there was the president of the Board Water Users of Lambayeque.

Additionally, information about the type of soil where paddy is cultivated was obtained from the National Institute of Agricultural Innovation. This institution performs studies of soil characterization and some of them were made available.

2.2 Describing the processes for obtaining 1 ton of paddy

The manuals published by the Agriculture Ministry were reviewed to describe the process of obtaining paddy, identifying each stage and activity of the agricultural phase (Ministerio de Agricultura y Riego del Perú, 2012); later it was checked through the interviews performed to paddy sector representatives.

2.3 Estimating the amount consumed for each resource

A survey was elaborated in order to quantify inputs and outputs, considering questions about fertilizer, herbicide, pesticide, seed and water consumption as well as agronomic handling, machines usage, paddy yield per hectare, and waste.

Two trips to the North of Peru were done so as to visit paddy crop fields and to interview to main paddy farmers and the president of the Board of Water Users of Lambayeque. Four farmers located in Lambayeque were interviewed in total. These farmers have crop fields from 7 ha to 10 ha, with average yield of 8.5 t/ha. The information was systemized and compared with agronomic handling manuals of paddy elaborated by the National Institute of Agricultural Innovation and the Board of Water Users of Lambayeque. The Excel worksheet was used to calculate the materials and energy consumption to obtain 1 ton of paddy in each agricultural phase activity. The calculations indicated that farmers used the manual. On the other hand, the active element of fertilizers, pesticides and herbicides were identified using the active elements table of equivalences for each kind of fertilizer and its technical file.

2.4 Evaluating the environmental impacts and aspects for obtaining one ton of paddy

The materials and energy consumption to obtain 1 ton of paddy for each activity of the agricultural phase and Life Cycle Assessment methodology (ISO 14040:2006) were used to quantify environmental impacts. Life Cycle Assessment (LCA) is an international standardized methodology to identify and quantify the environmental aspects and potential impacts of every stage of the life cycle, from obtaining resources and materials, production, distribution, and usage, to final disposal (ISO, 2006). According to international standard ISO 14040, an LCA is an iterative cycle of knowledge and optimization comprising the following steps: objective and scope, inventory assessment, impact assessment, and interpretation.

In the first step, determining the objective and scope, the limits of the study system as well as the functional unit are defined. The scope of the limits can be from cradle to grave, gate to gate, gate to grave, depending on the objective and data availability. The functional unit describes the main function of the system, for example, one cultivated hectare, one kilometer, or one produced ton. The environmental impacts are expressed in functional units. The inventory assessment identifies inputs and outputs of each unitary process of the system. Inputs are energy and materials from nature or the technosphere, and the outputs are the products, emissions, effluents and solid wastes. To process the information, IT support is generally used, such as SimaPro, Umberto, GaBi.

In the impact assessment step, potential environmental impacts are evaluated, based on the inventory analysis. In general, this process involves associating inventory data with specific environmental impacts. The environmental loads are to be classified according to different impact categories in order to obtain environmental indicators, and the relative importance of the different impact categories is assessed quantitatively and qualitatively. Finally, the interpretation stage integrates the findings of the inventory analysis and the impact assessment. The findings of the interpretation may take the form of conclusions and recommendations consistent with the objective and the scope of the study. Additionally, the results of an LCA study help identify activities of greater environmental impact and root causes, in order to make decisions that contribute to resource sustainability.

The following impact categories of this study were considered for the environmental assessment: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), and water depletion (WD). GWP was used to reduce the GHG emissions because of specific goals. Moreover, developing countries, in which most of the worldwide rice production concentrates, are now obliged to comply with the GHG emissions reduction objectives signed in the Paris Agreement (United Nations, 2015). On the other hand, eutrophication and acidification were included because agriculture is an important contributor to these categories (Hokazono, S. and Hayashi, K., 2012). The water depletion category was considered because water is an important resource in the coast of Peru, where there is water scarcity and the rainfalls reach only 100 millimeters annually. In order to assess each category, the following characterization factors were used: a) global warming potential for a 100-year time horizon (GWP100) from IPCC, 2013 (IPCC, 2013), b) Acidification Potential (AP) from CML (Heijungs et al., 1992), c) eutrophication potential (EP) from CML (Heijungs et al.,1992), and d) water depletion (WD) from Recipe (Goedkoop et al., 2008).

The scope of the study to evaluate the environmental impacts have considered from the seedling stage to the harvest stage, including the production of fertilizers, pesticides and herbicides as well as the production of diesel. The data were processed with the support of the Simapro software. The models for the calculation of the emissions generated in the crop fields by using fertilizers are shown in Table 1.

Table 1. Models to quantify field emissions

Emission	Model
Ammonia (NH_3)	EMEP (EEA 2013) or EMEP (EEA 2006)
Nitrous oxide (N_2O)	IPCC 2006 - crops
Nitrogen oxides (NO_X)	EEA 2013
Carbon dioxide (CO_2)	IPCC 2006 - crops
Methane (CH_4)	IPCC 2006 - crops
Nitrate (NO_3^-)	SALCA - NO_3 SQCB
Phosphorus (P, PO_4^{-3})	SALCA – P (Prasuhn 2006)

The materials and energy consumption indicated in Table 1, the emissions generated in the crop fields to obtain 1 ton of paddy, and Life Cycle Assessment methodology (ISO 14040:2006) were used to quantify environmental impacts.

2.5 Describing the processes to obtain rice husk (RH) and rice husk briquette (RHB)

The available literature and the interviews to mill owners were used to identify the process of obtaining RH and RHB. Interviews were conducted in order to estimate the quantity of resources consumed and the generated residues. In addition, the information was complemented with reports of the rice sector.

2.6 Identifying the main characteristics of Peruvian rice husk

Rice mills were visited in order to obtain samples of rice husk. In total, fifteen samples were obtained from the study area. These samples were transported from Peru to the BIOREN laboratory (Temuco, Chile) to perform the proximal and elemental analyses. Previously, the samples were dried at 105ºC for 24 hours, and then milled in a hand mill. The dried and milled samples were used in the elemental analysis and to obtain the heating value. On the other hand, the not-dried milled samples were used in the thermogravimetric analysis (TGA).

2.7 Selecting the technology to produce rice husk briquette

Literature review and interviews to machinery suppliers were carried out in order to identify different technologies and their main characteristics as well as their advantages and disadvantages. Subsequently, a comparative table was elaborated with the intention of deciding which the most appropriate technology to obtain rice husk briquette was.

2.8 Quantifying the cost of obtaining one ton of RH and one ton of RHB

Primarily, reports and studies focused on the rice sector were used to obtain information about resources and materials costs consumed in the process. These references are shown in Table 2 to obtain the cost of RH, and in Table 3 to obtain the cost of RHB, respectively.

Table 2. Sources used to calculate the cost of RH

Materials and resources	**Reference**
Paddy cost	The Ministry of Agriculture and Irrigation of Peru and interviews to farmers
Direct and Indirect costs	Questionnaire to mill owners

Table 3. Sources used to calculate the cost of RHB

Materials and resources	**Reference**
Rice husk	It was obtained in this investigation
Labor	Manufacturers
Machinery	Various manufacturers from Asia, America and Europe that offer suitable briquetting lines were found and quotations were petitioned, e. g. Lippel, Spänex, Ronak, Gongyi Xiaoyi Mingyang Machinery Plant, Agico, Zhengyang.
Average interest rate classified for sector	Working document of Central Reserve Bank.
Electricity	Manufacturers and the Ministry of Energy and Mines of Peru.
Maintenance	Manufacturers
Others (insurances and consumables)	Literature

The total cost for RH was calculated using the following equation:

$$C_{RH} = (C_{paddy} + C_{dc} + C_{ic})*A \quad (1)$$

Where C_{RH} is the total cost of RH, in US$/t, C_{paddy} is the cost of paddy, in US$/t, C_{dc} is the total direct cost, C_{ic} is the total indirect cost in mills, in US$/t, and A is the percentage of allocation to total cost of rice husk. The total cost for RHB was calculated using the following equation:

$$C_{RHB} = C_{cap} + C_{op} \quad (2)$$

Where C_{RHB} is the total cost of RHB, in US$/t, C_{cap} is the capital cost, in US$/t and C_{op} is the cost of operation, which includes raw material, labor, maintenance and others, in US$/t.

2.10 Quantifying the costs to obtain 1 MJ of thermal energy from RH, RHB and coal

Dryer technical specifications were used to obtain the total thermal energy required, which is calculated with the following equation:

$$TE_t = \frac{Q * \Delta h}{t_d} \tag{3}$$

Where TE_t is the total thermal energy required, in MJ, Q is the total thermal energy required per hour, in MJ/h, Δh is the difference of humidity before and after drying, in % and t_d is the drying rate per hour, in %/h.

The cost of obtaining thermal energy from each feedstock is calculated as follows:

$$CTE_i = \frac{TE_t * C_i}{HV_i * Ef} \tag{4}$$

Where CTE_i is total cost to obtain thermal energy, in US$, TE_t is the total thermal energy required, in MJ, HV_i is the heating value of the feedstock, in MJ/kg, Ef is the efficiency of the dryer, in % and C_i is the cost of the feedstock I, in US$/kg.

CHAPTER III

Agricultural residues in the world

3.1 Agricultural residues and rice husk available in the world

Literature review shows that research has been developed to obtain energy from agricultural residues, considering residue characteristics, using different technologies and their operational conditions, as the cases of Philippines and Myanmar (Pode et al., 2016; Pode, 2016; Burritt et al., 2009). In fact, if agricultural residues were to be completely used as renewable energy resources, they would provide approximately 10% of the total energy (Okeh et al., 2014), thus becoming an attractive alternative to fossil fuels. Governments worldwide, with the aim of diversifying their energy matrix and becoming less dependent on fossil fuels, are considering renewable energy strategies using a wide variety of biomass sources (forest residues, agricultural residues and domestic solid waste) (Zhang et al., 2010; Liu et al., 2012; Gabrielle et al., 2014) to contribute to the mitigation of GHG emissions. Generally, theoretical availability of agricultural residues is estimated by multiplying annual production by residue production ratio. Some studies have considered other criteria such as, crop rotation practices, harvest method, soil type, or tillage management practices in order to estimate effective availability of agricultural residues. Countries such as the United States, Canada or China have identified the availability of energy from effective available agricultural residues considering different criteria and ratios such as those shown in Table 4. Available energy potential is estimated using the following expression:

$$EP_{(j)} = \sum_{i=1}^{n} ARA_{(i,j)} \times HV_{(i,j)} \tag{5}$$

Where, $EP_{(j)}$ is the available energy potential of n crops at j*th* country or region in PJ, $ARA_{(i,j)}$ is the effective availability of agricultural residues of i*th* crop at j*th* country or region in tons, and $HV_{(i,j)}$ is heating value of i*th* crop at j*th* country or region in PJ ton^{-1}. The available energy potential affected by thermal or electrical efficiency of the used technologies is known as the technical energy potential. Energy conversion efficiency from chemical to thermal energy varies from 80% to 95% using technologies such as fluidized bed reactors, boilers, cyclonic fluidized-bed combustors, fluidized bed combustion boilers or conical fluidized-bed combustors (Natarajan et al., 1998; Lim et al., 2012; Madhiyanon et al., 2009; Saidur et al., 2011; Permchart et al., 2003). However, chemical to electrical energy conversion can vary from 30% to 50% using high-efficiency multi-pass, steam turbines or fluidized bed combustion steam turbine (McKendry, P., 2002; Shafie et al., 2012). On the other hand, large amounts of biomass produced annually in developing countries, such as rice husk, straw, nut shells, fruit shells, fruit seeds, plant stovers, green leaves and molasses, are barely recuperated (Okeh et al., 2014). Out of all these residues, it should be noted that rice husk is one of the least used (Okeh et al., 2014), despite the fact that there are approximately 134 million tons of rice husk in the world (as calculated in Table 2, based on Lim et al., 2012; Madhiyanonet et al., 2009; Delivand et al., 2011; Alvarez et al., 2014). Moreover, 90% are burned in open air or discharged into rivers and oceans (Lim et al., 2012; Okeh et al., 2014, Vitali et al., 2013; Abril et al., 2009; Giusti, 2009). Rice husk is a residue generated when processing rice in mills. In the field, when rice is harvested, roots, stems and leaves are obtained, leaving paddy (rice with husk) aside.

Table 4. Energy potential of agricultural residues by region

Country / Region	Main agricultural residues	Criteria for effective availability of agricultural residues	Ratio	Effective availability of agricultural residues 1000 t[(a)]	Available energy potential (PJ)	Ref.
Canada (2007)	Wheat, oats, barley, grain corn, mixed grain, canola, soybeans, flaxseed, rye, tame hay, fodder corn.	removal from the fields and also translates	0.5	25,786	412.62	Melin (2013)
United States 40 contiguous states (2011)	Corn, barley, rice, sorghum, wheat	harvest method, yield, crop rotation, soil type and tillage management practices	Is not indicated	150,900	2,414.17	Muth et al (2013)
European Union EU-27 (2000-2009)	wheat, barley, rye, oat, maize, rice, rapeseed and sunflower	crop yields, harvested areas and residue-to-product ratios.	0.4 – 0.5	100,331	1,500	Monforti et al (2013)
China (1995-2004)	Residues from corn, wheat, rice, oil-bearing crops, others	Residue / crop product coefficient.	0.1 - 3	630,000	5,998.48	Liu et al (2008)
Thailand (1997)	Residues from Sugar, rice and palm oil mills	Residue product ratio, surplus availability factor	0.01 - 2.6	37,304	366.61	Prasertsana and Sajjakulnukitb (2006)
Malaysia (2000 – 2009)	Residues from Sugar and palm oil mills	Residue product ratio	0.49 – 0.59	44,695	408.75	Shafie et al (2012)

(a) Dry ton

When paddy passes through the mill, rice husk, dust and other residues are generated. Rice husk constitutes the most important residue ranging from 20% to 33% of paddy weight (GIDCB, 2008; Lim et al., 2012), although most studies consider 20% paddy as rice husks. Agricultural rice activity reaches a global annual production of 670 million tons of paddy, of which 91% are harvested in Asia (Madhiyanon et al., 2009; Delivand et al., 2011; Alvarez et al., 2014), 5% in America, 3% in Africa and the remaining 1% in Europe (CIAT, 2010; Okeh et al., 2014). Available rice husk in the world is estimated by multiplying the amount of paddy by residue product ratio; in this case 0.2. Energetic potential from rice husk is calculated multiplying the amount of rice husk by its heating value (HV = 15 MJ/kg), as shown in Table 5.

Table 5. Rice husk energy potential per year (Lim et al., 2012; Madhiyanonet al., 2009; Delivand et al., 2011; Alvarez et al., 2014; CIAT, 2010)

Region	**Paddy (1,000 t)**	**Rice husk (1,000 t)**	**Energy potential (PJ)**
Asia	609,700	121,940	1828
America	33,500	6,700	102
Africa	20,100	4,020	60
Europe	6,700	1,340	20
Total	670,000	134,000	2010

According to Table 5, the energy potential of rice husk in the world reaches 2,010 PJ, which could satisfy the annual energy consumption of Peru per three years, approximately. It is necessary to consider different criteria in each region to estimate effective availability of rice husk and it is important to know the thermal and electrical efficiency of technologies used in each region to estimate technical energy potential.

3.2 Physical and chemical properties of rice husk

Rice husk is a tissue composed of three polymers: cellulose, hemicellulose and lignin. Generally, cellulose and hemicellulose are present in a larger amount than lignin, unlike in forest residues (McKendry, 2002). Cellulose and hemicellulose are formed by a polymer chain shorter than the lignin polymer chain. Lignin, together with cellulose, is one of the most important components to determine its suitability as an energy crop (McKendry, 2002), and has higher correlation with the heating value of rice husk, as shown in the following expression (Demirbas, 2001), where L is the lignin content (w% dry basis):

$$\text{HHV (kJ g}^{-1}\text{)} = 0.0877(L) + 16.4951 \tag{6}$$

There is a wide variation for each component: cellulose ranges from 28.6% to 41.52%, hemicellulose from 14.04% to 28.6%, lignin from 20.39% to 33.67%, and extractive matter from 10.77% to 18.59% (Worasuwannarak et al., 2007; Guo et al., 2011; Muhammad et al., 2013). Variations depend on weather conditions, agronomic handling, type of soil, among other parameters. Heating value, moisture content, volatile matter, ash content and density are among the physical properties of biomass. The heating value is the amount of energy that a mass unit releases when chemical reactions occur. Biomass humidity is the amount of water as a percentage of weight, which is released when heated, then part of the heat, released in the form of vapor, is absorbed by the evaporation process, consequently net heating value (NHV), known as lower heating value (LHV), decreases when the moisture content increases. Studies generally use LHV as the reference heating value (HV). Volatile matter content is expressed in weight percentage and is another important parameter to consider, because it is released in the form of acetylene, methane, ashes and hydrocarbons C_mH_n, when the biomass is heated between 400°C and 500°C. According to the literature, the HV of rice husk is directly proportional to the volatile matter (VM) and fixed carbon (FC) contents, and higher content of ash (ASH) have lower heating value. As shown in the following expression (Parikh et al., 2005):

$$HHV(MJkg^{-1}) = 0.1559VM + 0.3536FC - 0.0078ASH \quad (7)$$

Where VM, FC and ASH content are reported in w% on a dry basis. Table 6 shows the physical properties of rice husk in different areas (Alvarez et al., 2014; Muhammad et al., 2013; Wang et al., 2012; Fang et al., 2004), where the relationship among VM, FC, ASH and HV is shown.

Table 6. Physical properties and heating value of rice husk

Location	**Volatile Matter (wt%)**	**Fixed Carbon (wt%)**	**Ash (wt%)**	**Heating Value MJ/kg**	**Ref.**
Taiwan	80.45	8.60	10.95	17.40	Wang et al (2012)
Spain	70,50	16.6	12,90	16.80	Alvarez et al (2014)
Brunei	68,25	16.92	14,83	16.10	Muhammad et al (2013)
China	51.98	25.10	16.92	13.40	Fang et al (2004)

The chemical composition of agricultural residue is important because the content of C, H and O directly influences its HV, whereas the content of N, S and Cl can cause NO_X (NO and NO_2), SO_2 and HCl emissions in the combustion process. Table 7 shows ultimate analyses to identify the chemical composition of rice husk from selected geographical zones (Muhammad et al., 2013; Fang et al., 2004; Varón, 2005).

Table 7. Ultimate analysis of rice husk

Values in dry basis wt%			
Component	**Brunei** Muhammad et al (2013)	**China** Fang et al (2004)	**Colombia** Varón et al (2005)
C	39,48	37,6	39,1
H	5,71	4.88	5,2
O	39,29	32,61	37,2
N	0,665	1,88	0,6
Cl	0,025	0,00	-
S	< 0,10	0,094	0,1
Ash	14,83	16,92	17,80

As shown in Table 7, there is a relatively low content of S and N, and a minimum amount of chlorine, which minimizes the emissions of NOx, HCl and SO_2 in the combustion process. Nitrogen presents greater variation from 0.6% to 1.88%. The composition of rice husk ash is shown in Table 8, and depends on the type of soil where the crop has grown, agronomic handling, and weather conditions (Alvarez et al., 2014; Valverde et al., 2007; Van et al., 2014). It is important to know this composition for the operational conditions of different energy-obtaining technologies (Demirbas, 2001; Parikh et al., 2005).

Table 8. Elemental composition of rice husk ash (wt%)

Ref.	**Valverde et al (2007)**	**Alvarez et al (2014)**	**Van et al (2014)**
SiO_2	91.42	98.02	87.4
Al_2O_3	0.78	0.52	0.4
TiO_2	0.02	0.02	
Fe_2O_3	0.14	0.11	0.3
CaO	3.21	0.23	0.9
MnO		0.01	
MgO	< 0.01	0.11	0.6
Na_2O	0.21	0.10	0.04
K_2O	3.71	0.38	3.39
SO_3	0.72		0.4
P_2O_5	0.43	0.08	
Other		0.42	6.57

Rice husk ash is composed mainly of silicon oxide, whose values range from 87.4% to 91.4%. Different studies indicate that rice husk ash is a good component for building materials and ceramics (Van et al., 2014; Zain et al., 2011). It also fulfils the physical characteristics and chemical composition of mineral admixtures (Zain et al., 2011). Largely, the pozzolanic activity of rice husk ash (RHA) depends on the silica content and other factors such as the grinding method, combustion period and temperature, which influence the quality of the ash.

3.3 Technologies used to obtain energy from rice husk

There are several technologies for obtaining energy from rice husk such as combustion, pyrolysis, and gasification (Lim et al., 2012; Goyal et al., 2008; McKendry, 2002). In this study the first two technologies are analyzed because pyrolysis is a new technology and, on the other hand, direct combustion is the most studied method according to the literature. However, the most used worldwide continues to be direct combustion (Goyal et al., 2008; Caputo et al., 2005).

3.2.1 Direct combustion

Direct combustion is one of the oldest and most used processes through which energy can be obtained and can be used in drying processes of agricultural products or to generate heat and steam. These technologies are used in industrial activities, ranging from an open fire stove or boilers, up to fluidized bed combustion. During combustion, oxygen acts as an oxidizing agent in the oxidation reaction, which must be exothermic, with temperature increase. The biomass burns when reacting with oxygen, producing a sufficient amount of energy. This reaction releases heat to the medium, so it is exothermic, and the combustion products reach a temperature where the phenomenon called fire of flame appears (Caputo et al., 2005). When the inorganic compounds are completely burned, the fuel is completely oxidized by the combustive, resulting in the combustion products, as shown in the following expression:

$$C_xO_yH_zN_wS_v + aO_2 \longrightarrow Energy + bCO_2 + cH_2O + eN_mO_p + dSO_r \quad (8)$$

Direct combustion furnaces are widely used in agro-industrial processes (coffee, rice, sugar cane, etc.) in Central and South America (BUN-CA, 2002). Direct combustion furnaces have a combustion chamber, where the biomass is burned and heat is obtained. The released heat can be used directly or indirectly through a heat exchanger for the drying operation, whether for grains or agricultural products in general. It is important to consider the composition of the biomass because it may generate critical problems as slagging and fouling, due to inorganic components of the biomass (BUN-CA, 2002; Saidur et al., 2011). The presence of silica and sulfur, in combination with alkaline metals in the presence of chlorine, are responsible for many undesirable reactions in combustion furnaces and boilers (Demirbas, 2005).

Direct combustion emissions are particulate matter (PM), nitrogen oxides (NO, NO2, N2O) and sulfur oxides (SOx). Acid gases, such as HCl (condensed on fine ash fraction or gas phase), can also be an output (Demirbas, 2005). On the other hand, if combustion is performed at a low temperature with an insufficient mixing of fuel and combustion air, and a very short residence time of the combustible gases in the combustion zone, the following contaminants will be emitted: CO, HC, tar, Polycyclic aromatic, PAHs, CH4, and char particles (Demirbas, 2005; Khan et al., 2009). The operational variables that influence emissions of pollutants are: fuel feed rate (i.e., rice husk), air entry speed, excess air and equilibrium state temperature. Therefore, proper handling of these variables will be sought to achieve combustion not only to mitigate environmental impacts, but also to be more efficient. According to the literature, pollutant emissions will also depend on the direct combustion of different technologies (Fang et al., 2004; Madhiyanon et al., 2010; Duan et al., 2013), as shown in Table 9.

Table 9. Emitted pollutants of direct combustion technologies using rice husk

Pollutant	Unit	Circulating fluidized bed Fang et al (2004)	Fluidized bed of chamber short combustion Madhiyanon et al (2010)	Vortexing fluidized bed incinerator Duan et al (2013)
CO_2	%	14.1	11.4	
O_2	%	3.80	8.77	
CO	ppm	788	50.0	400
SO_2	ppm	65.0		80.0
NO_x	ppm	153	232	220
Carbon in fly ash	%	6.50		
Unburnt carbon in ash	%		0.80	
Combustion efficiency	%	97.3	99.8	

Direct combustion generates high contents of ash due to its operating conditions and the chemical composition of rice husk. Ash content in rice husk ranges from 15 to 18%; the main component in rice husk ash is SiO_2 (from 87% to 91%).

3.2.2 Fast pyrolysis

Pyrolysis is a thermal process where organic matter is decomposed in presence of high temperatures and absence of oxygen. This decomposition produces changes in the chemical composition and physical properties of biomass, which are irreversible and generate three types of products: liquids (bio-oil), gases and solids (char, solid residue) (McKendry, 2002; Neves et al., 2011; Qi et al., 2007). As shown in Figure 1, the biomass entering the pyrolysis process is heated constantly at an initial temperature of 250°C up to 700°C. These temperatures depend on the properties of the biomass and on operating conditions (Goyal et al., 2008; Qi et al., 2007).

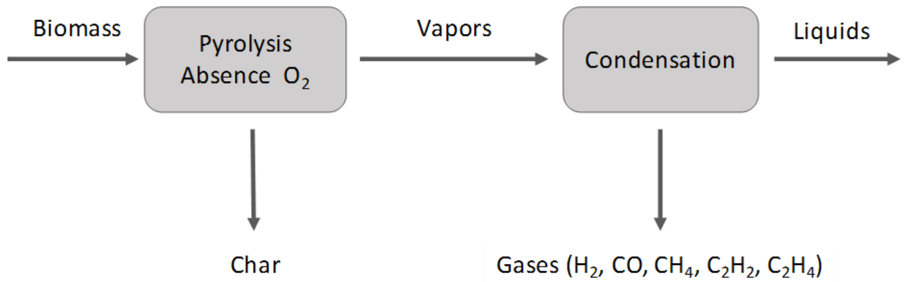

Figure 1. Pyrolysis process scheme

The main types of pyrolysis are: slow, intermediate and fast pyrolysis, which depend on several factors such as heating rate, residence time, reaction temperature, feed rate, among other parameters. In most cases, slow pyrolysis and intermediate pyrolysis are carried out at a temperature below 500°C, whereas fast pyrolysis is carried out at a temperature between 500°C and 700°C (Klug et al., 2013; Park et al., 2014; Bridgwater, 2012). Fast pyrolysis occurs in very few seconds and biomass decomposes in aerosols, vapors and charcoal, obtaining three by-product: Bio-oil, syngas and bio-char (Balat et al., 2009; Heo et al., 2010). It is important that biomass particles reach an optimum process temperature in order to increase bio-oil yield and minimize the formation of bio-char. According to the reviewed literature, rice husk appears to have better performance than other agricultural residues to obtain bio-oil, as shown in Table 10.

Table 10. Yields of pyrolysis products from agricultural residues under different conditions

Agricultural residue	Heating velocity (ºC min^{-1})	T (ºC)	Bio – oil (wt%)	Syngas (wt%)	Bio – char (wt%)	Ref.
Hazelnut shells	7	400	20.1	18.9	47.5	Putun et al (1999)
		700	20.8	26.7	37.5	
Rapeseed cake	30	400	45.2	26.9	28.0	Onay and Kochar (2003)
		700	47.7	32.5	19.8	
Cotton stalk	7	400	20.3	26.6	30.3	Putun et al (2005)
		700	18.6	32.0	25.6	
Rice husk	7	420	53.0	12.0	35.0	Zheng (2007)
		450	56.0	15.0	29.0	
Rice husk	200	500	36.0	16.0	48.0	Tsai (2007)
Rice husk	10	600	30.0	32.0	38.0	Hsu (2015)
Rice husk	n.d.	450	50.0	20.0	30.0	Heo (2010)
Rice husk	n.d.	450	70.0	26.0	4.0	Alvarez (2014)

n.d.= no data

Bio-oil from fast pyrolysis is a dark coffee liquid principally composed of water, carboxylic acids, carbohydrates and other chemical components, which can be recovered for the food industry or chemicals (Yanik et al., 2007; Karaosmanogly et al., 1999). Bio-oil is considered as a source of second generation biofuels (Zheng, 2007; Wang et al., 2007; Zheng, 2008; Sensoz and Angin, 2008), reaching an HV of 20 MJ/kg. However, its HV is lower than that of gasoline (44 MJ/kg) or diesel (42 MJ/kg). Additionally, bio-oil can be stored, transported and used in boilers and furnaces (Balat et al., 2009). Although it is related to the traditional pyrolysis processes in charcoal making, fast pyrolysis is an advanced process with carefully controlled parameters to obtain high yields of liquid products (Bridgwater, 2008).

The syngas by-product contains a mixture of gases such as hydrogen, carbon monoxide, methane, nitrogen, carbon dioxide and low molecular weight hydrocarbons. This type of gas is generally reused in the same process of fast pyrolysis due to its characteristics and the amount is sufficient to cover the entire process of pyrolysis (Park et al., 2008; Chen et al., 2011). Syngas can also be used as fuel in boilers, in the drying processes of biomass and as raw material for producing hydrogen (Dufour et al., 2009).

Bio-char is another product of fast pyrolysis; according to the literature, it sometimes has slightly higher energy content than bio-oil (McHenry, 2009; Bridgwater et al., 1999) and can be used as supplement or replacement coal as well as CO_2 storage and subsequent use in the soil to improve its organic content, retaining important nutrients for the growth of plants in its structure (McHenry, 2009; Heo et al., 2010).

Rice husk shows a series of characteristics that allow it to be considered an energy source through pyrolysis. The literature indicates that the most suitable technology for rice husk is fast pyrolysis, given its higher cellulose and hemicellulose content as compared to lignin and due to a higher volatile matter content than fixed carbon content (Zheng, 2007; Chen et al, 2011; Qiang et al, 2008). There are several studies on fast pyrolysis to obtain bio-oil from rice husk with different properties as shown in Table 11.

Table 11. Main properties of bio-oil from rice husk

Ref.	Guo et al (2011)	Qiang et al (2008)	Zheng (2007)	Chen et al (2011)	Chen et al (2011)
H_2O (wt%)	33.8	28.0	25.2	10.8	9.19
pH	3.36	3.20	2.80	4.10	4.40
HV (MJ/kg)	13.4	16.5	17.4	22.1	23.9
Yield (wt%)	46.4	50.0	56.0	42.7	39.5
Experimental conditions	Feeding rate (kg/h): 5, residence time (s): 1., T (°C): 450-550.	Feeding rate (kg/h): 120, residence time (s): 2., T (°C): 475.	Feeding rate (kg/h): 7.32, residence time (s): 2–3, T (°C) 465.	Feeding rate (kg/h) 1–5, T (°C): 500 using the cyclone.	Feeding rate (kg/h): 1–5, T (°C): 500 using the cyclone coupled with hot vapor filtration.

According to Table11, HV and yield values vary widely from 13.4 to 23.9 MJ/kg and from 39.5 to 56 %wt, respectively, due to different operating conditions and rice husk composition. The bio-oil obtained from rice husk by fast pyrolysis is a complex organic compound that contains water, acids and heterocyclic substances (Wang et al., 2012). The chemical composition of the bio-oil obtained from rice husk can be identified through Gas Chromatography/Mass Spectrometry (GC-MS). Some of the observed components include acids, alcohols, ketones, aldehydes, phenols, esters, sugars, furans, guaiacols and multifunctional compounds (Chen et al., 2011; Lu et al, 2012). Different studies have identified a wide variety of these components ranging from 23 to 112 components (Heo et al., 2010; Qiang et al., 2008; Chen et al., 2011; Worasuwannarak et al., 2007; Lu et al., 2012; Lu et al., 2011), which are generated due to operational factors and the complexity of the chemical reactions when obtaining bio-oil. The components identified through a GC-MS analysis can be clustered, as shown in Table 12. Furthermore, the compounds do not contain polyaromatic hydrocarbons, which are carcinogenic and/or mutagenic (Qiang et al., 2008).

Table 12. Main chemical components of bio-oil from rice husk (Alvarez et al., 2014)

Group of components	**(Yield %)**
Acids	7.07
Aldehydes	1.72
Ketones	8.65
Phenols	8.85
Ethers	2.73
Carboxylic anhydrides	1.08
Furans	3.97
Saccharides	1.12
Nitrogenated compounds	0.97

It is also important to consider that bio-oils contain some volatile and nonvolatile components. In both cases, it is not easy to identify the complex peaks appearing in the chromatogram. The main non-condensable gases are H_2, CO, CO_2, CH_4 and C_xH_y. Thermogravimetric analysis (TGA) is a technique used to characterize evaporation properties, thermal decomposition and combustion of bio-oils, which can be visualized by weight loss (TG) and weight loss rate (or gassing rate), which is the derivative of the TG (DTG) curve of bio-oil. According to the literature, bio-oil TGA curves obtained from rice husk through fast pyrolysis identify a starting weight loss at 200°C, reaching a noticeable loss between 350 °C and 500 °C (Qiang et al., 2008; Chen et al., 2011; Demirbas. 2001). The first stage shows rapid mass decrease caused by cellulose decomposition. In the second stage, lignin is decomposed through pyrolysis and its char burned through combustion (Gani and Naruse, 2007). Furthermore, the bio-oil DTG curve at different temperatures has two to three peaks, where light volatiles evaporate.

There are several methods to improve bio-oil quality, including the use of catalysts like zeolites and rice husk ash (Muhammad et al., 2013). This method can improve HV. Another alternative method is the exchange between nitrogen gas fluidizing medium and the gas developed in the pyrolysis, achieving a bio-oil yield of 60% and an HV of 24.8 MJ/kg (Heo et al., 2010).

Direct combustion and fast pyrolysis are among the most studied technologies for obtaining energy, achieving yields of 98% and 60%, respectively. Direct combustion is still the most used technology in industrialized countries due to its economic viability and domain of use. In contrast, for developing countries, nearly 90% of rice husks are burned in open field and/or disposed of in rivers or seas. The modernization of biomass technologies, leading to more efficient biomass production and conversion, is one possible direction for biomass use in developing countries. Technically, both technologies, direct combustion and pyrolysis, are feasible. Direct combustion is still the simplest and most appropriate technique to adapt and use in developing countries that have small rice husk availability for drying, using a fluidized bed combustor.

CHAPTER IV

Cost and environmental impacts for obtaining one ton of rice husk in Peru

Having identified the potential of rice husk as energy source, it is necessary to analyze the economic viability and to identify its impact on the environment compared to another solid fuel alternative. To calculate the costs and environmental impacts of rice husk, the agricultural and milling phases were considered.

4.1 Rice production in Peru

The rice Oryza Sativa, of Asian origin, is a grass plant with a phenological development of 150 days, divided in three periods (Agriculture Ministry, 2012; Orbegoso and Prado, 2013), as is shown in Figure 2.

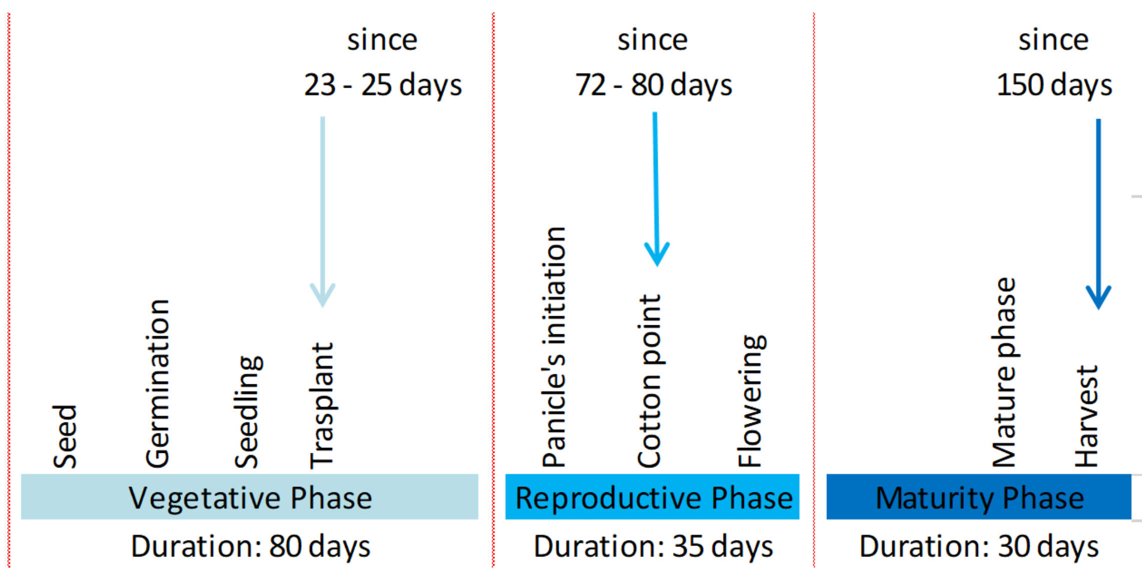

Figure 2. Oryza Sativa rice phenological development

The most commonly used seed varieties in the selected location are IR43 and Tinajones, because its roots have the ability of tolerating permanent immersion in hypoxic soils, according to the interviews to the representative of the mills guilds, Dr. Carlos Bruzzone (specialist in rice varieties and research director of Hacienda El Potrero SAC), rice seed supplier, as well as four farmers. Generally, rice campaign occurs once a year because of limited water availability in the Peruvian coast; the seeding is performed from January to March, and the harvest takes place from May to August. The product of the agricultural rice phase is rice with husk, which is known as paddy. The amount of cultivated hectares and annual production of paddy were used in order to identify the location of the main producers of paddy. The Northwest of Peru, integrated by the cities of Piura, Lambayeque and La Libertad, was selected because it produces 41% of total national production of paddy, as shown in Table 13.

Table 13. Geographic location of the paddy production in Peru (year 2015)

Geographic Location	Cultivated Area (ha)	Annual production (t)	Average yield (t /ha)	Share
North coast (Lambayeque, Piura, La Libertad)	139,652	1’302,965	9.33	41%
Central forest (San Martín)	90,069	682,497	7.57	22%
Forest (Loreto, Amazonas)	77,547	443,906	5.72	14%
Rest of the country	92,232	722,032	7.82	23%
Total	399,500	3’151,400	7.88	

Data source: Ministerio de Agricultura y Riego del Perú, 2016. Lima, Peru.

According to the interviews, because of improving the agronomic handling, the average paddy yield has reached between 8.5 t/ha and 9.5 t/ha in the selected area because of the improvements in agronomic management. Farmers have been supported by the National

Institute of Agricultural Innovation and Board Water Users of Lambayeque during the last years.

On the other hand, the Food and Agriculture Organization of the United Nations (FAO) recommends some adequate conditions for rice culture (Ministerio de Agricultura y Riego del Perú, 2012). These are shown in Table 14.

Table 14. Recommended conditions by the FAO to the rice farming

	Minimum	Optimum
Temperature to germinate (ºC)	10	30 – 35
Temperature to growth of stalk, leaves and roots (ºC)	7	23
Temperature to blossom (ºC)	15	30
Texture of soil	Sandy - Clay	
pH	6.6	
Humidity (%)	70 - 80	

The temperature of the selected area ranges between 20ºC and 30ºC, the humidity ranges between 72% y 84%. Environmental humidity does not have direct effects on rice farming, but it could influence the attack degree of pests and diseases. Considering these parameters, the selected area has adequate climatic conditions to cultivate rice. However, for a good crop yield, it does not only need adequate climatic conditions, but also good soil. In this sense, the characteristics of some soil samples of the selected area were obtained from the National Institute of Agricultural Innovation, these are shown in Table 15.

Table 15. Soil characteristics at the Northwest of Peru

	M1	M2	M3	M4	M5	M6
pH	7.6	7.4	7.40	7.30	7.00	7.6
Elect. Conduct. (mhos/cm)	4.08	4.00	3.40	2.15	1.52	2.04
O.M. (%)	1.27	0.43	1.65	2.32	2.78	0.85
P (ppm)	7.30	6.20	7.70	7.60	6.70	7.50
K (ppm)	352	306	324	412	326	336
Calcar. (%)	2.70	2.60	2.82	0.40	2.53	0.46
Texture	Sandy loam	Sandy loam	Sandy loam	Silt loam	Sandy clay loam	Sandy clay loam

As shown in Table 15, soil pH is slightly basic (7.1 – 7.6) with sandy loam texture, some parts of the soil are clay loam, low in organic matter (0.43% - 2.78%), moderate in phosphorus (6.20 ppm – 7.70 ppm) and high in potassium (306 ppm – 412 ppm). For that reason, it is necessary to be careful with the agronomic handling and the irrigation system.

Rice is the most important agricultural product of Peru contributing 8.23% to the agrarian GDP in 2012 (Ministerio de Agricultura y Riego del Perú, 2012). The surface area for cultivation in the 2012 agronomic period was 2,185,000 ha and about 400,000 ha were farmed with rice, whereas the surface of the second most important crop –yellow corn– just reached 296,900 ha (Ministerio de Agricultura y Riego del Perú, 2012). Although the acreage differs from year to year, it rose between 2002 and 2012 at an average of 3.6 %, reaching roughly 400,000 ha in 2012, as shown in Figure 3.

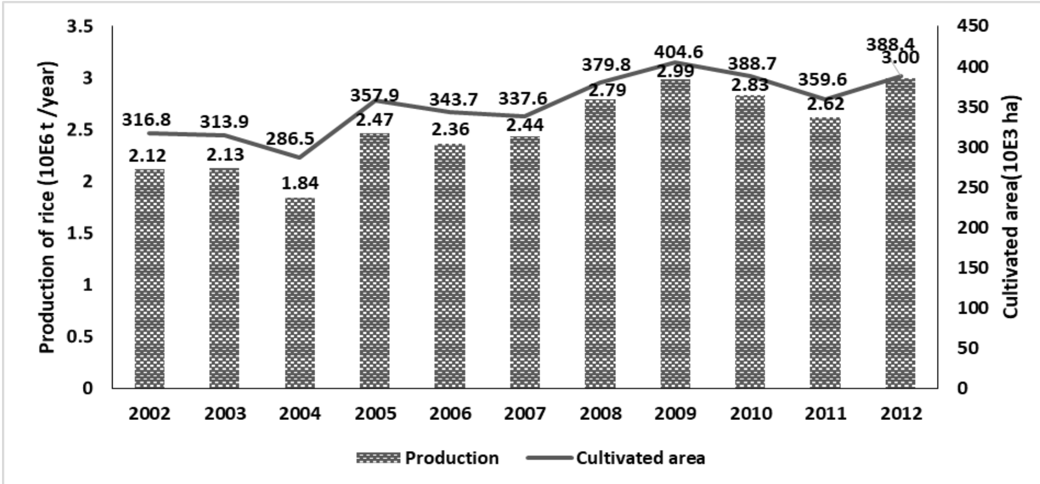

Figure 3: Production and cultivated area of rice 2002-2011
Source: Ministerio de Agricultura y Riego del Perú, 2012

The chart also illustrates the development of the production reaching about 3,000,000 tons in 2012. This unprocessed product is the so called (green) paddy.

Figure 4 displays that prices have been stable with a slightly decreasing tendency for farmers in the last years (Ministerio de Agricultura y Riego del Perú, 2012). In 2012 they obtained 0.34 US$/kg.

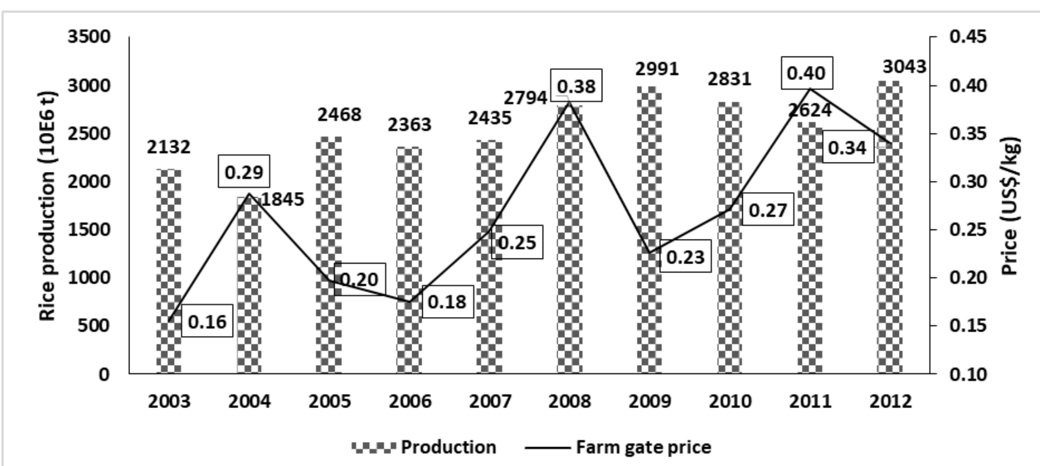

Figure 4: Rice production and farm gate prices 2003-2012
Source: Ministerio de Agricultura y Riego del Perú, 2012

The profitability for rice growers is between 600 and 850 US$/ha depending on the region. This figure is calculated as a function of the selling price as well as the average yield per hectare of every province and all the production costs, e. g. direct/indirect costs (Ministerio de Agricultura del Perú , 2012).

Consumer price in Peru is mainly calculated at national level as well as at the main market in Lima, the *Mercado Santa Anita.* Despite price fluctuations on the farm gate price, the retail price remained mainly constant with an uptick, as shown below (Ministerio de Agricultura y Riego del Perú, 2012) in Figure 5.

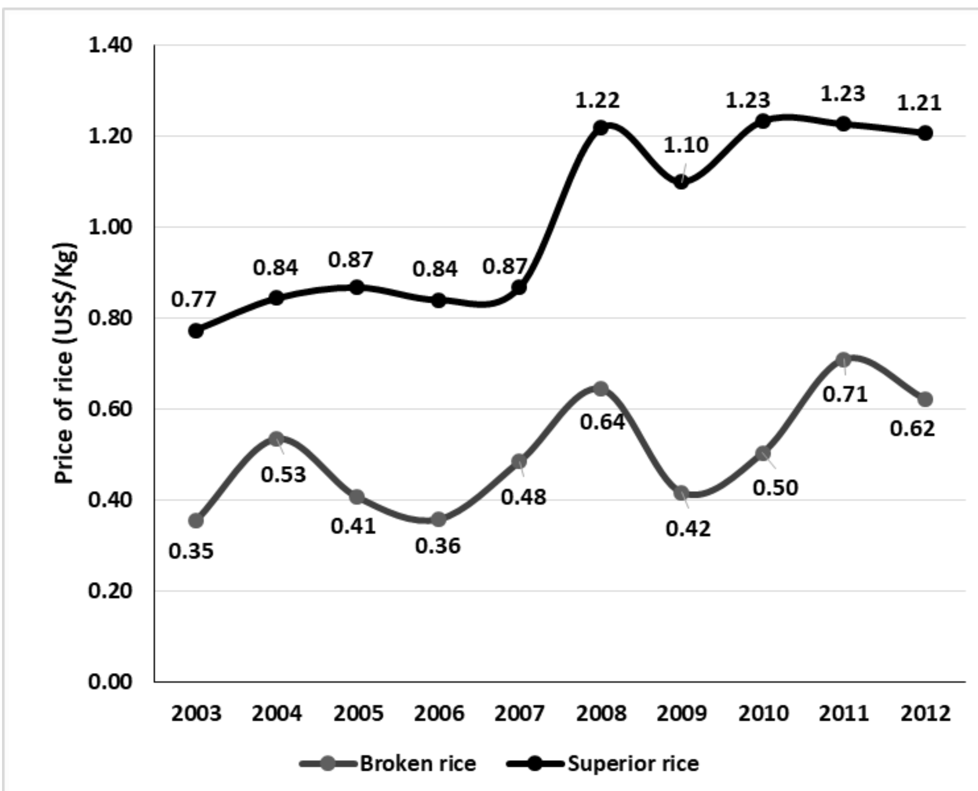

Figure 5: Retail prices for rice 2003-2012 at Mercado Santa Anita
Source: Ministerio de Agricultura y Riego del Perú, 2012
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Peru´s rice processing market consists of basically four mayor participants:

- Farmers: About 100,000 cultivators generating approximately 161,300 full time jobs. While about 70% of the farms can be seen as small entities cultivating less than 20 ha, 30% of them are regarded as large with more than 20 ha of cultivated area.
- Suppliers: Various enterprises in mainly two business categories.

  Agronomy: soil analysis and seeds, fertilizers, pesticides sale.

  Technical service: sale, renting, and service of agricultural equipment.
- Millers: Approximately 627 registered mills and an unknown number of small and simple mills (some are mobile) in remote areas.

  Processing (cleaning, peeling and drying) of paddy.
- Wholesalers, retailers and exporters.

The last three participants mentioned are mainly huge businesses processing 99% of Peru´s rice in the whole country.

Rice has not only a big economic influence, but also a social impact. Firstly it is one of the most important crops of the country and its handling offers many jobs. Secondly, Peruvians have a high per capita consumption of 63.5 kg/year. This is why changes in the market, e. g. rising prices, can cause social effects. Finally, the production of the plant requires a huge amount of water. One has to be aware of the improvements and problems – social and environmental– they might cause in the long-term (Ministerio de Agricultura y Riego del Perú, 2012).

4.2 Agricultural phase

The agricultural phase is divided in three stages: seedling, crop in definitive field and harvest (Abril, 2009; Orbegoso and Prado, 2013). The seedling yield is 1:20, for instance, one hectare of seedling yields twenty hectares of crop in definitive field. The activities carried out in each stage are shown in la Figure 6.

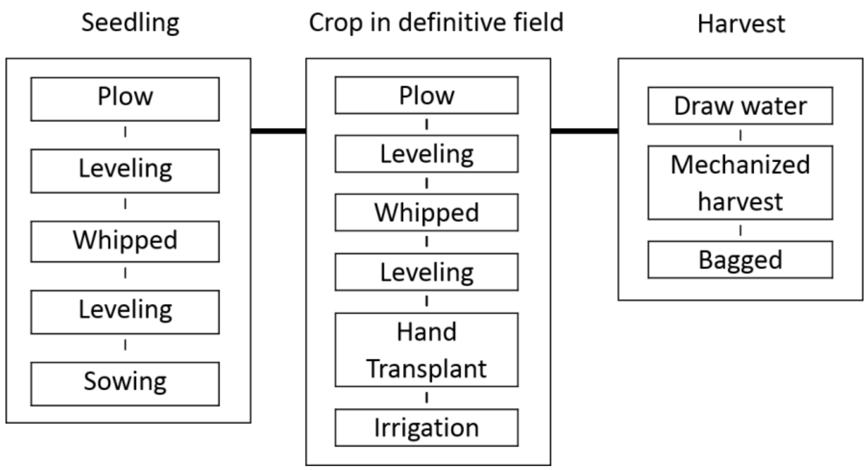


Figure 6. Activities in each stage of the agricultural phase

The resources consumed during the agricultural phase are diesel, seed, water, fertilizers, herbicides and pesticides. To prepare the soil it is necessary to use three kinds of similar machineries: the farming tractor, which is used to flip the soil and to crumble clods; the farming disc tractor, which is used for tilling the wet soil, after which, the tilled, wet fields are leveled with a rear-mounted tractor blade (the farming tractor with blade). These machines require diesel for their operation. Certificated seeds are bought in two seedbeds located in the study area. All fertilizers, herbicides and pesticides are generally imported from Russia and China. The consumption of materials and fuel as well as the emissions in the crop fields to obtain one ton of paddy are shown in Table 16.

Table 16. Inputs and Outputs for one ton of paddy

Inputs	Unit	1 ton of paddy	Outputs	Unit	1 ton of paddy
Diesel	l	13.8	Ammonia (NH_3)	kg	5.7
Water	m^3	1634	Nitrous oxide (N_2O)	kg	1.2
Seed	kg	9.4	Nitrogen oxides (NO_X)	kg	2.13
Fertilizers			Carbon dioxide (CO_2)	kg	40.16
Urea	kg	55	Methane (CH_4)	kg	8.83
Ammonium Sulfate	kg	39.6	Nitrate (NO_3^-)	kg	34.9
Diammonium phosphate	kg	26	Phosphorus (P)	g	58
Potassium Sulfate	kg	23.5			
Herbicide	g	540			
Pesticide	g	135			

Water is very important, considering that in the Peruvian coast it practically does not rain; the discharge of the rivers determines the availability of this resource. Rivers Chira, Santa and Tumbes have large water flows, whereas rivers Chancay and Jequetepeque have limited flow. In view of that, reservoirs and dams Poechos, San Lorenzo, Gallito Ciego and Tinajones have helped to provide water during partial drought. The area of study consumes water from reservoir Tinajones, predominantly, which has a storage capacity of 385 million m^3 of water. In addition, the rice crop has a good growth and nutrition in flooded soils, which feature a very efficient system for air flow; therefore, there is high water consumption, reaching 14,000 m^3 / ha or 1634 m^3/t paddy. Thus, one of the major difficulties to cultivate rice is the insufficient or inconsistent water supply, which sometimes, delays the rice campaign start or affects its performance.

Besides water consumption, the active elements were identified for each fertilizer as well as the amounts consumed per ton of paddy, which is shown in Table 17.

Table 17. Active element consumption per ton of paddy

	Active element	Amount (kg active element/ton paddy)
Urea (46% N)	N	20.39
Ammonium Sulfate (21% N)	N	6.74
Diammonium phosphate (46% P_2O_5)	P_2O_5	9.76
Potassium Sulfate (50% K_2O)	K_2O	9.52

Most of the farmers (90%) perform mechanized harvest, the machine is known as "combinada" and it requires diesel for its operation. Generally, machines are rented because in the Peruvian coast there is a campaign per year, but poor machine maintenance could lead to pest problems.

4.2.1 Costs for obtaining one ton of paddy

The direct and indirect costs of agricultural stage were calculated according to the data in Table16, the Ministry of Agriculture and Irrigation of Peru, and the farmers interviews. Data are shown in Table 18.

Table 18. Costs of the agricultural stage

Item	**Cost (US$/ha)**	**%**
Seedling	255.5	9.95
Supplies (fertilizes, water, pesticides, herbicides, others)	867.6	33.81
Machinery	397.0	15.46
Labor	556.1	21.66
Transport	118.2	4.6
Indirect costs	372.7	14.52
Total	2567.1	100

The share of the supplies reaches up to 33% of the total cost, whereas labor cost reaches 22% approximately. Considering the yield per hectare of 8.5 t, the cost is 302 US$/t paddy.

4.2.2 Environmental impacts for obtaining one ton of paddy

The evaluation considered environmental impact, the scope of the agricultural phase (from seedling to harvest stage) including the production of fertilizers, pesticides and herbicides applied to the paddies, as well as the production of the utilized diesel fuel.

The following impact categories for the environmental assessment of this study were considered: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and water depletion (WD). GWP was used because of the specific goals to reduce the GHG emissions. Moreover, developing countries, in which most of the worldwide rice production concentrates, are now obliged to comply with the GHG emissions reduction objectives signed in the Paris Agreement (United Nations, 2015). On the other hand, eutrophication and acidification were included because agriculture is an important contributor to these categories (Hokazono, S. and Hayashi, K., 2012). The water depletion category was used because water is an important resource in the coast of Peru where there is water scarcity and rainfall reaches only 100 millimeters annually.

In order to assess each category, the following characterization factors were used:

a) Global Warming Potential for a 100-year time horizon (GWP100) from IPCC, 2013 (IPCC, 2013).

b) Acidification Potential (AP) from CML (Heijungs et al., 1992).

c) Eutrophication Potential (EP) from CML (Heijungs et al.,1992).

d) Water depletion (WD) from Recipe (Goedkoop et al., 2008).

The scope of the study to evaluate the environmental impacts have been from seedling to harvest stage including the production of fertilizers, pesticides and herbicides as well as the production of diesel. Field emissions were calculated using the different models indicated in the methodology. These emissions comprise direct air emissions of ammonia (NH_3), nitrous oxide (N_2O), nitrogen monoxide (NO), carbon dioxide (CO_2) and methane (CH_4), as well as emissions of nitrates (NO_3) and phosphorus (P) to water (Nemecek et al, 2015). The information of Table 16 and Simapro software were used for calculations. The environmental impacts to produce one ton of paddy, considering a yield of 8.5 t paddy/ha, reach up to 801 kg CO_2-eq, 11.6 kg SO_2-eq, 6.5 kg PO_4^{-3}-eq and 1,645 m^3 according to the impact categories: global warming potential, acidification, eutrophication and water depletion, respectively. Mainly, these impacts are generated due to fertilizer emissions from the crop field and the emissions from the flooded field; together the two contribute with up to 76% of the environmental impacts in the GWP category.

4.3 Milling phase

The paddy is transported to mills in order to obtain rice. The stages of the milling phase are: cleaning, drying, shelling, first polishing and second polishing. Residues and byproducts such as rice husk, dust, broken rice and small grains are obtained in the milling phase (Espinal, C. and Martinez, H., 2006), as is shown in Figure 7. According to the interviews with mills owners, it is important to indicate that the drying process is performed in open air and this process takes 17 days, approximately. The husk is separated from the paddy in the shelling stage and the first residue (by-product) obtained is rice husk. Subsequently, the grain passes by the polishing stages to obtain rice.

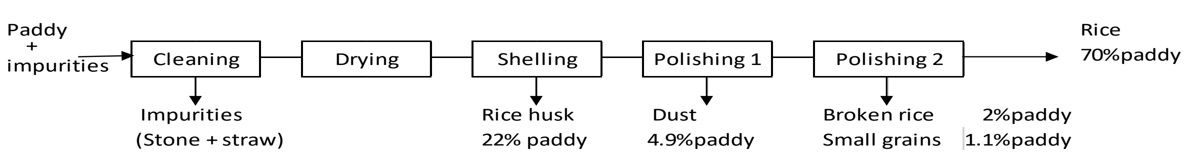


Figure 7. Stages of the milling phase

The residues and byproducts amount generated in the milling phase were given by mills owners and literature (Ministerio de Agricultura y Riego del Perú, 2012; GIDCB, 2008). The invoices of monthly electricity consumption provided by the mills we visited were used to calculate the consumed electricity quantity for one ton of rice, considering the cost of 1 kWh and monthly rice production. The consumed resources, generated byproducts and rice husk are shown in the Table 19.

Table 19. Inputs and outputs for one ton of white rice

	Unit	Quantity
Inputs		
Paddy	t	1.61
Electricity	kWh	52.8
Outputs		
Rice husk	kg	314
Dust	kg	70
Broken rice	kg	29
Smaller grains	kg	15

4.3.1 Main characteristics of the Peruvian rice husk

Fifteen samples of rice husk from Peruvian north coast were analyzed at the BIOREN laboratory in order to characterize their physical properties and chemical composition. The results were compared with other studies as are shown in the Table 20.

Table 20. Physical properties and heating value of Peruvian rice husk

Location	Volatile Matter (wt%)	Fixed Carbon (wt%)	Ash (wt%)	Heating Value MJ/kg	Ref.
Taiwan	80.45	8.60	10.95	17.40	Wang et al (2012)
Spain	70.50	16.6	12.90	16.80	Alvarez et al (2014)
Brunei	68.25	16.92	14.83	16.10	Muhammad et al (2013)
Peru	63.64	18.74	17.62	14.6	Calculated in this study
China	51.98	25.10	16.92	13.40	Fang et al (2004)

These results show that Peruvian rice husk characteristics are in the range of other previous studies and that it is a good alternative as a solid biofuel. Also, the direct relationship between volatile matter and heating value is validated, considering the different studies. In accordance with Table 21, the composition of Peruvian rice husk is very similar to the composition of rice husk from other countries; however, the S content is insignificant in the Peruvian case, which is a positive parameter for the combustion process.

Table 21. Ultimate analysis of Peruvian rice husk

	Values in dry basis wt%			
Component	**Brunei** Muhammad et al (2013)	**China** Fang et al (2004)	**Colombia** Varón (2005)	**Peru Calculated in this study**
C	39,48	37,6	39,1	38.96
H	5,71	4.88	5,2	5.39
O	54.12	49.53	55.0	55.07
N	0,665	1,88	0,6	0.577
S	< 0,10	0,094	0,1	ND

Knowing the heating value, humidity and chemical composition of Peruvian rice husk is important in order to assess the drying stage.

4.3.2 Costs of obtaining one ton of rice husk

The investigation found prices in PEN as well as USD. For the comparability of the results, figures in PEN were converted to USD with an exchange rate of 3.30, which was the average rate in May 2016, determined by the BCRP (Banco Central de Reserva del Perú, 2016). This research is based on the assumption that the existing storage space can be used for various fuels. The in situ study came to the conclusion that the mills have sufficient storing area for coal. If coal is replaced by rice husk or briquettes the space occupied does not significantly change. In addition, the plants have a lot of idle stockyard that is not used yet. Therefore, prices for fuel storage are not considered.

RH is a residue of rice processing. The peeling of every grain generates this kind of waste or byproduct. Only if an additional benefit can be made out of it, e. g. as biofuel, RH can be named byproduct. Yet it is difficult to relate a price to it because RH always occurs during rice processing and usually, it is disposed. However, this research takes the 'real price' into consideration. This means that it considers the real accruing production costs consisting of the average national producer price of rice per ton, retrieved from the Peruvian Farming and Irrigation Ministry (Ministerio de Agricultura y Riego del Perú) and interviews with farmers. The direct and indirect costs of shelling per ton were obtained from the questionnaire applied to mill owners. The cost of paddy is 302 US$/t. The direct and indirect costs in the milling stage adds up to 7.3 US$/t and considering 1.6 tons of paddy to obtain one ton of rice, the total cost of rice is 491 US$/t. To estimate the RH cost, a range for the allocation percentage of the rice total cost has been considered as the cost of rice husk. The cost variation according to the allocation percentage is shown in Table 22. In this study, RH cost was considered as an allocation percentage equal to 4%.

Table 22. Variation of price of rice husk according to % allocation

Total cost of Rice (US$/t)	491	491	491	491	491	491	491	491
% RH Allocation	2%	4%	5%	7%	10%	12%	15%	17%
RH Cost (US$/t)	9.82	19.6	24.55	34.37	49.1	58.92	73.65	83.47

4.3.3 Environmental impacts to obtain one ton of rice husk

All the inputs and outputs of the milling phase, including the production of electricity as well as the processing and transport of paddy to Lambayeque where the mills are located, have been considered to calculate the environmental impacts. The paddy crop fields are located in Piura and La Libertad. The mills are located in Lambayeque, 207 km from Piura and 336 km from La Libertad. It is important, in an LCA, to consider derivative products and assign them the corresponding environmental impact. Impact allocation consists of defining the percentage of the environmental burden to each by-product. This is done according to the economic value and the weight of the by-products according to the equation shown below:

$$Ai = \frac{P_i \times W_i}{\sum(P_i \times W_i)} \tag{9}$$

Where, Ai is the allocation percentage of by-product i, P_i is the economic value of by-product i reported in US$, and W_i is the weight of by-product i reported in kg. Another method to assign the impact is only according to the weight of the outputs. The allocation percentage of the environmental impacts, using both allocation methods, were calculated using equation 9, as shown in Table 23.

Table 23. Allocation criteria for rice product, by-products and rice husk

Product	Production (t/day)	Economic Value (US$/t)	Weight Allocation (%)	Economic Value Allocation (%)
Rice	70.0	818.8	70	95.4
Broken rice	2.0	478.1	2	1.6
Smaller grains	1.1	300.0	1	0.5
Dust	4.9	228.1	5	1.8
Rice husk	22.0	18.8	22	0.7

The results show that roughly 95.4% of the total impact was assigned to milled rice, and 0.7% was assigned to rice husk, considering an economic value allocation. However, if an weight allocation is considered, the allocation percentages would be 70% and 22% for rice milled and rice husk, respectively. Certainly, there is an important difference between the two methods when assigning the environmental impacts. In this study, the allocation criteria by economic value was used, because rice is the main product of the analyzed system.

Thus, about 95.3% of the total impact was assigned to white milled rice and 0.7% was assigned to rice husk. Considering the LCI, the impact categories and allocation criteria of milling phase, the environmental impacts to obtain one ton of rice, by-products and rice husk were calculated. esults are shown in Table 24.

Table 24. Environmental impact for one ton of output

Product	GWP kg CO_2-eq	Acidification kg SO_2-eq	Eutrophication kg PO^{-3}_4-eq	Water depletion m^3
Rice	1322	18.3	10.1	2534
Broken rice	776	10.74	5.93	1487
Smaller grains	441	6.10	3.37	845
Dust	356	4.93	2.72	683
Rice husk	30.8	0.43	0.24	59

According to Table 24, one ton of rice impacts 1322 kg CO_2-eq whereas one ton of rice husk impacts 30.8 kg CO_2-eq, of which 93.6% corresponds to the agricultural phase and 5.1% to the transport of paddy rice to mills. The results have considered a yield of 8.5 t paddy/ha and the drying process in the open air.

CHAPTER V

Cost and environmental impacts for obtaining one ton of rice husk briquette and coal in Peru

Sometimes, it is difficult to handle and transport rice husk due to its very low density of 102 kg/m^3. In order to improve this situation there is the alternative of obtaining rice husk briquette. Rice husk briquette is obtained by compacting or densification of rice husk applying high compression and elevated temperature in order to agglomerate the particles.

RHB is considered as solid biofuels and used in furnaces and boilers to generate heat or steam. Generally, these briquettes have a cylindrical shape with variable diameter ranging from 3 to 20 cm and total length of 15 - 50 cm. According to the literature, rice husk briquette emits lower amounts of particulate matter than rice husk when burnt, and its HV and density ranges from 13.5 MJ/kg to 16.3 MJ/kg and from 360 kg/m3 to 600 kg/m3, respectively (Ndindeng et al., 2015; Yank et al.,2016; Thao et al., 2011).

A blocks diagram was elaborated in order to identify the different stages of the processes to obtain RH and RHB as is shown in the Figure 8.

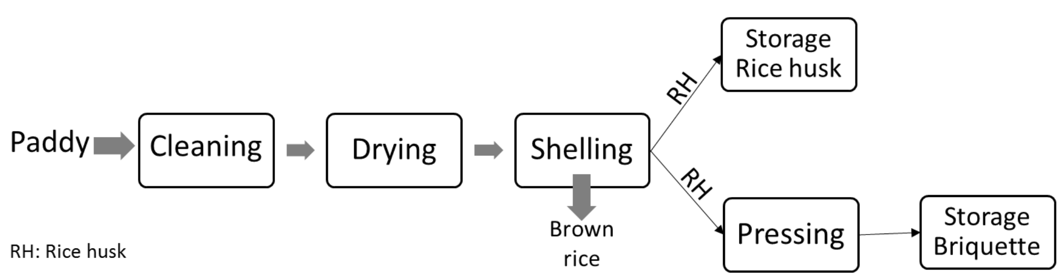


Figure 8. Stages to obtain RH y RHB

5.1 Technologies to obtain rice husk briquettes

Briquetting is an easy and cheap way to enhance the efficiency of biomass residues. Due to the densification storage, handling and transportation are improved (Kaliyan, N. and Morey, R. V., 2009). The overall fuel costs are usually decreased when using briquettes as combustible, especially in emerging countries. As the value creation is made in situ, new jobs are created which supports the local economy (El-Saeidy, E.A., 2004). Additionally briquetting protects the environment in at least two ways. Firstly avoidance of open-air burning of residues because they are used for briquetting. Secondly the deforestation rate decreases as briquettes are a substitute fuel to wood (Oladeji, J. T., 2015).

5.1.1 High pressure compaction (HPC)

Typical technologies for the high pressure compaction are the mechanical and hydraulic piston as well as the screw press (Grover, P.D. and Mishra, S.K., 1996). The biomass is usually pressed in a die at a very high pressure (150 MPa) by a reciprocating ram. Due to the compression the temperature of the biomass reaches about 120 °C. Both, pressure and temperature, liquefy the lignin. As the pressure and thus the temperature decrease the lignin cools and coagulates. Thereby it works as a binder for the biomass and forms it into solid briquettes (Fulford, D. and Wheldon, A., 2011).

5.1.2 Medium pressure compaction with a heating device (MPC)

The screw extruder press is the most common technique for the medium pressure compaction. The biomass is conveyed by a rotating screw from the silo through the barrel and compacted against the heated taper die. Heating is powered external, e. g. by electricity, and also reduces the friction. During the whole transportation process the feed material is forced to intimate sliding contact with the tube walls. The combination of three simultaneous effects: the friction on the wall, the heat from the die heater and the rotation speed of the screw (600 rpm); lead to a heating up of the biomass in the closed system. In the end of the process the material is forced through an extrusion die where the shape of the briquette is formed (Ahiduzzaman, M. and Sadrul Islam, A.K.M., 2013). Usually the shape is normally cylindrical or rectangular.

The biomass gets compressed further at temperatures of about 280 °C while forming the briquette (Grover, P.D. and Mishra, S.K., 1996). At temperatures of 280 – 290 °C the lignin can be released optimally from the husk and serves as binding material (Alam, M. et al, 2011). After cooling down the solid bridges get hardened.

Densification and removal of the steam take place simultaneously. The pressure is exerted uniformly throughout the material and finally a strong and durable briquette with consistent density is fabricated (Kaliyan, N. and Morey, R.V., 2010). The chemical processes are the same for the high pressure compaction. The main difference is that here the heat is only generated with pressure while in the medium pressure compaction an additional heating is required (Oladeji, J. T., 2015).

Table 25 gives a general overview of the two latter compression technologies, the piston press and the screw extruder. It shows that both technologies have its strengths and weaknesses.

Table 25. Characteristics between HPC and MPC technologies

	Piston press	**Screw extruder**
Maximum moisture content of raw material	10 – 15%	8 – 9 %
Wear of contact parts	low in case of ram and die	high in case of screw
Output from the machine	in strokes	continuous
Power consumption	50 kWh/t	60 kWh/t
The most important facts	• Low wear of the gear • Simple and cheap machinery High maintenance costs, especially ram and die • Medium briquette quality	• Moderate wear of the gear (only screw) • Higher initial costs • High maintenance costs • High briquette quality
		

Generally, these briquettes have a cylindrical or polygonal, e. g. octagonal shape with variable diameter ranging from 3 to 20 cm and total length of 15 - 50 cm. According to the literature, rice husk briquette emits lower amounts of particulate matter than rice husk when burnt, and its HV and density ranges from 13.5 MJ/kg to 16.3 MJ/kg and from 360 kg/m3 to 600 kg/m3, respectively (Ndindeng et al., 2015; Yank et al.,2016; Thao et al., 2011).

5.1.3 Low pressure compaction with a binder

The third technology, the low pressure compaction, needs an additional binder to achieve a solid and steady briquette. Both technologies, the mechanical and hydraulic piston press, are used but because of the lower temperatures and pressures the lignin does not develop its bonding agent properties. Depending on the country or region various binders can be used to stabilize the briquette. Biomass binders are e. g. gum arabic, starch, corn stover, switchgrass (Kaliyan, N. and Morey, R.V., 2010), yucca, glycerin (Sakkampang, C. and Wongwuttanasatian, T., 2014). Besides these renewable bonding agents also non-renewable binders exist, for instance tar, coal or sodium silicate (Oladeji, J. T., 2015). The selection of the binder is usually made regarding price and local availability. Additionally they should burn efficiently and have a high binding effect.

Some of the binding agents not only stabilize the briquette but can also improve the combustion properties or the heating value. Especially latter is the case if the binder has a higher calorific value than the main material of the briquette. An example for this is the mixture of rice husk (HV: 13.80 MJ/kg) and glycerin (HV: 24.59 MJ/kg) that leads to a higher heating value of the briquette as a function of the mixture of both biomasses (Sakkampang, C., Wongwuttanasatian, T., 2014).

Considering the three technologies, the main limitation of briquetting is that the combustible is a solid fuel. This excludes the use of briquettes in internal combustion machines, for instance car engines that require liquid fuels. Another problem occurs especially in the screw extrusion process. The life of the screw is limited as already shown in Table 25. Replacement or repair can interrupt the production process. Thirdly a weatherproof storage facility is indispensable as the briquettes do not resist direct contact with water. Moreover the heating value is lower than of mineral fuels, e. g. coal, thus a larger storage area is necessary. Finally only temperatures up to 1000°C can be attained, this restricts the application of briquettes in heat intensive industrial processes, e. g. iron melting (Oladeji, J. T., 2015).

The first choice was a technique that does not need any binder. This has several advantages for the millers:

• No need to find and negotiate with a binder supplier

• No additional transport costs

• No additional storage place (for the binder) required

• No additional environmental impacts

• Mill is in charge 100 % of the whole process

In addition, taking into account the information in Table 25, the piston press technology was chosen for this investigation with a production capacity of 5,000 tons per year.

5.2 Cost and environmental impacts of obtaining one ton of RHB

After the technology selection, the costs for briquetting can be regarded. The conventional framework is derived from the FAO study on The briquetting of agricultural wastes for fuel (Eriksson, S. and Proir, M., 1990) . In this elaboration the costs depend of the capital charge and the costs of operation.

The capital charge is a function of the asset, capital and other costs. The asset costs are formed by direct asset cost, transport and installation.

The direct asset costs describe the initial costs of assets, e. g. machines. The first step to find the convenient briquetting machine was to take a look at the properties of RH regarding it as base product of the process. RH does not need any preparatory work, e. g. shredding or dripping. Moreover thanks to a low humidity of about 9 – 14 % no additional drying equipment is obligatory. It can be processed like it is obtained after the milling process. Thus only inquiries for briquetting machines – without additional equipment – were made.

Various manufacturers in Asia, America and Europe that offer suitable briquetting lines were found and quotations were solicited, e. g. Lippel,Spänex, Radhe, Ronak, Gongyi Xiaoyi Mingyang Machinery Plant, Agico, Zhengyang, Jinan Xinneng Machinery Equipment Co. In the end the price of US$ 20,000 is an average value of the offers and reflects neither the cheapest nor the most expensive machinery.

On the other hand, as there is no market of briquetting machinery in Peru all the equipment has to be imported. The cheapest way of import heavy equipment from far away, e. g. Asia, America or Europe, is sea freight. Prices for sea freight, customs and truck transport were retrieved from the shipping companies *Maersk* and *Sealand* in Lima and are typical for this industry. All in all charges will amount to a total of 2,300 $, corresponding to transport costs.

The installation costs cover the engineering before the purchase, the planning and the realization. They are derived from the arithmetic mean of a study on five biomass briquetting plants all over the world. The price of 10.6 % is a percentage of the total amount of costs (Eriksson, S. and Proir, M., 1990).

Capital costs, all these investments are converted to periodical expenses with the help of the capital costs.

A projected investment of more than 10,000 US$ is usually financed by enterprises.

This means that one part is paid by the firm and the other part by an investor or bank.

A typical debt equity ratio in developing countries is 1.5 (60/40) (Eriksson, S. and Proir, M., 1990) for projected investments.

The purchase of a briquetting machine is an extraordinary expenditure and some mills may not have the required financial resources. Therefore a debt equity ratio of 100:0 is assumed in this elaboration. The transport and installation costs are paid with the company´s resources but all the asset costs are financed.

The costs of capital are calculated with the annuity method which combines non recurring and recurring costs of an investment regarding the interest rate and lifespan. The result – the total costs – is a constant payment for a certain period, e. g. one year in the study. This factor allows a comparison of different investments for a given period. This method was chosen because it highlights not only the initial capital costs but also the costs of capital for the entire redemption period. Especially for investments on renewable energies that usually have high initial charges and low current costs the annuity allows a good presentation and comparability of the expenses.

Firstly the so called annuity factor ***a*** is calculated as follows:

$$\boldsymbol{a} = \frac{(1+i)n * i}{(1+i)n - 1} \tag{10}$$

Where i is the interest rate, in % and n is the redemption period. Secondly ***a*** is multiplied with the asset costs Ca.

$$A = a * Ca \tag{11}$$

The redemption period of the equipment is the same as its lifespan, 10 years. An annual mortgage loan interest rate of 11.3 % was chosen in the calculation which applies for the medium-scale entrepreneurial sector where most of the Peruvian mills can be found. Thus, the obtained value of factor ***a*** is 17.2% and with the value of Ca = US$ 20,000, the annual cost reaches up to US$ 3,439. Considering an annual production equal to 5,000 tons, the capital cost reach to 0.69 US$ for one ton of RHB.

The costs of operation are recurring costs per unit or quantity that depend on the amount produced, e. g. raw material, labor, maintenance, electricity and others such as, insurances and consumables.

To calculate the raw material cost, it is important to considerate that the rice husk residue is the feedstock for the briquetting process and does not require any conditioning. Therefore the costs for the raw material can be taken over from the costs for obtaining one ton of RH. Thus, considering 1.1 tons of RH to obtain 1 ton of RHB, the raw material cost is 21.4 US$ to obtain one ton of RHB.

The labor costs depend mostly on the machinery and the type of integration of the plant as well as the kind of residue collection. The machinery selected works automated at a high degree. For instance, the whole procedure does not need any labor work, starting from the feeding until the finished product. In the end of the process the briquettes must be handled and stored manually. This work can be made by two unskilled workers. As the briquetting gear is part of a rice mill the surveillance of the equipment can be operated by the mill technician. Labor expenses of 22 US$ for a laborer per shift are retrieved form the questionnaire on milling. The mills usually work in two-shift operation. Moreover the briquetting is an in-house operation which means that the product is crafted and also utilized as a fuel at the same place. Thus, no additional personnel for handling and marketing is needed. A small percentage of his salary is assigned to the briquetting costs, reaching 2.3 US$/t RHB.

The briquetting plant is situated at the same place – the mill – where the RH accrues. After shelling the residue is kept in situ and conveyed to the briquetting machine. Therefore no additional costs for the residue collection arise.

Maintenance costs are 2 % per year of the initial asset costs. This figure is the average value retrieved from various manufacturers in the course of investigation.

To calculate the electricity costs was considered that the briquetting equipment is part of an existing mill that is connected to the electricity network. Thus only the direct running costs have to be taken into account without extra charges, e. g. connection for power supply, basic fee. For the price of electricity the average tariff for commercial customers with a consumption up to 50,000 kWh per month was selected. The price of 115 US$/MWh, respectively 0.12 US$/kWh, in 2013.

The power consumption of the machinery is given by the manufacturers and is a mean value of the different models. It varied from 45 to 60 kW. In this study was considered 50 kW.

Others are expenses for e. g. taxes, insurances and consumables. A global mean value of 1 US$/t is suggested by Eriksson and Proir and applied in this elaboration.

The capital cost and costs of operation are shown in Table 26.

Table 26. Costs for one ton of RHB

Item	Cost (US$/. / t)	%
Capital cost	0.69	2.23%
Raw material (rice husk)	21.4	67.94%
Labor	2.3	7.33%
Maintenance	0.08	0.25%
Electricity	6.00	19.08%
Others (insurances and consumables)	1.00	3.17%
Total	31.5	100%

The cost of raw material (rice husk) reaches to 68% of the total cost whereas the electricity and labor costs reaches to 19% and 7% respectively.

In order to calculate the environmental impacts, it were considered the consumptions of 1.10 tons of RH and 50 kwh to obtain one ton of RHB as well as the environmental impacts for producing RH and electricity in Peru. The environmental impacts to produce 1 kWh in Peru for the impact categories GWP, AP, EP and WD were considered, they are: 341.4 g CO_2-eq, 1.2 g SO_2-eq, 0.096 g PO^{-3}_4-eq and 0.015 m^3 water, respectively (Vázquez-Rowe et al., 2015). The results are shown in Table 27.

Table 27 Environmental impacts for one kilogram of RH and RHB

	GWP	AP	EP	WD	
	$CO_{2\text{-eq}}$	$SO_{2\text{- eq}}$	$PO^{-3}_{4\text{- eq}}$	Unit	Quantity
g/ kg RH	30.8	0.43	0.24	l/kg RH	59
g/ kWh	341	1.2	0.1	l/kWh	15
g/ kg RHB	50.93	0.53	0.27	l/kg RHB	66

5.3 Cost and the environmental impacts of obtaining one ton of coal

In Peru various types of coal can be found. These are low rank coals, e. g. Lignite and Sub-bituminous as well was hard coals, e. g. Bituminous and Anthracite. Anthracite coal is a very high quality coal with the highest carbon content and thus highest calorific value of all coal types and the fewest impurities (Mendiola, A. and Aguirre, C., 2013).

The grain size determines the category, the coal is the same for all varieties with almost similar properties. As the anthracite coal is a very high quality coal its price is about double the price of thermal coal in many countries. Because of the informality in Peru´s coal business prices are significantly lower and comparable with thermal coal prices.

Prices were retrieved from Explotación del carbón antracita: viabilidad del yacimiento Huayday-Ambara, a study on anthracite coal in a Peruvian mining area (Mendiola, A. and Aguirre, C., 2013).

The price for 1 t of anthracic coal in Peru ranged from 90 to 120 US$ in 2013 (Mendiola, A. and Aguirre, C., 2013). In the further calculations the average price of 105 US$/t is assumed. In order to calculate the environmental impacts for one ton of anthracite coal, the Ecoinvent databases and Simapro software were used and the results are: 613.4 kg CO_2-eq, 2.8 kg SO_2-eq, 3.2 kg PO^{-3}_4-eq and 1.1 m^3 water according to the impact categories GWP, AP, EP, and WD, respectively. In addition, the transport of coal from the "San Benito" mine located 400 km from Lambayeque (where the mills are located) was considered.

CHAPTER VI

Costs and environmental impacts to obtain 1 MJ of thermal energy from RH, RHB and coal

6.1 Costs to obtain 1 MJ of thermal energy from RH, RHB and coal

The heating value of RH and RHB is 14.6 MJ/kg and coal is 32.6 MJ/kg On the other hand, the dryer efficiency was considered of 50% according to the literature and employees (Marshall, W. and Wadsworth, J. I., 1993; Billiris, M.A. et al, 2014; Ahmad, M. and Mirani, A. A., 2014). Thus, the feedstock consumption to obtain 1 MJ of thermal energy from RH or RHB is 0.137 kg/MJ and from coal is 0.061 kg/MJ.

Technical information on the dryer, e. g. thermal energy required (1,213.4 MJ/h) and drying rate (1%/h), were obtained from the technical specification sheet of dryer *Suncue.91* to dry 30 t. The humidity at the beginning (23%) and the end of the drying process (13%) is retrieved from the questionnaire. Thus, it is required 12,134 MJ.

To illustrate the influence of the results in an existing rice drying plant the costs are applied for drying 30 tons of paddy in the *SUNCUE PHS-300B* dryer. It can be fired with solid fuels, e. g. RH, or coal. Table 28 shows the total fuel cost for drying 30 t of rice from 23% to 13% humidity. This process lasts about 10 h and requires 12,134 MJ to obtain 26.55 tons of dried paddy. In addition, it was considered a cost allocation percentage of 7% for the RH cost in consequence for the RHB cost as well.

Table 28. Costs of drying one ton of paddy

	RH	RHB	Anthracite coal
Feedstock consumption (kg/MJ)	0.137	0.137	0.061
Thermal energy required (MJ)	13,710	13,710	13,710
Total feedstock consumption (kg)	1878	1878	836
Cost (US$/kg)	0.020	0.032	0.105
Total cost (US$)	37.56	60.01	87.78
Cost (US$/t dry paddy)	1.25	2.00	2.93

According to Table 28, the costs to obtain one ton of dried paddy with RH is cheaper than drying with coal in 57% and cheaper than drying with RHB in 32% approximately.

On the other hand, it is analyzed the variation of the costs to obtain one GJ from RH, RHB and coal considering different cost allocation percentages for feedstock RH and RHB. The results are shown in Table 29.

Table 29. Total cost to obtain 1 ton of GJ from RH, RHB and Coal (US$/GJ)

% Cost allocation	RH	RHB	COAL
0.7%	0.47	1.90	6.41
2%	1.35	2.86	6.41
4%	2.69	4.34	6.41
5%	3.36	5.08	6.41
7%	4.71	6.55	6.41
10%	6.72	8.78	6.41
12%	8.07	10.26	6.41
15%	10.09	12.48	6.41

According to Table 29, if it is used the same environmental allocation percentage (0.7%) which was calculated considering weight and economic, besides RH is a residue, then using RH or RHB will be cheaper than mineral coal in US$ 5.9 and US$ 4.5 per one GJ generated, respectively. On the other hand, it will be convenient to use RH or RBH as energy source if the cost allocation percentage is less than 10% and 7%, respectively.

6.2 Environmental impacts to obtain 1 MJ of thermal energy from RH, RHB and coal

The heating value of RH and RHB is 14.6 MJ/kg and coal is 32.6 MJ/kg On the other hand, the dryer efficiency was considered of 50% according to the literature and employees (Marshall, W. and Wadsworth, J. I., 1993; Billiris, M.A. et al, 2014; Ahmad, M. and Mirani, A. A., 2014). Thus, the feedstock consumption to obtain 1 MJ of thermal energy from RH or RHB is 0.137 kg/MJ and from coal is 0.061 kg/MJ.

The emissions for direct combustion using rice husk with an air flow rate 2.3 m3/min and feeding rate 41.6 kg/hr obtained of the literature (Duan et al., 2013) were calculated as following: the emissions for 1 kg of burning RHP are: 4.2 g CO, 0.41 g SO_2 and 0.48 g NOx. Otherwise, the emission factors for coal were obtained of the literature (IPCC, 2007) as following: the emissions for 1 kg of burning coal are: 1,603 g CO_2, 4.90 g CH_4, 0.043 g N_2O and 17.16 g SO_2. The environmental impacts to obtain coal were indicated in the point 5.3. A summary table of the inputs and outputs to obtain paddy, rice husk and one MJ from rice husk was elaborated as shown in Table 30.

Table 30. Inputs and Outputs of the rice husk system

	Unit	Agricultural phase 1 ton of paddy (*)	Milling phase 1 ton of rice	Direct combustion 1 MJ	Emission factors
Inputs					
Diesel	l	13.8			
Water	m^3	1634			
Seed	kg	9.4			
Fertilizers					
Urea	kg	55			
Ammonium Sulphate (AS)	kg	39.6			
Diammonium phosphate (DAP)	kg	26			
Potassium Sulfate	kg	23.5			
Herbicide	g	540			
Pesticide	g	135			
Electricity	kWh		52.8		
Paddy	t		1.61		
Rice husk	g			137	
Outputs					
Ammonia (NH_3)	kg	5.7			5% of total N for DAP, 8% of total N for AS and 15% of total N for urea.
Nitrous oxide (N_2O)	kg	1.2			The model provided by Nemecek et al., 2015 was used for the emission factors.
Nitrogen oxides (NO_X)	kg	2.13			2.6% of total N for DAP, AS and urea.
Carbon dioxide (CO_2)	kg	40.16			1.570 * urea-N applied (kg/ha) = CO_2 (kg/ha)

	Unit	Agricultural phase 1 ton of paddy (*)	Milling phase 1 ton of rice	Direct combustion 1 MJ	Emission factors
Methane (CH_4)	kg	8.83			The model provided by IPCC, 2006 was used for the emission factors.
Nitrate (NO_3^-)	kg	34.9			The model provided by Nemecek et al., 2015 was used for the emission factors.
Phosphorus (P)	g	58			The model provided by Nemecek et al., 2015 was used for the emission factors.
Rice husk	kg		314		
Dust	kg		70		
Broken rice	kg		29		
Smaller grains	kg		15		
Carbon monoxide (CO)	g			0.57	
Sulfur dioxide (SO_2)	g			0.06	
Nitrogen oxides (NOx)	g			0.07	
Ash	g			22	

(*) Yield = 8.5 t paddy/ha

According to the LCA methodology, the environmental impacts were calculated considering from feedstock obtaining stage to energy obtaining stage in the four impact categories as are shown in the Table 31.

Table 31. Environmental impacts to obtain 1 MJ from RH, RHB and coal

	RH	RHB	coal
g $CO_{2\text{-eq}}$	4.23	6.98	145
g $SO_{2\text{-eq}}$	0.16	0.23	1.44
g $PO^{-3}_{4\text{-eq}}$	0.04	0.05	0.20
l water	8.1	9.0	0.07

The results show that, if RH or RHB was used as energy source instead of coal, it would avoid issuing 141 g $CO_{2\text{-eq}}$ or 138 g $CO_{2\text{-eq}}$ to environment respectively in order to obtain 1 MJ. It is important to indicate that 93% of the impacts corresponds to the agricultural phase in the GWP impact category if rice husk was used as energy source to obtain 1 MJ whereas the 74% corresponds to the combustion phase if coal is used.

CHAPTER VII

Discussion

7.1 Comparative analysis with other similar studies

According to the reviewed literature, most LCA studies of rice residues to obtain energy have focused on the thermochemical conversion to obtain electricity and in the GWP environmental impact category (Quispe et al., 2017). In addition, the paddy production stage was excluded from the system in the majority of these studies, despite the fact that it represents up to 40% of the environmental impacts (Shafie et al., 2014).

On the other hand, LCA studies on biomass conversion (forest wastes, oil crops, starch crops and agricultural residues) for heat or electricity generation through different technologies, such as biochemical conversion, direct combustion and thermochemical conversion, have been developed to calculate their environmental impacts. The environmental impact categories commonly used in these studies are global warming potential, acidification potential and eutrophication potential (Muench and Guenther, 2013). In this study, paddy production (agricultural phase) was included in the calculation of environmental impacts to generate heat. The category water depletion was considered because of the conditions of the Peruvian coast (i.e. water scarcity), which was the location of the present study. In the GWP category, as can be seen in Table 32, the results of the environmental impacts to obtain heat from rice husk in Peru are in the lower limit of the range in comparison to other studies.

Table 32. Life cycle environmental impacts from biomass conversion to heat and electricity*, **(Muench and Guenther, 2013)

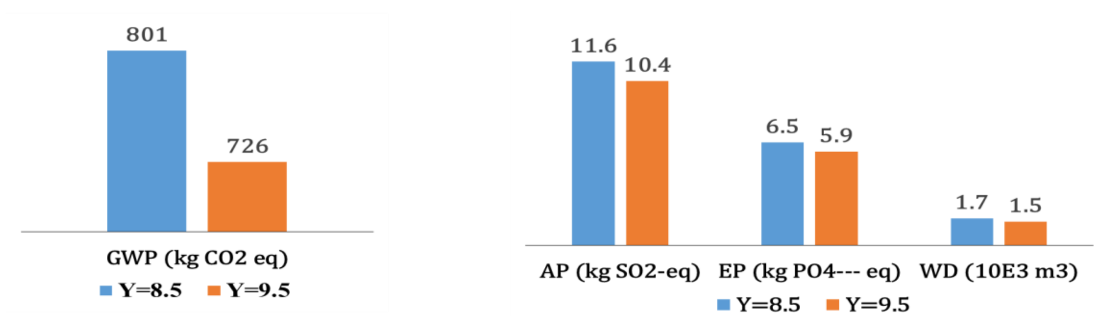
Environmental impact category	Units	Heat generation	Rice husk from Peru This study
GWP	g.CO_2 eq. / MJ	1.65 - 21.4	4.23
AP	g.SO_2 eq. / MJ	0.01 – 0.27	0.16
EP	g.PO^{-3}_4 eq. / MJ	0.00 – 0.04	0.04
WD	l water / MJ	n.a.	8.1

* It considers biochemical conversion, direct combustion and thermochemical conversion.
** Biomass: forest and agricultural wastes, oil crops and starch crops.

7.2 Sensitivity analysis

The life cycle approach for environmental analysis helps provide a broader vision to identify the greatest contribution stage to the environmental impact for decision making, not only considering the combustion stage.

According to the results obtained, in the rice husk system, the agricultural phase has been identified as making the greatest contribution to the environmental impact of obtaining heat from rice husk, whereas in the coal system, it is the combustion stage. The environmental impacts to obtain a ton of paddy rice with an increased yield to 9.5 t/ha were calculated, as can be seen in Figure 10. The results show a reduction of 75 kg CO_2-eq and 200 m^3 for each ton of paddy rice produced in the GWP and WD, respectively.

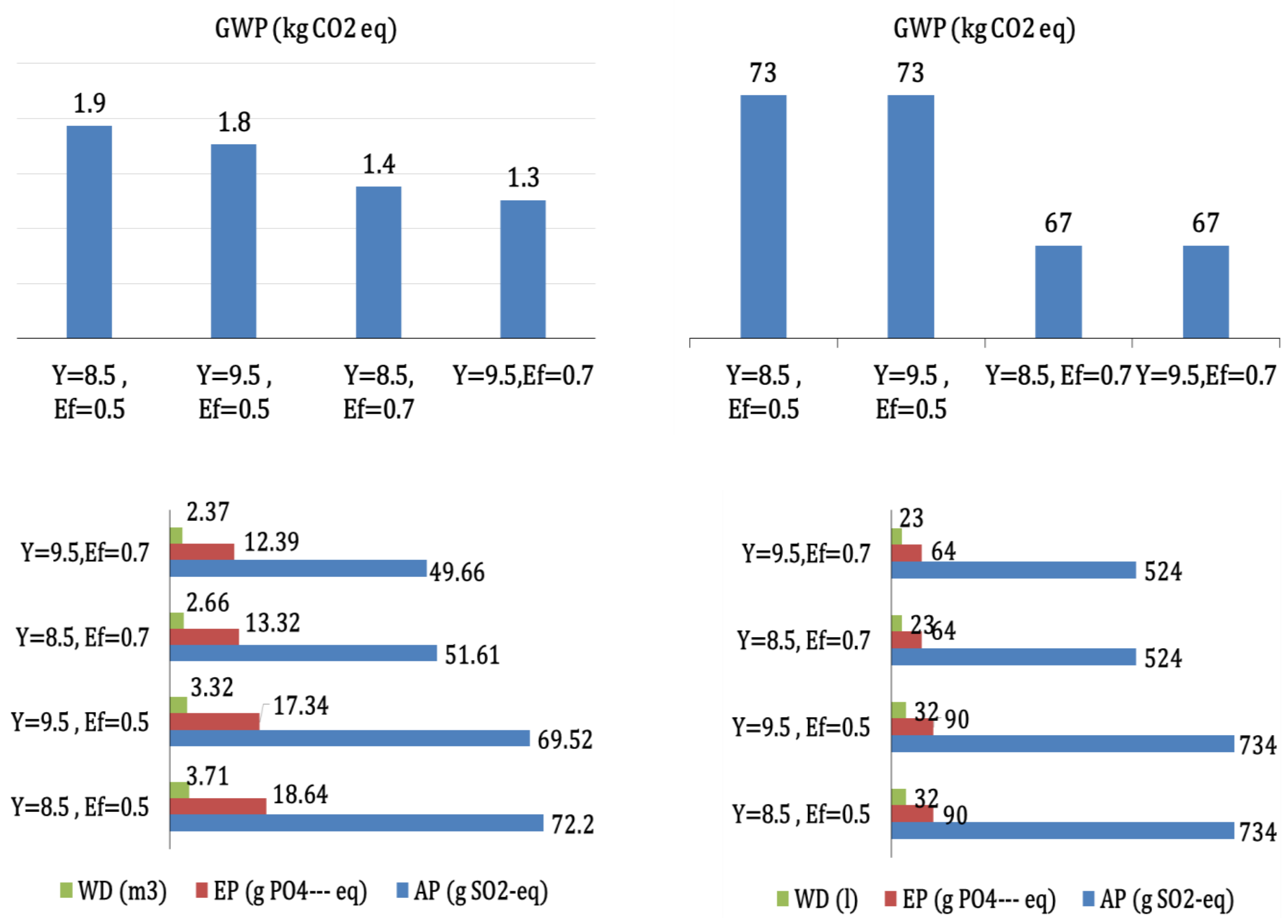


Y: Yield (t/ha)

Figure 10. Environmental impacts for one ton of paddy changing the yield

Subsequently, an analysis was done to dry one ton of paddy using rice husk and coal as feedstock, considering the variation of the paddy yield and the dryer efficiency for the environmental impact categories: GWP, AP, EP and WD as shown in Figure 11.

a) Rice husk system **b) Coal system**



Y: Yield (t/ha) Ef: Dryer efficiency (%)

Figure 11. Environmental impacts to generate 457 MJ (1 ton of dried paddy)
(a) Rice husk system (b) Coal system.

If rice husk was used to dry paddy instead of coal, with a paddy rice yield equal to 9.5 t/ha and dryer efficiency equal to 70%, the environmental impacts would drop by 98%, 97% and 89% in the GWP, AP and EP impact categories, respectively. However, if rice husk were used to dry paddy instead of coal in the same conditions, the environmental impact would increase by 99% in the WD impact category.

An additional analysis was done variating the percentage cost allocation and the percentage of environmental allocation, considering a paddy yield equal to 8.5 t/ha and a dryer efficiency equal to 50% as shown in Figure 12 and Figure 13.

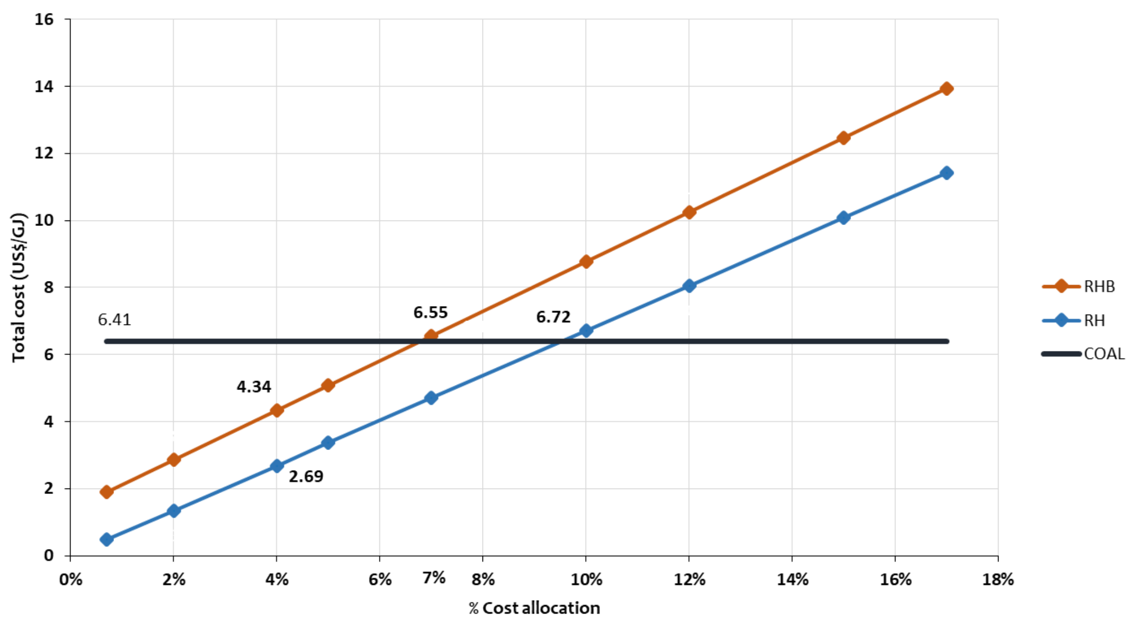


Figure 12. Total cost to obtain 1 GJ from RH, RHB and Coal

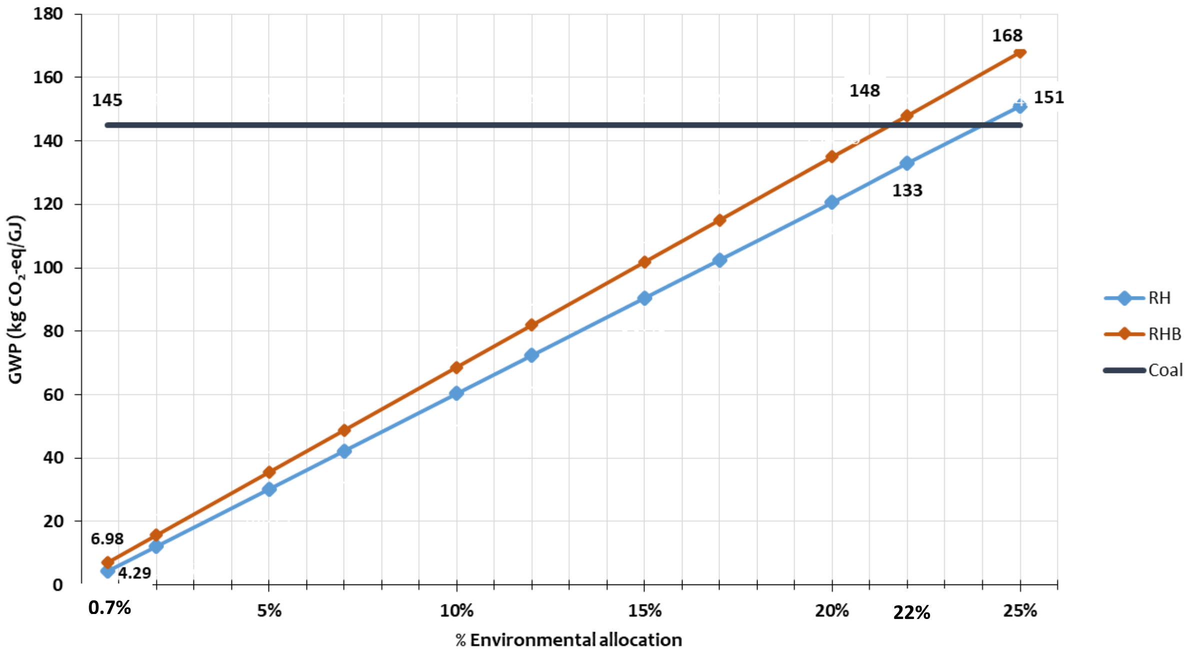


Figure 13. Enviromental impact to obtain 1 GJ from RH, RHB and Coal

According to Figures 12 and 13, it will be convenient to use RH as energy source instead of coal if the cost allocation percentage is less than 10% and the environmental allocation percentage is less than 24%. In addition, it will be convenient to use RBH as energy source instead of coal if the cost allocation percentage is less than 7% and the environmental allocation percentage is less than 22%.

7.3 Improving the paddy-drying process

The paddy rice drying process is currently done in the open air, leading to many problems such as production leak, around 13% to 23%, due to weather conditions and rodent infestation, and the use of drying space, which could be better used for storage of finished product or furnace installation. In addition, quality is lost because drying is not uniform and the finished product cannot be delivered in time. Moreover, the majority of the mills face problems when eliminating rice husk. Generally it is disposed in rivers or burned in the open air, causing environmental and health impacts, such as respiratory problems to the neighboring populations.

In this study, it is proposed to make a technological change to lower paddy humidity using a dryer instead of open air. This would improve the productivity and competitiveness of rice-producing companies by reducing losses and delays in the delivery of their products. This proposal is feasible because mill companies process between 80 and 100 tons of paddy per day generating between 15 and 20 tons of rice husk, of which 4.4 t and 5.5 t are necessary to dry all the paddy. Thus, there is enough amount of rice husk to be used in drying processes by other nearby companies and in this way, the rice husk could generate an additional economic income for mill companies.

CHAPTER VIII

Conclusions and recommendations

8.1 Conclusions

Rice husk from Peru can be used as an energy source in the drying process because of its physical properties and chemical composition and it is important to indicate that 93% of the environmental impacts corresponds to the agricultural phase in the GWP impact category if rice husk was used as energy source, whereas the 74% corresponds to the combustion phase if coal is used. The environmental impact would decrease by 97% (141 g CO_2-eq) in the GWP category per each generated MJ if rice husk were used as thermal energy source instead of coal.

These biofuels are significantly cheaper than coal, thus mills can save up to 57% or 32% of the drying costs and even protect the environment. Additionally, mills could diversify their products and sell RHB. Only 30% of the rice husk generated in Peru is used to dry all the paddy national production, thus there is enough rice husk to be used in other drying processes. It will be economically advantageous and environmentally friendly to use RH as an energy source instead of coal, if the cost allocation percentage is less than 10% and the environmental allocation percentage is less than 24%.

In addition, it will be economically and environmentally convenient to use RBH as and energy source instead of coal, if the cost allocation percentage is less than 7% and the environmental allocation percentage is less than 22%.

A general conclusion of this study is that energy recovery from RH is technically, economically and ecologically viable.

Finally, mill companies would be eco-efficient and more competitive, if rice husk was used instead of coal.

8.2 Recommendations

The study performed clarifies that the use of RH and RHB is generally feasible, cheaper and an economical alternative to the existing fuels. Moreover, the minimized environmental impact and the possibility of a new self-sufficient fuel market (RH and RHB) in Peru open long-term advantages for mills and the country, as well as related businesses.

Yet, the biggest problem in Peru is the missing market availability for RH briquetting machines. A potential buyer has found this technology in other countries. Prices vary significantly between the manufacturers and planning has to be done on their own. Therefore, many millers do not know about the technology and its benefits, or are indecisive about applying it. For a higher acceptance and wider use in Peru, these obstacles have to be solved.

Peru is an agro-industrial country where more than 16 million tons of agricultural residues are generated annually and the methodology developed in this study can help decision-making providing a more integral overview, analyzing the technical, economic and environmental viability.

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