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Local rice parboiling and its energy dynamics in Ghana

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ABSTRACT

The study presents baseline data on local rice parboiling process and its energy supply, use and impacts in three communities in the Northern region of Ghana. The process as practiced is rudimentary and time-consuming requiring several hours of soaking and wood collection. Parboiling energy is supplied solely from wood which accounts for 11.9% of the total rice processing cost. The average specific soaking energy per batch of 11 and 40 were estimated to be 16.5 and 8.4 MJ/kg, respectively while that of steaming were 18.3 and 10.3 MJ/kg, respectively. Energy consumption was mostly influenced by the amount of paddy processed and the steaming duration. These results imply that specific energy use in these communities are at least 7 times higher than the average parboiling energy reports in the literature and considerably reduces the income of parboilers. The use of improved stove, utilization of rice husk as an energy source and higher processing capacity are recommended interventions for reducing energy use and cost, mitigating the environmental and health impacts as well as improving rice productivity.

1. Introduction

Rice has become a traditional staple food in most parts of Africa with the fastest relative growth in its demand in the world (Balasubramanian et al., 2007). Ghana, like most West African countries, has more than doubled rice consumption in last decade, recording an increase in per capita rice consumption from 17.5 to 38 kg between 1999 and 2008 which is expected to reach 63 kg by 2018 as a result of rapid population growth and urbanization (Ministry of Food and Agriculture, 2009). This may be due primarily to the ease of preparing rice based food compared to other local delicacies for urban dwellers and the relative higher cost of rice for those living in rural areas. This calls for an increase in local rice production in meeting this demand. Unfortunately, local rice processing is laborious and demand thermal energy from wood with associated environmental and health implications. As part of the local processing method, parboiling, a hydrodynamic process is practiced to enhance rice quality. This process enhances head rice yield and improves nutritional and organoleptic qualities. Generally, parboiling as reported by many scholars is energy intensive. Ahiduzzaman and Sadrul Islam (2009) reported parboiling energy consumption of 1680 MJ/tonne equivalent to a specific energy consumption of 1.68 MJ/kg. Roy et al. (2006) also measured energy consumption for total parboiling (pre-steaming and steaming) and reported 2583, 2758 and 1659 MJ/tonne for vessel, small-boiler and medium-boiler processes, respectively equivalent to 2.58, 2.76 and 1.66 MJ/kg. At the laboratory scale energy consumption in traditional parboiling was also found to be 1400–2441 MJ/tonne depending on the treatment time (Kirubi et al., 2009). All these results have been based on the direct combustion of rice husk which are collected at the milling centres at no cost.

Although, parboiling energy in West Africa is known to be met by fuelwood which are either carried over long distances or purchased from wood vendors and combusted in a three stone fire (TSF) stove (Demont et al., 2012; Kwofie and Ngadi, 2016), there are currently no quantitative reports on energy use at the various stages in the value chain and how the process conditions affect consumption. Therefore, to enhance efficiency and reduce energy cost, a baseline study is required to establish current energy consumption and identify areas where improvement can be achieved. This will provide stakeholders necessary data for rice processing improvement projects.

The objectives of this study are therefore, (1) to assess the current rice parboiling process within three villages in the Northern region of Ghana, (2) estimates energy consumption and examines factors affecting energy use, and (3) evaluates the impact of energy on local rice processing.

2. Materials and methods

2.1. Study location

The study was conducted in three rice producing communities Sishiagu, Nyankpala and Vitin in the Northern region of Ghana. Sishiagu is located in the new district of Sagnarigu is at an elevation of 173 m and

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lies N9° 24.288′ W0° 52.805′. Nyankpala, located in the Tolon District is 168 m above sea level and at N9° 23.378′ W0° 51.527′. Vitin is in the Tamale metropolitan area and lies at N9° 23.133′ W0° 48.356′. The vegetative cover of the selected areas is generally Guinea Savana interspersed with short drought resistant trees and grassland. The soil is mostly of sandy loam type except in the low lands where alluvial deposits are found. Major trees species include the sheanut, dawadawa, and mango. The standard of living in the region is very low as compared to the national average (MoFeP, 2014). The people earn very little as majority of its inhabitants are peasant and subsistent farmers. Agricultural production is the main economic activity offering employment for about 74% (MoFeP, 2014). Most people are into cultivation of food crops like maize, rice groundnuts and yam. The region was selected because of its dominance in parboiled rice production in Ghana.

2.2. Field studies

The study was completed in two visits. The initial planning visit was in February 2014 followed by the second visit in June, 2014. During the initial planning visit parboilers were interviewed and observational data were also collected. Seven rice producing communities within the region were visited: Sishiagu and Sagnarigu in the Sagnarigu district, Nyankpala in the Tolon district, and Nangbu, Vitin, Kasalgu and Lamashegu in the Tamale metropolitan district. During the initial visit three groups of observational data was collected to appreciate the (a) Parboiling equipment and energy supply (b) Factors influencing parboiling energy use (c) cost of energy to rice parboiling. Energy supply data was collected from the different stakeholders in the wood supply chain — wholesalers, retailers, local wood collectors and wood users (the parboilers). Local wood collections points, parboiling centres, milling centres and rice markets were visited.

The objective of the second visit was to measure parboiling energy use and evaluates the factors influencing fuel consumption. Observations from the initial planning visit suggested eight factors may affect parboiling use. These included (a) paddy mass (b) soaking water temperature (c) soaking water mass (d) paddy to water ratio (e) steaming water mass (f) steaming duration (g) wood species (h) wood sizes. The survey information collected during the two visits are shown in Table 1. Since the practices were similar among parboilers in the different communities, only Sishiagu, Nyankpala and Vitin villages were selected for measurement during the second visit. Overall 88 observations were made during the two visits.

2.3. Energy consumption measurements

Measurements of energy consumption was completed at the parboiling centres. Steaming energy in this study was defined as the amount of thermal energy supplied to precook a batch of paddy. Soaking energy on the other hand was defined as the energy supplied to raise the soaking water temperature to the desired temperature before soaking of paddy. A 100 kg Camry two-dial platform scale — model FD100 (Zhongshan Camry Electronic Co. Ltd., China — Mainland) with minimum capacity of 2 kg and readability of 200 g was used for all weight measurement. Quantities of paddy were weighed before soaking, steaming and drying. Water temperature was measured by mercury glass thermometer with range of 0–360 °C and 1 °C resolution (Shiv Dial Sud & Sons, India). Wood consumption was estimated by finding the difference between the initial and final weight of wood. The initial wood weight was the mass of wood planned to be used. The final wood weight was the weight of unused wood, unburnt wood taken from the fire and the charcoal generated. Total distance travelled and time spent in a round trip for wood collection was recorded with Etrex 10 Garmin GPS (Garmin International, Inc., Kansas, USA). This included time spent in exchanges between people collecting wood and farmers working on their farms. Energy from human activities was not included in the study.

3. Results and discussion

3.1. Local parboiling process

3.1.1. Parboiling equipment and material supply

3.1.1.1. Stove. The three-stone fire (TSF) was the main type of stove used in parboiling. 82% (n = 51) of parboilers owned two or more of the TSF. This enables them to run two or more batches at a time especially during the peak of the harvesting season. 35% of parboilers also owned metal crafted coalpot for burning charcoal retrieved from burning wood. Although this was not used in parboiling due to its size, it was used mainly for domestic cooking and heating. The TSF is known to be inefficient with efficiency of 10–15% (Alakali et al., 2011; Bhattacharya et al., 2002; Bhattacharya and Abdul Salam, 2002). This inefficiency and health impact of the TSF have been implicated in deforestation and regional climate change (Bond and Sun, 2005; Manibog, 1984; Ramanathan and Carmichael, 2008). An improved stove with higher efficiency and lower emissions will there be required to achieve energy economy in local rice processing. Improved natural draft brick stoves with higher efficiency of 11–53% have been reported for both domestic and economic activities (Bank, 2011) and can also reduce fuel use by 33%, CO emissions by 75% and particulate matter (PM) emissions by 46%, when compared with the TSF stove (MacCarty et al., 2010).

3.1.1.2. Vessels. Two types of vessels were used in the parboiling process — a smaller vessel (50 L), which can hold up to 50 kg of dry paddy and a 75 L pot. The smaller vessel was used usually for

Table 1
Survey information.

	Observation (POT)	Soaking test (SKT)	Steaming test (STT)
Description	Researcher interview parboilers, wood retailers, millers and milled rice sellers.	Researcher measures the data at the start end of the soaking session	Researcher measures the data at the start end of the steaming session, observe the session and records time-series log of parboilers' activities
Quantitative data	Cost of harvested paddy and milled rice	Initial soaking water temperature	Steaming duration
	Transport cost	Soaking duration	Mass of paddy
	Cost of wood	Mass of paddy	Mass of water
	Rate of wood collection	Initial mass of soaking of water	Initial mass of wood
	Quantity of paddy milled	Final mass of water after soaking	Final mass of wood
		Initial mass of wood (for hot water)	Mass of complementary fuel (rice husk/bran)
		Final mass of wood	Time-series parboiling activity log
Categorical data	Type of stove	Soaking method (warm or cold)	Steaming methodology
	Type of fuel used	Type of soaking vessel	Type of steaming vessel
	Type of wood	Size of Soaking vessel	Type of stove
	Use of rice husk	Time of day	Number of fires
			Wood name
			Size of steaming vessel
			Time of day
			Ignition method

Fig. 1. Parboiling equipment and material. (a) Winnowing vessels (b) soaking and steaming vessels (c) parboiling stove with vessel (d) water supply (e) paddy supply and transport (f) bulk parboiling energy supply.

steaming but may also be used for soaking. When the larger vessel is used in soaking the hot water is produced in the smaller vessel and transferred to the larger vessel before the paddy is added. Fig. 1b shows soaking and steaming vessels.

3.1.1.3. Paddy supply. Paddy is sold in sacks of about 70–75 kg by rice farmers. Parboilers usually buy paddy in bulk and transport them by cattle to the processing centres. Paddy soaking may be done usually as full sack or half sack. However, due to smaller steaming vessel, all the parboilers steam half sack per batch or less. Paddy supply and transport is shown in Fig. 1e.

3.1.1.4. Water supply. Water is supplied from boreholes and stored in 200 L plastic drums. There are people who fetch water from the boreholes and sell to parboilers at GHS 1.2 per drum (1 US$ = 3 GHS). A drum of water supplied is used to parboil a sack of paddy. All parboilers own at least two drums for the rice processing. The water supplied is sometimes used for domestic cooking. Parboiling water supply and storage is shown in Fig. 1d.

3.1.1.5. Fuel supply. The fuel used for parboiling is wood. There are four stakeholders involved in the wood supply chain namely wholesalers, wood retailers, local wood collectors and wood users. Wholesalers transport wood from other districts (116–212 km) and sell to retailers who are central energy suppliers to the parboilers. Retailers may also buy wood from local wood collectors who collect wood from the local wood collection points (4–8 km) and transport them by bicycles or on foot. 35 $\pm$ 2.2% of the parboiling energy is supplied by parboilers themselves from the village wood collection points. Wood is sold in packs of 100–120 pieces of different wood species known as 'seat'. A 'seat' weighs about 360–450 kg depending on the wood sizes and species, sells for GHS 60 (1US$ = 3 GHS) and could be enough for processing 3–4.5 sacks of paddy. The main type of wood supplied in the area is shown in Table 2.

3.1.2. Soaking

Soaking is the first stage and the most time consuming of the parboiling process. Prior to this process, paddy is winnowed by pouring paddy over a height while the wind blows the chaff away. The winnowed paddy is subjected to sorting and washing to remove debris and dust in clean water after which it would be ready for soaking. Hot water soaking was practiced by all parboilers with soaking temperature ranging from 60 to 85 °C. The cleaned paddy is poured into the soaking vessel containing hot water and covered. The soaking duration varies across different parboilers even in the same village. Parboilers in Vitin for example, generally soak for shorter duration (10–12 h) while most of the other parboilers soak for 20–22 h. The average soaking parameters measured and estimated are shown in Table 3. In this study two soaking parameters were estimated — water to paddy ratio and the specific water uptake. The water to paddy ratio is the ratio of soaking water mass to paddy mass estimated from the water and paddy measurement taken. The specific water uptake was estimated as the average quantity of water absorbed per unit kilogram of paddy. The result shows that longer soaking duration does not necessarily result in increased

Table 2
Wood species supplied for parboiling.

Wood species	Other name	Fraction in 'seat'	HHV (MJ/kg)	Source
Azadirachta indica	Neem tree	28	18.09	Dhillon et al. (2008)
Anacardium occidentale	Cashew tree	24	18.90	Venture Renewable Energy (2012)
Tectona grandis	Teak tree	20	20.30	Günther et al. (2012)
Vitellaria paradoxa	Shea tree	10	18.20	Nhuchhen and Abdul Salam (2012)
Irvingia gabonensis	Africa mango tree	18	19.17	Biomass Energy Foundation (2009), Nhuchhen and Abdul Salam (2012)

Table 3
Average soaking parameters.

Village	Mass of paddy (kg)	Initial soaking water temperature (°C)	Soaking duration (hours)	Water to paddy ratio
Nyankpala	29.67 ± 14.57	73.33 ± 7.64	17.33 ± 4.62	0.89 ± 0.19
Sishiagu	60.67 ± 17.93	76.33 ± 12.50	20.33 ± 0.58	0.73 ± 0.36
Vitin	10.67 ± 0.58	68 ± 12.16	11.67 ± 0.58	0.89 ± 0.09

Table 4
Steaming parameters.

Village	Mass of paddy (kg)	Steaming duration (minutes)	Water to paddy ratio
Nyankpala	38.2 ± 14.2	28.4 ± 5.4	0.098 ± 0.029
Sishiagu	38.4 ± 2.2	28.2 ± 5.4	0.088 ± 0.016
Vitin	15.5 ± 5.5	28.8 ± 4.6	0.129 ± 0.045

water uptake as shown in Fig. 2, however, higher initial water temperature does. During soaking of paddy, water molecules adhere to the surface of the husk and then penetrate through the microspores of the husk into the rice kernel where they may be retained in the void or inter-granular spaces due to capillary action. This movement of water will continue as long as vapour pressure inside the grain is less than the soak water and stop when equilibrium is reached. The result shows equilibrium may be reached even before the 12th hour therefore any additional soaking time may not result in water uptake or further swelling. However, in Nyankpala where the average initial water temperature was 78 ± 3 °C, water uptake was high (0.043) about 65% more than the other villages. This is because there is a direct relationship between water temperature and rate of soaking and at higher temperature a rapid water uptake is expected. Araullo et al. (1985) reported that the rapid water uptake is due to the fact that the husk absorbs water very quickly and becomes saturated. Thus, the space between the husk and the kernel becomes filled with water immediately. Paddy spores are originally filled with air which resists entry of water at low temperature. As the temperature increases the air expands and makes way for water entry hence an increase in water uptake. Again, water absorption being a diffusion process depends on the diffusion coefficient which increases as temperature increases with a corresponding rise in energy use. The effect of these soaking parameters on energy consumption has been considered in Section 3.2.

3.1.3. Steaming

Steaming is the starch gelatinization stage of rice processing. This occurs when heat is supplied to the grain. Saturated or superheated steam may be used. In the selected villages, steaming commences right after the long hours of soaking. Some quantity of water is heated in the steaming pot to a temperature of about 80–85 °C. The sieved paddy is then transferred into the steaming pot and covered with a thick jute sack to aid heat retention. During the steaming period the water boils to produce steam which supplies heat to the paddy and

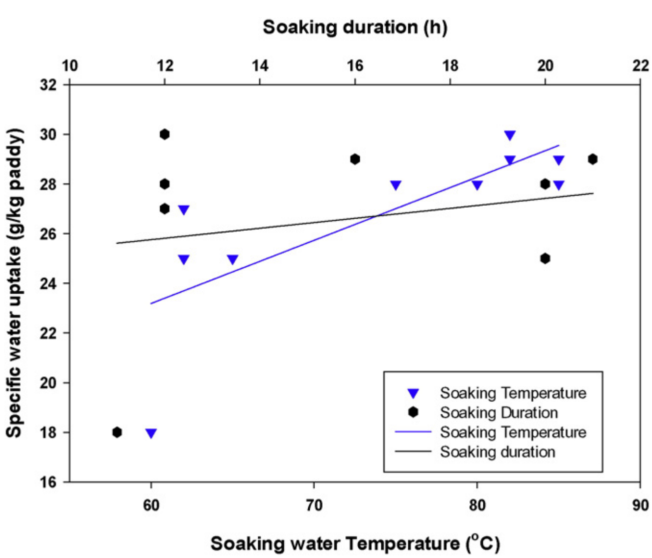


Fig. 2. An overlay plot of water temperature and soaking duration on water uptake.

also add to the moisture content after condensation. The average paddy steamed in Nyankpala and Sishiagu was about 38 ± 2.2 kg which is usually half sack. In Vitin there was variation between the paddy quantities ranging from 10.8–24 kg. The average steaming time across all the villages was about 28 min. The average steaming parameters are shown in Table 4.

Steaming was said to be over when a dense vapour appears on top of the jute sack used in covering the paddy. During the steaming period the fuel is monitored and kept at high power by supplying wood to maintain heating levels.

3.1.4. Drying

Steamed rice is dried immediately on floors using energy from the sun. The platform is usually a cemented floor or a tarpaulin laid on the floor. The tarpaulin is made of plastic sacks sewn into a bigger material for use. Drying of the steamed paddy is very important for reduction of moisture content to suitable limits for proper milling and storage. However, this type of drying is different from raw paddy drying because steamed paddy is expected to have a moisture content of about 45–50% (Araullo et al., 1985). In the study location, while steaming pot was on fire, parboilers fetch paddy and throw onto the drying platform, however, during the study steaming pot with paddy was measured before drying commenced. Due to the region's weather conditions and the quantity of paddy processed daily, complete drying was achieved in a day. The average observed drying time for half sack paddy was 7 h ± 10 min (n = 24) and paddy less than 30 kg for 5.4 ± 0.64 h (n = 9). Drying space for half sack steamed paddy was estimated to be 22.0–32.5 m^2. During the drying period, there was a regular turning and raking of the paddy to ensure uniform drying (every 30–45 min).

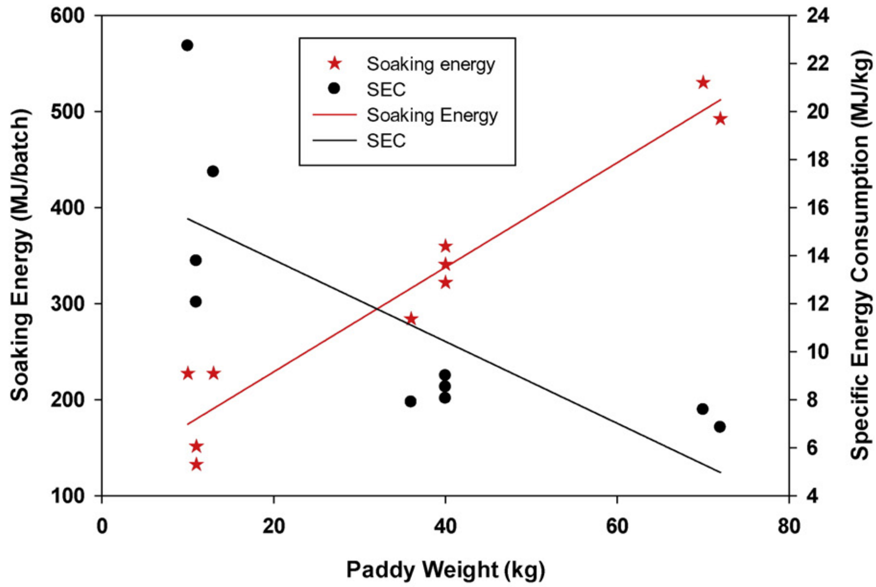
3.1.5. Milling

Milling is the final processing stage before rice is packaged for the market. The basic objective of a rice milling system is to remove the husk and the bran layers to produce edible white rice kernel for consumption. The paddy is gathered after drying and packed in sacks (75–80 kg) and transported to a nearby milling centre in the community. There are usually two or three milling centres per village. Due to the absence of grid electricity, energy for milling is supplied by diesel generators.

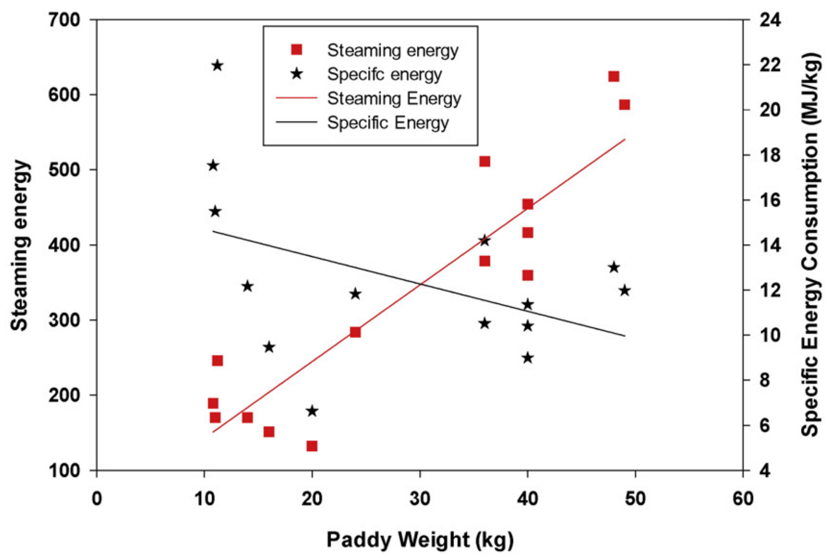
3.2. Parboiling energy consumptions and factors affecting it

3.2.1. Parboiling energy consumption

Energy consumption for soaking and steaming was estimated per batch of paddy processed across the villages which varied widely from 10.2 to 72.0 kg. Soaking energy was estimated based on the amount of wood used in heating soaking water to the desired temperature and similarly steaming energy was also based on the wood used during steaming. Different species of wood were used therefore an average value of 18.93 MJ/kg was used as the heating value for energy consumption estimation. This was estimated based on the higher heating value (HHV) for the five main wood species used and their fraction in a 'seat' in the study location as shown in Table 2. Plots of soaking and steaming energy consumption is shown in Fig. 3. The average soaking energy per batch of 11, 40 and 71 kg was estimated to be 167.7, 296.7 and 464.4 MJ/batch, respectively. This is expected because more heat is needed for the starch gelatinization as the paddy mass increases. To



(a)



(b)

Fig. 3. Variation of parboiling energy consumption with paddy weight (a) soaking (b) soaking.

allow comparison among parboilers, the data was normalised and presented as specific energy consumption (SEC) displayed in Fig. 3.

Specific soaking energy reduced from 16.50 ± 4.72 MJ/kg for a batch of 10–12 kg to 8.36 ± 0.50 MJ/kg for a batch of 36–40 kg. Although, further reduction of 1.1 MJ/kg was recorded when a batch of 70–75 kg is processed, it was however not significantly different (p-value = 0.6809) from a 40 kg batch. Steaming energy also follows the same trend. The average steaming energy per batch of 11 and 40 kg was estimated to be 194.05 ± and 408.90 ± 47.49 MJ/batch, respectively with SEC of 18.33 ± 3.31 and 10.26 ± 1.48 MJ/kg. It is clear from these results that parboilers processing smaller quantities (<36 kg) use more energy than required. This is a strong indication that parboilers could save energy if the quantity of paddy processed at a time is increased. The implication of these results are that if parboilers can increase their processing capacities to at least 40 kg, energy consumption and energy cost could reduce by up to 50%. Translating this to a bulk processing would mean, a total net energy input of 2679.43 MJ of energy would be required to process a tonne of paddy assuming a processing capacity of 40 kg/batch. The energy consumption from this study has been compared with other studies and shown in Table 5.

3.2.2. Effect of process condition on energy consumption

Besides the amount of paddy processed, other process conditions may affect energy consumption during parboiling. In the selected villages there were no strict rules on the conditions so processing conditions vary even within the same village. The effect of three process conditions – soaking temperature, water–paddy ratio, and steaming duration – on energy consumption was examined. Though, eight factors had been identified to have affected energy consumption from the initial planning visit, some factors were combined or eliminated. For example, parboilers use different wood species and different sizes in a single process therefore their effect on energy consumption could not be properly estimated. The soaking and steaming water used also depend on the mass of paddy being processed, therefore, water use was

Table 5
Parboiling energy comparison.

Parboiling system	Processing capacity (kg)	Parboiling conditions	Energy consumption (MJ/kg)	Energy type	Source
Hot water soaking	11–14	Soaking@ 60–85 °C for 12–22 h; steaming @ 85–90 °C for 3–8 min;	34.8	Wood	This study
Hot water soaking	36–40	Soaking@ 60–85 °C for 12–22 h; steaming @ 85–90 °C for 3–8 min;	18.7	Wood	This study
Laboratory scale parboiling	1	n/a	1.4–2.4	Electrical	Roy et al. (2003)
Vessel parboiling	500–1200	n/a	2.6	Rice husk	Roy et al. (2006)
Hot soaking and steaming	n/a	Soaking @65 °C for 3–4 h; Steaming @ 85–90 °C for 15–20 min;	0.4	Rice husk	Kapur et al. (1996), Kapur et al. (1997)
Hot soaking and steaming	0.5	Soaking @ 70 Steaming @ 100 °C for 10 min	0.3	Electrical	Sridhar and Manohar (2003)
Hot soaking and steaming	n/a	n/a	1.68	Rice husk	Ahiduzzaman and Sadrul Islam (2009)
Boilerless parboiling	160	n/a	5.9	Rice husk	Tiwary and Ojha (1981)

n/a = not available.

normalized and presented as water to paddy ratio which provides uniformity in the parameter for all batches.

3.2.2.1. Soaking water temperature. Soaking water temperature influences the water absorption rate. As discussed earlier, higher temperature results in better absorption and requires more energy. However, it does not appear to be so in the selected villages as shown in Fig. 4. There was no correlation ($r = 0.0474$) between water temperature and specific energy consumption, although, some correlation does exists ($r = 0.548$) between water temperature and total energy consumption. The anomaly in the observation suggest other parameters other than water temperature accounts for the variation in data. This could be explained considering that soaking energy is based on heat to the soaking water which means more energy may be expended for large amount of water at lower temperature and vice versa. Although, higher temperature may account for increase in energy use, it could not be establish in this study.

3.2.2.2. Water–paddy ratio. The ratio of water to paddy during parboiling may influence energy consumption. In both soaking and steaming, a higher ratio results in greater energy use because more water is heated. Water paddy ratio was higher in soaking than in steaming because more water was used for complete immersion of paddy during soaking and also water absorption may have reached maximum after soaking. During steaming lower ratio is required because the paddy moisture content is already high after soaking and only heat from steam is needed to complete the gelatinization. The steaming method used in all the selected villages requires very little amount of water (2–5 kg) per batch. The steaming water evaporates to produces steam and may be condensed and is absorbed by paddy. Some parboilers (13.3%) had to decant some steaming water after the process because all was not converted into steam. The water–paddy ratio was 0.5–1.15 and 0.075–0.182 for soaking and steaming, respectively. Energy consumption increases with increasing water to paddy ratio as observed in the bivariate plot of specific energy consumption and water–paddy ratio shown in Fig. 5. It appears parboilers who use ratios more than 1 during soaking use less energy but this is not exactly be true because these parboilers only heated the soaking water to 65 °C. This means a lower ratio and temperature can reduce total energy use.

3.2.3. Steaming duration

Steaming energy is determined by the steaming duration which is also dependent on the quantity of paddy processed. With the same type of vessel used in all the villages, paddy quantity variation was small and therefore the steaming energy was largely dependent on the steaming duration. The average steaming duration range from 22 to 36 min with an overall study average of 28.8 min. Bivariate plot showing specific energy consumption variation with steaming duration is displayed in Fig. 6a. The result shows an overall increase in specific energy consumption from 6.63 to 21.97 MJ/kg. A plot of simple vertical bar chart with error bars (mean ± SEM) showing the observations segregated into groups is shown in Fig. 6b. Although, Fig. 6b depicts

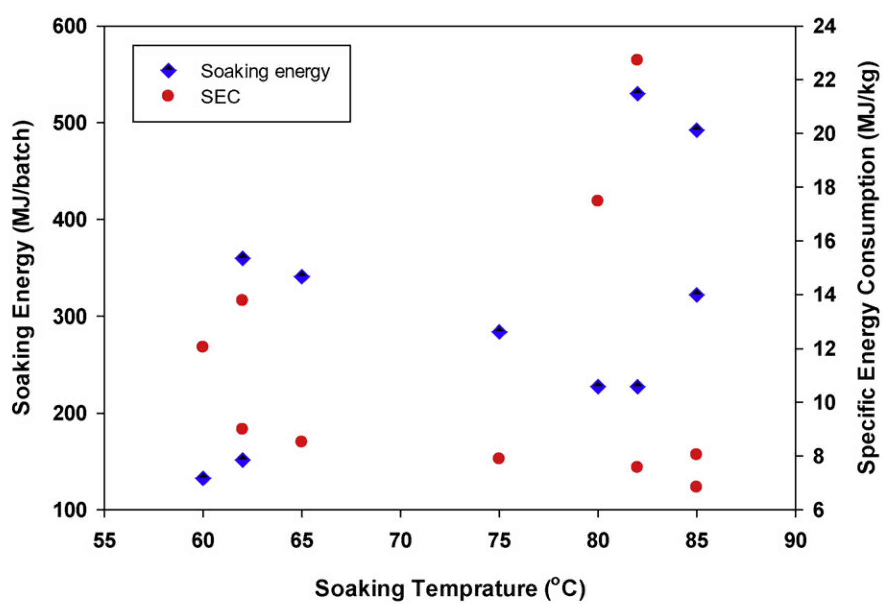


Fig. 4. A plot of soaking water temperature and energy consumption.

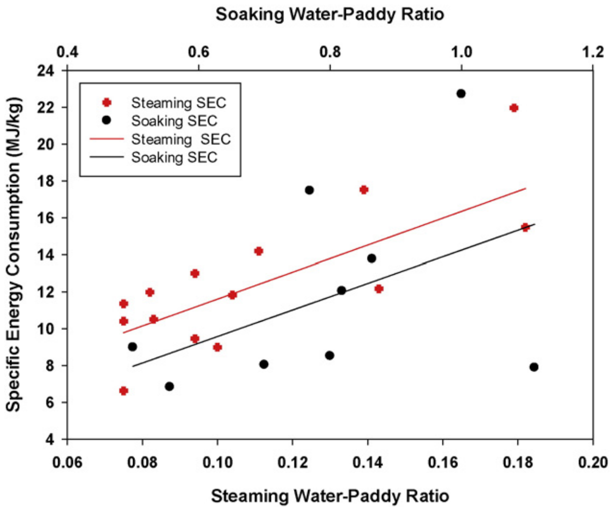


Fig. 5. Variation of soaking and steaming water–paddy ratio with specific energy consumption.

an upward trend, a comparison of means for each pair among the groups using Student's *t* test reveals that there is no statistical significance between the groups (p-value = 0.1089, 0.1175 and 0.9674). This implies that the variation in the current steaming duration among parboilers does not necessarily affect their energy consumption.

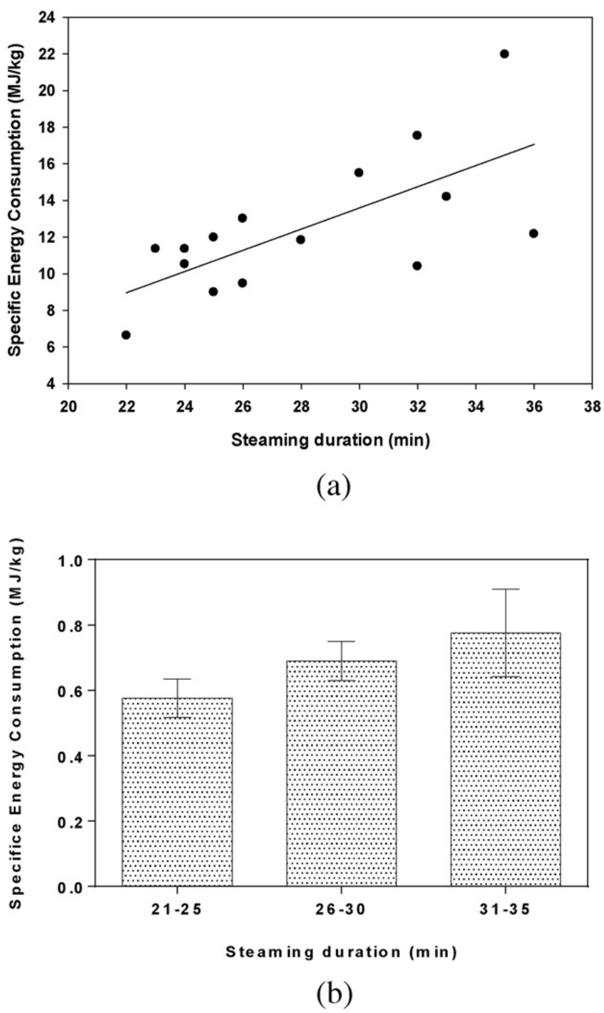


Fig. 6. Specific energy consumption and steaming duration plots (a) scatter plot (b) group bar plot.

3.2.4. Estimating parboiling energy use

Simple linear and multiple regressions were performed on the energy use for parboiling to enable prediction of parboiling energy consumption. The equations can be used for estimating soaking or steaming. Paddy mass, soaking water mass, soaking water temperature, steaming duration and steaming water mass were used as the parameters for estimation. The regression models did not include parameters such as stove type, wood dimension, wood species and parboiling vessel size. This was because all parboilers use the three-stone fire stove and same parboiling vessel hence their effect would be the same. Also, a range of wood sizes and species which could not be represented by a single quantity were used for parboiling. The regression analysis was done using forward selection due to the fewer number of variables. The estimator that explains the variation most was selected then other estimators that explain residual variations were also added until no further estimator was significant to the linear model. Table 6 shows the regression models using estimators that are statistically significant at least to the 90% significant. To avoid overfitting of a regression model with estimators which barely explain model variation, the Akaike information Criterion (AIC) was used (Akaike, 1998). Also, adjusted R-squared (R^2) which compares explanatory capacity of a regression model with several estimators was chosen over R-squared since the latter increases anytime an estimator is added to a model which may be misleading perhaps due to chance or noise in the data (Frost, 2013). Lower AIC and higher Adjusted R^2 were taken as improvement. Paddy mass, soaking water mass and soaking water temperature were the variables that significantly explain variation in soaking energy use. All soaking energy estimators had at least 10 observations. For soaking energy ($E_{soaking}$) estimation, paddy mass Eq. (1) had the least AIC and a high adjusted R^2 which explains variation in data set better than soaking water mass Eq. (4) and water temperature Eq. (5). Interestingly, when different paddy mass are considered soaking temperature seems not to be a good predictor as shown in Eq. (5) with highest AIC and the least adjusted R^2 for soaking energy estimation. This was because for different paddy quantities the energy used cannot be explained only by the water temperature. For instance, a 70 kg paddy being soaked at 60 °C consumes 2.2 MJ more energy than a 36 kg paddy soaked at 80 °C. However, developing a model using five observations with paddy mass in close range (32–40 kg) tells a different story as can be seen in Eq. (6). AIC decreases by 51.5% and adjusted R^2 improves by 0.81. This implies, for parboilers processing the same quantity of paddy, variation in their energy use would be dependent on the water temperature. The model fit (Eq. (1)) can be improved by including soaking water temperature (Eq. (2)).

Similarly, paddy mass and steaming duration can be used in quantifying the steaming energy ($E_{steaming}$) although paddy mass (Eq. (9)) explains steaming energy variation better than steaming water (Eq. (10)). Using both steaming duration and paddy mass as estimators can explain energy use variation among parboilers and gives a better steaming energy prediction with lowest AIC and a high R^2 as shown in Eq. (7). Depending on the measurement made, total parboiling energy can be estimated using the methodology chart shown in Fig. 7. Although, some Eqs. (3), (5), (6) and (10) were not included in the chart, they have been presented for discussion purposes. Eqs. (1)–(4) presents four ways of estimating soaking energy while Eqs. (7)–(10) also offers four ways of estimating soaking energy. The sum of soaking and steaming energies gives the total parboiling energy.

To estimate the total error in using the parboiling energy estimation model shown in Fig. 7, a weighted sum of error for soaking and steaming energies was used. The weighted error takes into consideration the average error of a process and its contribution to the total energy. Using data for processing 40 kg paddy, soaking was found to consume 44.2% to the total parboiling energy. Eqs. (2) and (7) were used to calculate the model soaking and steaming energies, respectively. The absolute value of the difference between calculated and measured energy during parboiling expressed as a fraction of the measured energy was

Table 6
Regression models of parboiling energy use.

Process	Estimator (MJ/batch)	Model number	Number of observations	Adjusted R^2	AIC
Soaking	$119.97^{***}+5.44^{***}\times P_m$	(1)	12	0.9268	107.6
	$21.72^{***}+(5.17^{***}\times P_m)+(1..46\times Sk_T)$	(2)	10	0.9303	111.8
	$119.97^{***}+(5.06^{***}\times P_m)+(0.47\times Sk_m)$	(3)	10	0.9184	113.4
	$150.92^{**}+4.59^{**}\times Sk_m$	(4)	10	0.7218	122.1
	$-165.53^{*}+6.40\times Sk_T$	(5)	10	0.1617	132.0
	$788.3^{***}-6.88\times Sk_T$	(6)	5	0.97704	64.0
Steaming	$-251.36^{*}+(8.69^{*}\times S_d)+(11.97^{***}\times P_m)$	(7)	16	0.8940	181.0
	$-239.93^{*}+(43.04^{*}\times St_m)+(9.03^{**}\times P_m)+(7.09\times S_d)$	(8)	16	0.9011	182.9
	$30.09^{*}+10.83^{***}\times P_m$	(9)	16	0.8436	184.7
	$-67.94^{*}+151.13^{***}\times St_m$	(10)	16	0.8095	187.9

Significance for each estimator denoted by *** < 0.001; ** < 0.01; * < 0.05; y < 0.1 or blank for no significance. The variables used are: P_m is the mass of paddy; Sk_m is the mass of soaking water; St_m is the mass of steaming water; Sk_T is the soaking water temperature; and S_d is the steaming duration.

used to estimate the error for each process. Having found the error of all data points, the mean error for each process and its contribution to the total error was estimated. The results show that soaking energy error were between 5.03 and 25.42% with a mean value of 10.95% while steaming energy error ranges 1.68–35.26% (mean error = 15.09). The average error for estimating parboiling energy was found to be 3.16–30.91% with an average value of 13.26%. The results also indicate steaming contributes the most to the estimated total error accounting for 63.5%.

3.3. The impact of energy on rice productivity

Energy supply and use affect the productivity in different ways. The impact of energy on rice processing has been examined considering the reliability of energy supply, efficiency and cost, available time, health and environment. The summary of energy impact and possible intervention for increase productivity is shown in Fig. 7.

3.3.1. Energy supply reliability, efficiency and cost

The supply of energy affects rice productivity in several ways including reliability of energy supply, energy collection time and cost of energy supply. Productivity, to a large extent depends on the availability of energy. In the selected communities 65% of parboiling energy is bought from the retailers who also buy from wholesalers. The wholesalers also buy wood from villages in other district and transport them by trucks. It takes about three to six weeks to fill up a truck depending on the season (raining or dry). Since these trucks are very old they are subject to regular breakdown which delays wood delivery for a week or two. During raining season and major event period such as festivals or funerals in the supply villages, further delays in energy supply are encountered. This unreliable supply of energy may slow the rate of processing and impact productivity. In an attempt to manage wood supply irregularity, some parboilers buy and store wood in excess.

Another notable factor impacting productivity is the cost of parboiling energy which was found to be high in the selected villages. A typical parboiling expenditures and income from rice sales are shown in Table 7. Parboiler buy harvested paddy from rice farmers in sacks of about 70–75 kg for GHS 80. These sacks are transported either by cattle, bicycle, motorbikes or cars. Water and wood are sold in barrels and 'seats' for GHS 1.2 and GHS 60 respectively. Parboiled paddy is transported to the milling centres at cost of GHS 1.5/sack and to the market at a cost of GHS 2/sack. From Table 7, energy is the second

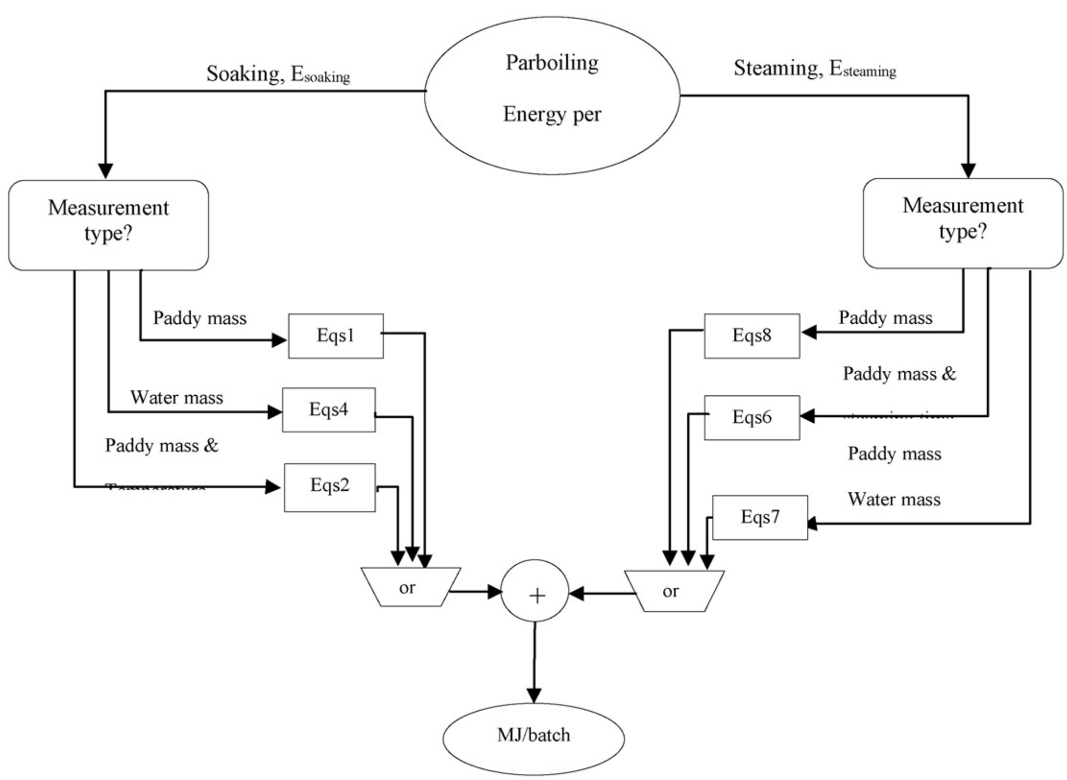


Fig. 7. Parboiling energy estimation methodology.

Table 7
Income and expenditure for processing 5 sacks of harvested rice.

Cost/income component	Unit	Quantity	Unit cost (GHS)	Total amount (GHS)	Cost fraction
Harvested paddy	Sack	5	80	400	79.1
Wood	Seat	1	60	60	11.9
Water	Barrel	5	1.2	6	1.2
Milling	Sack	5	5	25	4.9
Transportation to milling centre	Sack	5	1.5	7.5	1.5
Transportation to market	Sack	3.5	2	7	1.4
Total cost				505.5	100.0
Milled rice	Sack	3.5	200	700	
Profit				194.5	

largest cost component besides cost of raw paddy and accounts for 11.9% of the total cost. It must be noted that the energy cost is based on current practices of 10–70 kg soaking capacity and 10–40 kg steaming capacity. This cost fraction may be reduced if a cheaper alternative energy source such as the rice husk was used and processing capacities increased.

The three-stone fire (TSF) is the main type of stove used in processing. Local parboiling is energy intensive and requires 1659–2758 MJ/tonne of paddy depending on the parboiling process (Roy and Corscadden, 2012). In this study this net energy use was found to be 2679.43 MJ/tonne which requires an energy input of 17,862.87–20,611.0 MJ/tonne using three-stone fire stove with efficiency 13–15% (Johnson and Bryden, 2012a, 2012b) or 6231.23–24,358.45 MJ/tonne using improved natural draft wood stoves with efficiency of 11–43% (Johnson and Bryden, 2012a, 2012b; Lin et al., 1998). It is evident that parboiling systems in the selected study area are largely inefficient due to the use of low efficient stoves. Parboilers therefore use more wood than is required and incur high cost of energy for rice processing. The high energy supply cost could be reduced by using an improved wood stove. Again, the results from the study show the specific soaking energy could be reduced by more than 50% (from 12.05–22.72 to 6.84–7.57 MJ/kg MJ/kg) if processing capacity could be increased from 10–12 kg to 70–75 kg. A comparison of the total parboiling energy with vessel parboiling energy consumption of 2.58 MK/kg reported by Roy et al. (2006) shows that parboilers use at least 7 times more energy than required. Aggregation of processors will certainly be a possible option to improve energy use and efficiency. Therefore, if processors could work together to increase their capacity, energy cost will be reduced and rice productivity would improve.

3.3.2. Social, health and environment

The current energy option being used therefore does not only affect the income but in a broader sense their entire livelihood. Considering the fact that 35% of parboiling energy is collected by parboilers, available time to process paddy and do other things is reduced. An average of three and half hours is spent commuting to wood collection centres and back. Another four to six hours a day for three to four days is also spent gathering wood in the collection week. This lost time could be invested in processing rice if an alternative readily available energy source is provided. World Health Organization (WHO) in a recent report (WHO, 2014) stated wood collection activities in developing countries consumes a significant amount of time and limits the other income generating activities and keeps children away from school.

Besides, the above social impact, reliance on fuel wood has become a serious problem in most African countries. For example, in Ghana, tropical forest area has been reduced to a quarter in less than 50 years with an annual forest depletion rate of 22,000 ha (Duah-Yentumi and Klah, 2004). Therefore with the current wood consumption rate of 640 kg per capita coupled with forest growth dropping to less than half the demand (Duah-Yentumi and Klah, 2004) fuel wood use cannot be a sustainable energy option for rice processing. In addition, the inefficient use of wood as energy in traditional three-stone fire stove and small hand-crafted cookstoves is considered responsible for several cases of respiratory illness and death, burns, cuts, and scalds (Desai et al., 2004; Johnson and Bryden, 2012b; Wickramasinghe, 2003). Rice production process is also characterised by large quantities of rice husk, an agro-industrial residue. The husk is removed as a by-product during rice milling. For each kilogram of rice paddy, a corresponding 200–330 g of rice husk is generated (Lim et al., 2012). However, the large amount of rice husk generated during rice processing is considered as waste material and usually burnt without energy recovery. Adding to the deforestation and emissions from wood combustion, inefficient burning

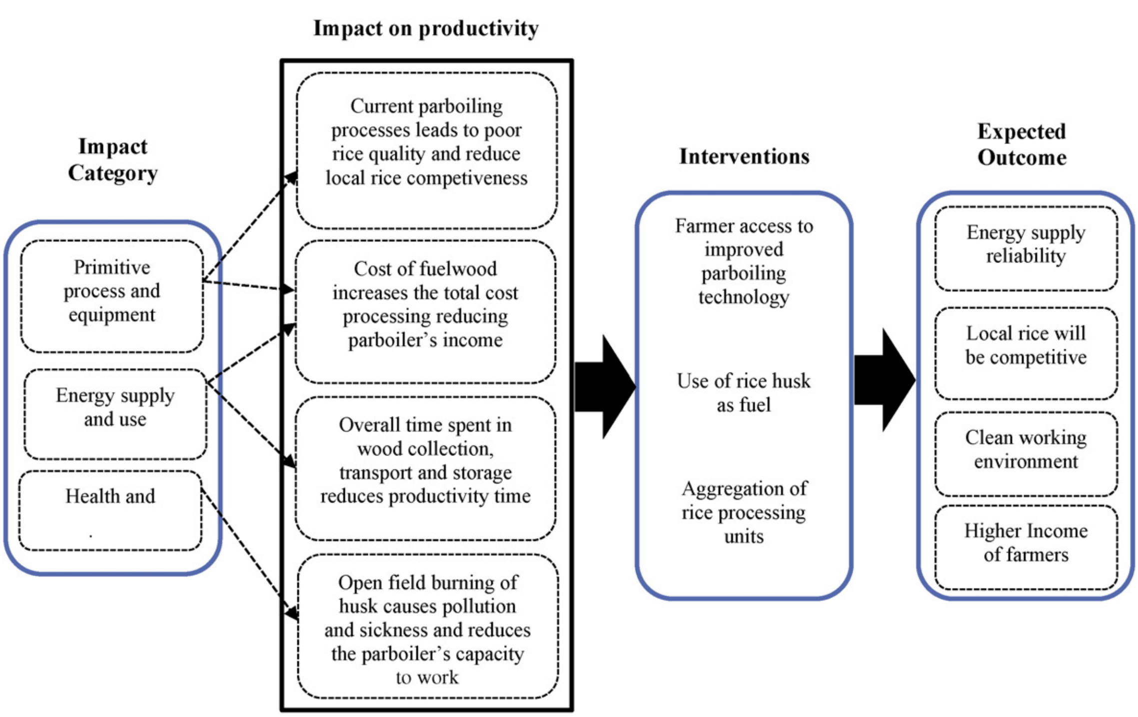


Fig. 8. Energy impact on productivity and possible interventions.

of the rice husk result in greater air pollution releasing carbon dioxide (CO_2), carbon monoxide (CO), un-burnt carbon (with trace amount of methane) as well as NOx and trace amount of sulphur dioxide (SO_2) (Lim et al., 2012). The burning process also contributes to particulate matter emissions and introduces several compounds including carcinogenic/mutagen mainly polycyclic aromatic compounds (PAHs) (Yang et al., 2006). It is clear that the interventions mentioned in Fig. 8 ought to be considered by all stakeholders because it may improve not only the parboiling process but also the livelihood of parboilers.

4. Conclusion

The paper presents the result of field measurement of parboiling energy use and it impacts in three rice producing communities in the Northern region of Ghana. It provides data with which improvement in parboiling energy development can be measured. The hydrodynamic process as practiced is very basic using an inefficient three-stone fire stove technology, time-consuming requiring up to 22 h for soaking and 3–6 h for daily wood collection and transport. Energy for the process is not only costly accounting for 11.9% of the total rice processing cost but also high. Specific total parboiling energy consumption found to be 34.8 and 18.7 MJ/kg, respectively for 11 and 40 kg processing capacities were at least 13 and 7 times higher than small vessels systems operating up to 200 kg per batch. Of all the factors affecting parboiling energy consumption, paddy weight had the most influence. Although not all the factors considered showed great relationships, but they provide stakeholders and other development agencies or researchers which factors to consider in rural energy development. It is evident from this study that for any meaningful improvement towards an energy economy in rice processing these steps may be necessary; firstly, an improved stove design to increase energy efficiency, secondly, a switch from wood to rice husk as alternative energy source will be necessary to mitigate environmental and health impact as well as reduce energy expenditure and finally an increase in processing capacity will make a substantial savings even if current systems are maintained.

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