PERFORMANCE MODELLING AND OPTIMISATION OF HEAD RICE YIELD OF TWO RICE VARIETIES IN A TWO-STAGE DRYING PROCESS

By

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ABSTRACT

A considerable loss of milled rice (percentage of broken kernels) is traced to inadequate and untimely drying of harvested paddy. Therefore, an effective drying process or technique is required to minimise the reduction of head rice yield during paddy processing for an improved milled rice quality. In view of that, this study sought to integrate multi-criteria analysis and response surface methodology to optimise selection and operation of a two-stage drying process to maximise head rice yield. The study applied the method of Analytical Hierarchy Process (AHP) in the selection of an appropriate two-stage drying technique and factors (influencing the unit operations involved in obtaining a proper milled rice after harvesting and cleaning) based on its level of significance on head rice yield (HRY). A fluidised bed and tunnel dryer were selected as the best two-stage drying technique. Factors selected for the experimental design were fluidised bed drying temperature, tunnel drying temperature, paddy variety and storage time. A central composite design (CCD) in conjunction with a response surface methodology (RSM) based on four factors at three levels, which included six centre points, was used to evaluate the effects of the fluidised bed drying temperature (60 °C, 80 °C and 100 °C), tunnel drying temperature (40 °C, 45 °C and 50 °C), paddy variety (*Amankwatia* and *AGRA*) and storage time (1, 2 and 3 months) on the percentage of head rice yield were determined prior to optimising the operating conditions for optimal head rice yield. A regression model(quadratic), with a p-value of 6.5E-0.6 (<0.05), R^2 of 0.995, RMSE of 1.14, AdjR^2 of 0.986 indicated that the quadratic model was significant. Fluidised bed drying temperature, tunnel drying temperature and paddy variety were found to have significant effects on the head rice yield with p-values of 1.9E-0.5 (<0.05), 5.5E-0.6 (<0.05) and 2.5E-0.5 (<0.05) respectively. However, storage time had no significant effect on head rice yield with a p-value of 0.6 (>0.05). The optimal operating conditions for *Amankwatia* rice variety yielding 69.25 % head rice yield were as follows: fluidised bed drying temperature of 73 °C, tunnel drying temperature of 41.5 °C and storage time of three months. The optimal operating conditions for *AGRA* rice variety yielding 62.56 % HRY were as follows: fluidised bed drying temperature of 79 °C, tunnel drying temperature of 42 °C and storage time of three months.

Keywords: AHP, two-stage drying, performance modelling, CCD, RSM, HRY, Paddy

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LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
CCD	Central Composite Design
FBDT	Fluidised Bed Drying Temperature
FBD	Fluidised Bed Dryer
HRY	Head Rice Yield
RSM	Response Surface Methodology
ST	Storage Time
TDT	Tunnel Drying Temperature
TD	Tunnel Dryer
wb	Wet Basis
db	Dry Basis

DECLARATION

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has to a substantial extent has been accepted for the award of any other degree or diploma at Kwame Nkrumah University of Science and Technology, Kumasi or any other educational institute, except where due acknowledgement has been made in the thesis.

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DEDICATION

This thesis is dedicated to the Almighty God and

To all my loved ones.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of Study

Rice, a tropical cereal which supplies about 20 % of direct human calorie intake worldwide, is one of the most important food crops in the world (Zeigler and Barclay, 2008). More than 3 billion people depend wholly or partially on rice (Malekmohammadi *et al.*, 2011). This crop is a staple food which is consumed by more than half of the world's population (Manikantan *et al.*, 2013; Yousaf *et al.*, 2017; Meas *et al.*, 2018). A report by FAOSTAT (2013) indicated that, in terms of global rice production, Africa ranks third with a total production of 25,878,000 tonnes. In sub-Saharan Africa, rice is the second largest source of energy-giving food and the food commodity with the most rapid growth (Seck *et al.*, 2013). Moreover, according to Campbell *et al.* (2009), West Africa consumes more rice than any other parts of the continent. MoFA (2009) reported that, rice is a priority crop to Ghana's economy and agriculture and it has become the second most consumed food staple after maize. It is one of the major sources of calories, especially for urban dwellers in Ghana. Its consumption in Ghana increases exponentially as per population growth, with production taking place in all sixteen regions of Ghana (MoFA-SRID, 2011).

Rice is mostly cultivated as an annual crop by local farmers and it is usually harvested in the rainy season at high moisture content to reduce shattering losses (Chakraborty *et al.*, 2017). At harvest, the moisture content of rice is about 20 % - 24 % wet basis (Akowuah *et al.*, 2012). Rice respires actively when it contains a lot of moisture, and this makes the nutrients contained in rice to become used up. This high moisture content encourages the growth of mould, insects which cause rice to deteriorate and also induces yellowing of grains if drying is delayed (Harein and Meronuck, 1995; Atungulu *et al.*, 2015, as cited in Kolb *et al.*, 2019). It is therefore essential to lower the moisture content of paddy (rough rice) to a safe level of approximately 14 % or less for ease of storage, milling and processing (Cihan *et al.*, 2007).

1.2 Problem Statement

Drying is the most crucial operation after harvesting of paddy (IRRI, 2013). This operation helps in reducing grain moisture content to a safe storage level, and it is also imperative to dry grains immediately following harvesting that is within 24 h to maintain grain quality (IRRI, 2013; Alam *et al.*, 2019). Traditionally, local farmers usually leave the harvested paddy in heaps to dry on the fields where moisture reabsorption at night lead to cracks in the kernel. They sometimes resort to open sun drying by spreading it on mats or pavements next to their homes; mostly causing fissuring of the rice kernels due to uncontrolled temperatures especially when the sun is too high. Too low temperatures or waiting for the sun to come up also causes delays in the drying process and leads to yellowing of grain kernels (Akowuah *et al.*, 2018). During the wet seasons, especially when the weather is unfavourable, drying is almost impossible for smallholder farmers due to the unavailability of the sun. Delays, inadequate and untimely drying of the harvested paddy pose a grave threat to food safety and security in Ghana and also affect the quality of grains and its marketability (Folaranmi, 2008).

Lack of adequate knowledge by smallholder farmers on the factors affecting drying of paddy such as drying air temperature, moisture content of the grains, variety of paddy, tempering time and how to effectively handle paddy right after harvest causes losses and reduces the quality of milled rice (Dokurugu, 2009). Although cracks can occur prior to harvesting on the farm during threshing, drying, storage and milling, among all these unit operations, Ghasemi *et al.* (2018) reported that, a considerable loss of milled rice (percentage of broken kernels) is traced to the drying stage. During the drying process, rice grains can crack due to steep gradient of the moisture content caused by the drying between the surface and the interior part of the grains and these cracked grains readily break during milling and result in a lower milling yield that affects head rice recovery (Schluterman and Siebenmorgen, 2007). Studies by Chakraborty *et al.* (2017) further confirm that, excessive drying of paddy causes tiny cracks in kennel and consequences of these breakages reduce the head rice yield. The quantity of whole grains in a milled sample is termed as the head rice yield (HRY) or recovery which is an important criterion to determine quality of rice. Cracks in grain kernels is a major concern in the rice industry since consumers prefer whole grains. This decreases the economic value of rice since broken grains sell for roughly half the price of whole grain rice (Taechapairoj *et al.*, 2004; Chakraborty *et al.*, 2017).

Therefore, an effective drying process or technique is required to minimise the reduction of head rice yield during paddy processing for an improved milled rice quality thus solving the problems farmers face especially in the rainy season and the outmost concern to the rice industry in producing optimal HRY (Khir *et al.*, 2019).

1.3 Justification

Several studies have shown that, paddy (rough rice) when harvested contains a high level of moisture. Again, harvesting at high moisture leads to a decrease in fissuring of kernels when dried and an increase in milling recovery (Thakur and Gupta, 2006; Chakraborty *et al.*, 2017; Truong *et al.*, 2019). Paddy, which is harvested especially in the rainy season when conditions are not suitable for open sun drying, can be dried conveniently using the two-stage dying method (Tumambing, 1986). According to Bunyawanichakul *et al.* (2007), the two-stage drying technique is where in the first stage, a fast rate dryer is used to quickly drop the very high moisture content of freshly harvested rice to about 18 – 19 % wet basis (wb), as studies by Sutherland and Gholy (1990) revealed that, head rice yield is significantly affected, if drying of paddy in the first stage extends below 18 – 19 % wb. Also at this moisture content, Discroll and Adanezak (1987) stated that it is more manageable since there would be no excessive deterioration if kept for about three weeks as drying is continued in a slow rate dryer to a safe level of about 13 % wb.

Two-stage drying is known as the best and most efficient method to dry paddy resulting in high head rice yield and an improved milled rice quality (Chakraborty *et al.*, 2017; Truong *et al.*, 2019). Bhattacharya *et al.* (1971) cited in Chakraborty *et al.* (2017) reported higher rice yield with two stage drying due to minimal breakage of rice throughout the milling process. Ng *et al.* (2005) further reported that, a two-stage drying system must be employed to improve rice quality attributes (head rice yield) as well as its whiteness.

Although two-stage drying is considered as the best technique due to its high performance in the drying of agricultural food grains, there are two questions that come up when using the two-stage drying technique; the first being “which of the individual drying techniques to combine?” Although using a fast rate dryer such as a fluidised bed dryer can dry grains at a faster rate, not weather dependent and gives a high head rice yield, its usage comes with high cost and energy. Also using sun drying is cheaper but it is weather dependent, causes discoloration of grains and is labour intensive. A fixed bed dryer such as a tunnel dryer which is another option is labour intensive, dries grains at a slower rate but it is not weather dependent compared to sun drying (IRRI, 2013). Each of the drying techniques comes with its advantages and disadvantages, and care must be taken in selecting and combining the right drying techniques (Wankhade *et al.*, 2012). The second question is “will the optimal conditions for the individual drying techniques be the same if combined?” This is asked because, the fast rate fluidised bed drying technique at (140 °C – 150 °C) air temperatures as reported by Soponronnarit and Prachayawarakorn

(1994) and Taweerattanapanish *et al.* (1999) caused tiny cracks and breakage of kernels. Dokurugu (2009) dried *Jasmine* using a fluidised bed dryer with grain moisture content of 22.44 % wb, airflow rate of 2.8 m/s at two different air temperatures (60 °C and 100 °C) and reported a higher head rice yield at 60 °C than at 100 °C under the same conditions. Also Truong *et al.* (2019) reported that using slow rate dryers such as a tunnel dryer at an air temperature of 35 °C, moisture content of 18 % wb and an airflow rate of 0.5 m/s gives a good head rice yield. According to reports by IRRI (2013), using sun drying with layer thickness between 2 - 4 cm and a mixing interval of 30 minutes enhance head rice yield.

Since different rice varieties behave differently under different drying conditions, will the combination of these dryers and their individual optimal operating conditions still yield optimum results for *Amankwatia* and *AGRA* rice varieties? Therefore, to help address this issue, the focus of this work was to establish an optimal drying system or condition using a two-stage drying technique to dry *Amankwatia* and *AGRA* rice varieties with the objective of increasing the head rice yield, thereby increasing the economic value and wholesomeness of the dried product. The results of this study could help farmers and researchers to achieve the desired quality of milled rice during processing.

1.4 Objectives

1.4.1 Main Objective:

The objective of this study was to establish a framework that systematically integrates multicriteria analysis and response surface methodology to optimise selection and operation (maximising head rice yield) of a two-stage drying process.

1.4.2 Specific Objectives

The specific objectives of the study were to:

i. Perform a multi-criteria analysis for selection of the appropriate two-stage drying technique.
ii. Model the performance of the two-stage drying process and determine the factors that significantly affect the head rice yield.
iii. Determine the operating conditions that optimise Head Rice Yield (HRY).

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Paddy processing

2.1.1 Paddy

Paddy rice (*Oryza sativa L.*) is one of the major cereals in the world's economy (Mounir and Allaf, 2014). Rice production in the world stands at more than 487 million tonnes of milled whole rice (FAO, 2012). Paddy (rough rice), when harvested, contains a lot of moisture usually above 22 % (wb) and needs to be dried to a safe moisture level before storage or processing it into edible rice (Chakraborty *et al.*, 2017). Since drying conditions have significant effect on the head rice yield, it is important to complete the drying process with care (Tirawanichakul *et al.*, 2004, 2009; Truong *et al.*, 2019). Sarker *et al.* (1996) cited in Rehal *et al.* (2017) also reported that, drying is an important phase in the postharvest processing of paddy and, if not done properly, could induce breakages during milling, hence, reducing the market value of the milled rice. In a related study by Taweerattanapanish *et al.* (1999) and Lilhare and Bawane (2013), they reported that, percentage rice yield (% RY) is a major factor that affects the market value.

Rice quality attributes (percentage rice yield and whiteness) depend on the quality of paddy processing methods. Producing quality grains after harvest requires the appropriate postharvest process at the right time. Postharvest processes are a series of handling techniques carried out after harvesting of paddy with the purpose of adding value to the final product (IRRI, 2013). Postharvest processes in paddy cultivation include threshing, drying, cleaning, bagging and storage, and milling.

2.1.2 Harvesting and threshing

Harvesting operation in paddy cultivation includes collecting mature paddy from the field (IRRI, 2013). Paddy rice contains a lot of moisture at harvest (Golmohammadi *et al.*, 2012). It is normally harvested at a moisture content of 22 – 30 % wb, in order to improve head rice recovery after milling (Thakur and Gupta, 2006). Further studies by Chakraborty *et al.* (2017) suggest that, harvesting at a high moisture content improves head rice yield and also prevents field losses, damage, dropping and shattering. According to Bautista *et al.* (2009) cited in Ilieva *et al.* (2014), optimal harvest moisture content for long grain varieties is usually in the range of 18 - 22 % and 19 - 20 % for medium grain varieties. Siebenmorgen *et al.* (2007) cited in Ilieva *et al.* (2014) also recommended optimal harvest moisture content of 18.7 - 23.5 % for long grain varieties and 21.5 - 24 % moisture content for medium grain varieties. Though, paddy is generally harvested at high moisture content, it is recommended to dry down to 12 14

% wb for safe storage (Prakash and Pan, 2012). Threshing operations refer to separation of the paddy from the straw. Harvesting and threshing can be performed individually or with a combine harvester to perform these operations simultaneously. Delay in harvesting have been reported to reduce head rice yield as a result of low grain moisture content (Sajwan *et al.*, 1990). Applying the appropriate harvesting techniques leads to high grain yield and reduced grain damage (IRRI, 2013).

2.1.3 Drying

Grain drying is a phase in the postharvest process, where paddy is dried to a safe moisture level for storage, milling, hulling, and whitening (Igathinathane *et al.,* 2008). After harvesting, one critical postharvest operation is drying. Research has indicated that paddy contains a lot of moisture at harvest and therefore must be subjected to the right drying process to preserve grain quality and prevent mould growth and ensure a longer storage life (Hacihafizoğlu *et al.*, 2008). Drying temperature and air moisture have significant effect on milled rice quality (Mounir and Allaf, 2014). High temperature drying causes damage that affects the quality of rice (Rehal *et al.*, 2017). Among the drying process is traditional sun drying which employs high temperature heated air generated by the sun (Golmohammadi *et al.*, 2012) and mechanical drying technologies which include fluidised bed drying, tunnel bed drying, and thin layer drying.

A late or unsuccessful drying process results in losses and subsequently reduced rice yield (IRRI, 2013). However, severe drying conditions can induce internal cracks as a result of moisture and temperature gradients (Chakraborty *et al.,* 2017). Numerous researchers have reported that two-stage drying results in less fissured kennels, as paddy is generally dried under controlled environment (Truong *et al.*, 2019). This technique is effective and yields the maximum whole rice compared to high temperature drying only.

2.1.4 Storage

Safe, effective storage of grain is vital in assuring quality and prevents postharvest losses (IRRI, 2013). As with any cereal grain, paddy rice will deteriorate without the right storage conditions and facilities. The major determinants of storage are grain moisture content, air temperature, and time of storage (Kaleta and Górnicki, 2013). Storage and drying operations can sometimes occur in small bags, or in large facilities (IRRI, 2013). Good storage facilities provide the right storage conditions (temperature, air moisture) and minimise losses caused by weather, moisture, birds and insects, and rodents. Rice for food purpose is stored in paddy form, as the husk will protect brown rice against insects and it is recommended that paddy should be dried below 14 % moisture content (wb) for safe storage (IRRI, 2013).

2.1.5 Milling

Paddy rice is made up of the brown edible rice covered by an outer protective husk. The brown rice on the other hand, is made up of the bran which comprises the exterior layer and edible portion (Dhankhar and Hissar, 2014). Milling operation is the process of removing the husk to obtain an unpolished form called brown rice (Rehal *et al.*, 2017). This is further processed by polishing to remove the outer layer called bran to obtain the final product (white rice). A rice milling system can be a simple one or two-step process, or a multistage process. The latter (Figure 2.1) is the most prevalent paddy milling framework which shows a detailed modern commercial milling process (Yadav and Jindal, 2008). However, the efficiency of milling depends on moisture content of paddy during harvest, after drying, milling conditions, and the type of milling machine employed. According to Akowuah *et al.* (2012), rice quality (head rice yield) is the most important determining factor in rice processing, since broken rice is less preferred and its market value is very low compared with unbroken rice. However, efficiency of every milling process is defined by its head rice yield, as well as the whiteness (Li *et al.*, 1998; Ghasemi *et al.*, 2018). According to Rehal *et al.* (2017), head rice yield (HRY) is stated as the percentage weight of paddy that is whole (3/4 th kernel or higher) after complete milling. Therefore, the key objective of every rice milling operation is a final product with highest rice yield.

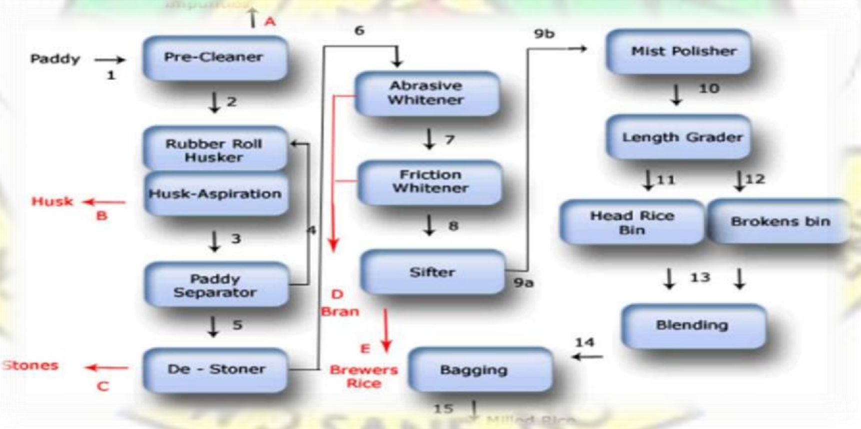

Figure 2.1: Flow diagram of a commercial paddy milling process (Tangpinijkul, 2008)

2.2 Principles of grain drying

2.2.1 Moisture content and moisture removal

The measure of the amount of water present in paddy is defined as its moisture content and it is usually specified on wet basis (wb). Moisture has significant influence on the rice quality, and these effects have been studied by numerous authors (e.g. Malekmohammadi *et al.*, 2011; Akowuah *et al.,* 2012). In grain drying, moisture removal is dependent on ambient conditions (velocity of drying air), drying temperature, and relative humidity (Lilhare and Bawane, 2013). Researchers have recommended a two-phase drying process as the best grain moisture content removal (Elbert *et al.,* 2001). This process achieves the best grain drying and results in a higher milling yield.

2.2.2 Equilibrium moisture content (EMC) and relative humidity

For given environmental conditions, initial moisture content of paddy will drop until it reaches equilibrium state with ambient air (Prakash and Pan, 2012). The final moisture is defined as the Equilibrium Moisture Content of grain (EMC), and this decides the minimum moisture a grain has to be dried before storage (Brooker *et al.,* 1992). Any hygroscopic material (including grain) has its peculiar characteristic balance (equilibrium) between the ambient water vapour and the grain moisture content (Mrema, 2011). Grain storage temperature, initial moisture of grain and relative humidity of ambient air decide the final moisture content (IRRI, 2013). When dried paddy is exposed to moist conditions, its moisture content rises to the value of its equilibrium moisture content (Prakash and Pan, 2012).

Allen (1960) cited in Prakash and Pan (2012) defined a concept known as dynamic EMC. During a drying process, the kennel outer surface of a kernel loses moisture rapidly more than the inner surface, and this phenomenon creates a steep moisture gradient, that is the inability of moisture movement from the interior of the kennel to the surface of kennel at equal amount. This steep moisture gradient induces internal cracks within the kennel (Akowuah *et al.*, 2012). Hence the breakage of kennel during the milling process which leads to a lower head rice yield.

2.2.3 Drying rate and fissures formation

Drying of grain begins from the outer surface of kennels and progresses to its internal surface (Mehdizadeh and Zomorodian, 2009). Although moisture is present at different locations (outer and inside the kennel), the drying cycle is not linear with respect to moisture reduction. Drying rate depends on the air drying temperature, initial grain moisture content, variety of rice, relative humidity, and air flow rate (Lilhare and Bawane, 2013; Sadeghi *et al.*, 2013; Mujumdar, 2016). Severe drying induces tiny cracks in the rice endosperm and this results in breaking of kennel during the milling process (Dong *et al.*, 2010, as cited in Ghasemi *et al.*, 2018).

The major causes of these tiny cracks is temperature gradients and moisture gradient within the kennel during drying. According to researchers, Yang *et al.* (2003) cited in Truong *et al.* (2019) and Wu *et al.* (2017) cited in Ghasemi *et al.* (2018), temperature gradients are created approximately within 20 s after the onset of drying and disappear after 2 to 3 min. “These gradients inside a kennel cause tensile and compressive stresses and they are usually ignored. This phenomenon results in kernel fissuring during the milling process” (Jia *et al.*, 2002 cited in Akowuah *et al.*, 2012). Research by Aquerreta *et al.* (2007) reported that, head rice yield depends on the method of drying. Some problems related to improper drying are heat build-up in the grain, mould growth, insects, yellowing, and reduction of head rice yield.

2.2.4 Effects of drying on milling qualities of paddy rice

It is important to understand the changes caused during postharvest handling of grains leading to formation of fissures, to control and optimise drying conditions for maximising the quality of milled rice. High yield of broken grains is the major problem of the rice industry *(Rehal et al.,* 2017).

2.3 Drying technologies

2.3.1 Dryers

The drying operation is an important process after harvesting, to preserve paddy and also extend its shelf life or process it into edible white rice (Thakur and Gupta, 2006). However, the method of drying affects the final product. The method of drying and type of dryer are important for maximising the milling quality of rice (Lilhare and Bawane, 2013). Selecting the best dryers for the milling process is very important since the ultimate objective of every milling process is a product of high quality. Drying systems available for drying paddy include traditional sun drying, fluidised bed drying and solar tunnel drying.

2.3.2 Sun drying

Traditional sun drying is one common drying process used by farmers to dry paddy. Though traditional open sun drying is cheap, the mode of drying however, is not suitable for large volumes of grains. Drying of grains is relatively slow and weather dependent compared to solar drying, and usually leads to product deterioration (Mustayen *et al.,* 2014). Sun drying is labour intensive, since grains are dried on the ground, pavements and on mats. Grains dried using open sun usually fail to meet international quality standards (Mustayen *et al.,* 2014). Drying is practically impossible during the rainy season which results in a lot of losses, since grains, especially paddy, must be dried within 24 h to a safe storage moisture content. It is difficult controlling air temperature during drying, hence severe drying and overheating of grain can induce internal cracks resulting in poor product quality during milling (IRRI, 2013).

Plate 2.1: Traditional sun drying of paddy on the field

2.3.3 Solar tunnel dryer

Tunnel dryer, compared to traditional sun drying method, is a better alternative method for drying industrial produce (Sharma *et al.,* 1995). The tunnel dryer consists of a semi cylindrical structure which collects solar energy. Solar tunnel dryers are more efficient than traditional sun drying, simple in construction, and convenient in operation. The inside structure is coated with black paint to absorb sunlight entering the tunnel, and this causes the air temperature to rise in order to accelerate evaporation of moisture from grains kept inside the dryer (Rathore and Panwar, 2015). Tunnel dryers protect produce against unfavourable weather conditions and also minimise heat loss. The unit is made up of a transparent material that allows energy (heat) through and simultaneously gives protection from rain and dust (Mustayen *et al.,* 2014).

Moisture is removed from the chamber by rising air current.

2.3.4 Fluidised bed dryer

Fluidised bed drying was developed by Soponronnarit and Prachayawarakorn (1994) and it is widely considered as a quick method of drying (Truong *et al.*, 2019). This dryer was developed as the solution to traditional open sun drying, since sun drying has longer drying time, is unreliable, and there is reabsorption of moisture at night. A fluidised bed is generally used with other dryers in a two-stage drying of grains. It is the preferred dryer for the first stage drying in a two-stage drying owing to its higher rate at drying food produce (Chakraborty *et al.*, 2017). Several studies have shown that, fluidised bed dryers are effective and efficient in grain drying (e.g. Aquerreta *et al.*, 2007; Jaiboon *et al.*, 2009, as cited in Sadeghi *et al.*, 2013; Yousaf *et al.*, 2017; Truong *et al.*, 2019). Fluidised drying factors that affect paddy quality attribute (head rice yield) are air temperature, bed thickness, grain moisture content and air flow rate (Sutherland and Gholy, 1990).

A Fluidised bed dryer is made up of four main components, namely biomass furnace (heating chamber), fluidised bed riser, blower and cyclone separator. Fresh air enters the heating chamber where the heat generated from burning of biomass heats up the air. The heated air is then passed to the wet paddy grains inside the riser at a speed using the blower. The temperature of the hot air is controlled by adjusting the amount of biomass burning in the furnace. The side exit of the bed riser is connected to the inlet of a cyclone separator. The bottom exit is kept open for dried grain collection and the hot air goes out through the top exit of the cyclone (Kalita *et al.*, 2018).

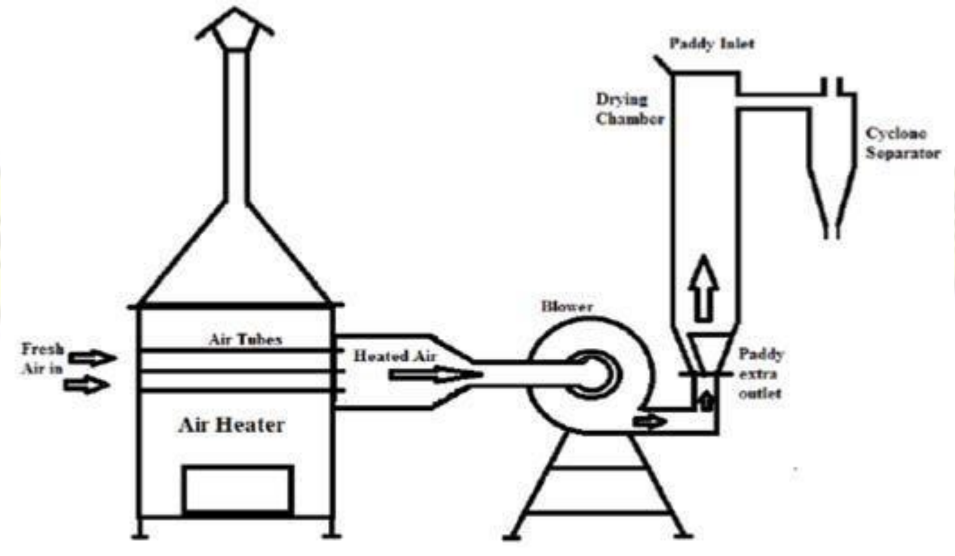

Figure 2.2: Schematic diagram of a Fluidised Bed Dryer (Source: Kalita *et al.*, 2018)

The advantages of using fluidised bed dryers are as follows (Poomsa-ad *et al.*, 2002):

- Uniform product quality
- Fast drying
- Complete mixing of grains
- Uniform moisture content of product Smaller dryer size

2.4 Single versus two-stage drying principle

Researchers have studied single drying versus two-phase drying methods and their effects on head rice yield (HRY). In two-phase drying, the first drying phase makes use of high temperature, fast dryers to rapidly dry the product at a constant rate followed by a slow rate dryer (El-Sebaii and Shalaby, 2012). Wiset *et al.* (2001) cited in Karbassi and Mehdizadeh (2008), studied two drying methods and their effect on the final product quality; in the first scenario, paddy was dried at 90 ^{o}C and a duration of about 11 minutes (single stage drying). With respect to the two-stage drying, grain was dried down to 18 % (wb) in a fast rate dryer in the first stage, and subsequently dried in a slow rate dryer under ambient temperature. They concluded that, rice yield in the single drying method was low, whereas two-stage drying produced much higher yield. The effectiveness of the two-stage drying technique is due to its high moisture removal rate (Chakraborty *et al.*, 2017). Its energy cost is significantly reduced when ambient air is used during the second stage drying (Soponronnarit *et al.*, 1999). It was recommended that, freshly harvested paddy should be dried to a moisture content of 22 % (db) within 24 h period using a high temperature dryer (fast rate drying) and subsequently using a low temperature dryer (slow rate drying) to a safe moisture content (Discroll and Adanezak, 1987; Soponronnarit *et al.*, 1999).

2.5 Multi Criteria Analysis (MCA): Decision making techniques

The Multi Criteria Decision Making (MCDM) tool is an operational research model with the aim of making decisions out of multiple objectives (San Cristóbal, 2011). These decision making techniques handle the difficulties decision makers go through in handling complex information (DCLG *et al.*, 2009). The following are examples of MCDM methods: Analytical Hierarchy Process (AHP), VIKOR method, TOPSIS, ELECTRE, Multi-attribute utility theory (MAUT) and Case based reasoning (Velasquez and Hester, 2013). MAUT is a utility theory that decides the best action in a given decision making by assigning a utility to every possible consequence and determining the outcome (Konidari and Mavrakis, 2007). MAUT is generally applied in the financial sector, agriculture related problems, and in energy and waste management (Velasquez and Hester, 2013).

Yoon and Hwang developed a technique they referred to as “technique for order of preference by similarity to ideal solution” (TOPSIS), that relies on assembling functions close to the ideal function (San Cristóbal, 2011). TOPSIS approach identifies the best alternatives close to the ideal solutions in a multi-dimensional computing space (Qin *et al.*, 2008, as cited in Velasquez and Hester, 2013). Its application has been in business and marketing, environment, human and water resource management and manufacturing systems. Although different decision making techniques have been developed over the past decade to aid decision making, none of these multi-criteria analyses has seen a wider application than Analytical Hierarchy Process (AHP). According to research, AHP is the most widely applied Multi-Criteria Analysis technique, due to its successful application in complex decision problems (Roman, 2012 cited in Aşchilean *et al.,* 2017).

2.5.1 Analytical Hierarchy Process (AHP)

Saaty developed AHP, as a method of analysing decisions by structuring the decisions in a hierarchical structure (Aşchilean *et al.,* 2017). The Analytical Hierarchy Process technique is used to determine the consistency of weightings for criteria through constructing a matrix of pairwise comparisons (Chabuk *et al.*, 2017). The AHP is the most used multi-criteria decision making method to solve very complex problems in different fields (Saaty, 1980 cited in Chabuk *et al.*, 2017). AHP uses pairwise comparisons matrix to determine the relative importance of the individual criterion thus, significant weightings (Chabuk *et al.*, 2017). AHP also uses procedures to derive the weights and the scores; that is using pairwise comparisons to determine how important is criterion X relative to criterion Y?

2.6 Process modelling and optimisation techniques

“A model is an intellectual tool which represents an abstract of a system or a process using mathematical concepts and languages. Modelling involves recording observations, analyses (model fitting) and based on the results, predicting the behaviour of a particular process or parameter in the future. Different models to predict the drying behaviour, water absorption trend etc. have been evaluated in rice processing” (Rehal *et al.,* 2017). Vasquez *et al.* (2011) developed a modelling framework to study and analyse equilibrium moisture content in foods, and achieved satisfactory results suggesting its application for analyzing equilibrium moisture content in the food industry (Rehal *et al.*, 2017).

2.6.1 Response surface methodology (RSM)

Numerous researchers have studied different ways to optimise analytical procedures, by means of statistical procedures. Bezerra *et al.* (2008) stated that, the most preferred technique by researchers to optimise analytical procedures is Response Surface Method (RSM). Response Surface Method is an excellent approach to optimise factors affecting head rice yield. Response surface methodology evaluates the optimum condition using a combination of statistical and mathematical approaches to reduce the total number of experiments between factors and responses (Yousaf *et al.,* 2017).

Application of RSM in optimising analytical procedures is largely diffused and consolidated principally because of its numerous advantages to classical one variable a time optimisation. Thus, it generates large amounts of information from a small number of experiments and also the possibility of evaluating the interaction effects between the individual variables on the response. Choosing an experimental design is necessary when using RSM in experimental optimisation. Experimental design helps to evaluate the model quality as well as its accuracy (Bezerra *et al.*, 2008). Factorial experimental design for more than two variables requires additional experimental runs. Factorial designs are generally used because they have the advantage of testing the effects of two or more independent variables at a time (Stitt and Moore, 2015).

Central Composite Design (CCD) is a symmetrical second order experimental design generally utilised for the development of analytical procedures (Bezerra *et al.,* 2008). Central Composite Design contains an imbedded fractional factorial design with centre points that are augmented with group of star points that allow estimation of curvature (Boyer, 2000). Central Composite Design (CCD) has three different design points, namely

(i) Edge points as in two-level designs (±1),

(ii) Star points at ±α; |α| and |≥1that takes care of quadratic effects and (iii) Centre points.

The edge points (factorial points) are at the design limits. The star points are at some distance from the centre depending on the number of factors chosen for the design. The star points extend the range outside the low and high settings for all design factors. The centre points completes the design (Drain, 1997). Note that, if the distance from the centre of the design to a factorial point is ±1 unit for each factor, the distance from the centre of the design space to a star point is $|\alpha| \geq 1$. The precise value of α depends on certain properties desired for the design and on the number of factors involved (Boyer, 2000).

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Overview of materials and methods

Figure 3.1 presents a synopsis of the methods used in the study. The figure shows the different stages, the inputs (tools / techniques) required at every stage as well as the results obtained following the successful completion of each stage.

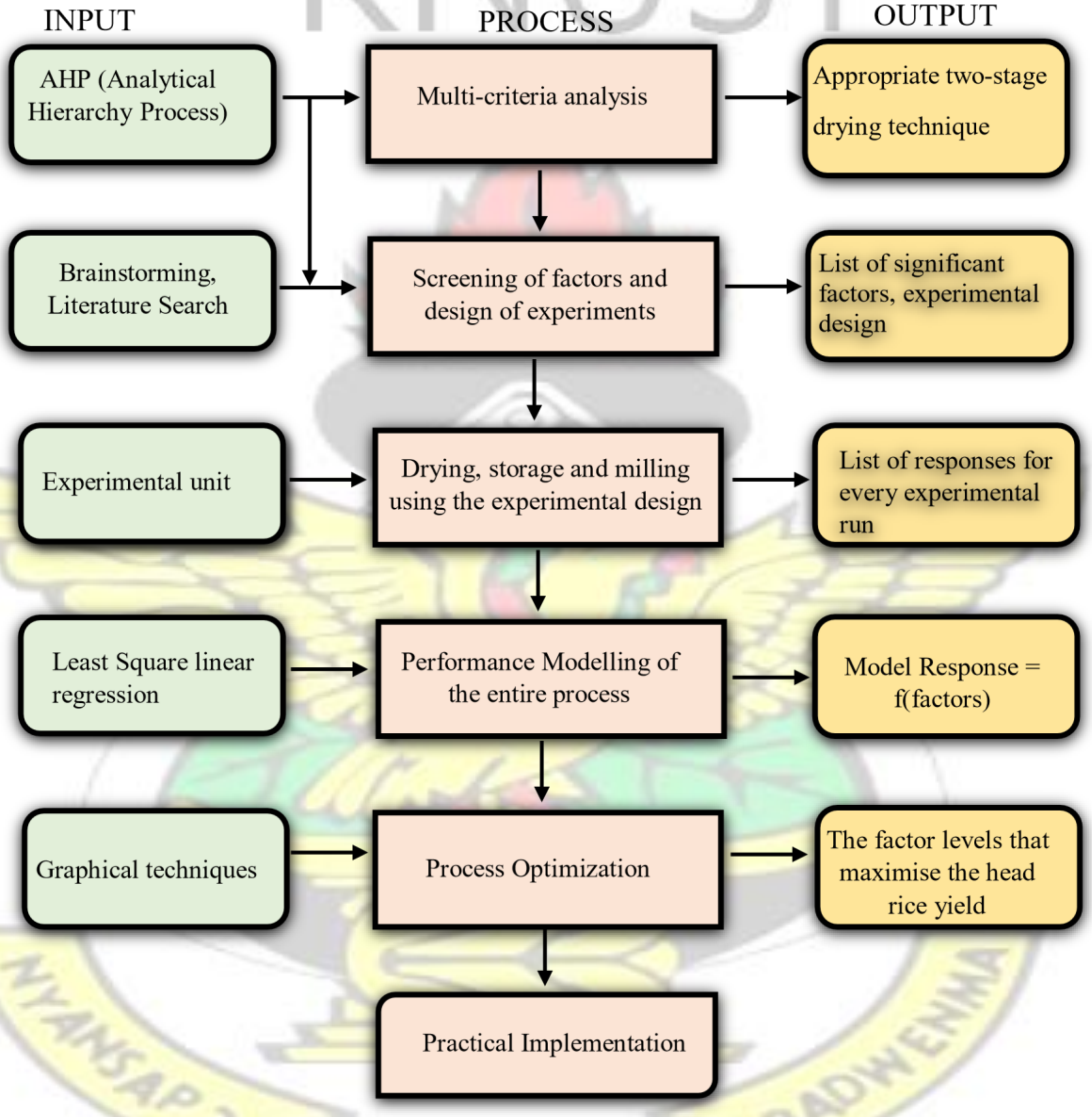

Figure 3.1: Methodological framework of study

3.2 Theoretical Method: Selection of an appropriate two-stage drying technique This section of the study focused on applying Analytical Hierarchal Process (AHP) method for the selection of an appropriate two-stage drying technique out of three alternatives, due to its success in the selection of the best alternative out of a lot.

3.2.1 Materials

In order to dry paddy for a proper milled rice quality, two-stage drying technology could be applied (Truong *et al.*, 2019). The two-stage technologies which were considered in this study are presented in Table 3.1.

Table 3.1: Matrix of alternatives

Alternative's symbol	Alternative name
A1	Fluidised bed dryer + Tunnel dryer (FBD + TD)
A2	Fluidised bed dryer + Sun drying (FBD + SD)
A3	Tunnel dryer + Sun drying (TD+ SD)

3.2.2 Method: Application of AHP in the study

In order to choose the best drying technique (alternative) for the proper milling yield of *Amankwatia* and *AGRA* rice varieties, extensive literary analysis was undertaken to assess the performance of the alternatives. Knowledge on the efficiency of the alternatives in relation to their operational, product and performance characteristics was needed in order to evaluate the AHP method appropriately. Table 3.2 gives a description of all criteria considered for the selection of the appropriate two-stage drying technique (alternative).

Table 3.2: Set of decision criteria to select an appropriate two-stage drying technique for proper milled rice yield

SN	Criterion	Name of Criterion	Objective	Description
1	C1	Colour	Maximised	The alternative should enhance the colour as much as possible
2	C2	Contamination	Minimised	The contamination should be as low as possible.
3	C3	Drying Rate	Maximised	It is preferable the time for drying to be as quick as possible.
4	C4	Energy/ Cost	Minimised	The cost involved using the alternative should be as low as possible.
5	C5	Head Rice Yield	Maximised	It is advisable to select that alternative that can increase the head rice yield and reduce breakages.

6	C6	Labour	Minimised	It is necessary to select an alternative that is not labour intensive.
7	C7	Moulds / Aflatoxins	Minimised	The alternative should minimise Aflatoxins/moulds production as low as possible.
8	C8	Weather Susceptibility	Minimised	It is advisable to choose an alternative that is not weather dependent

The relative importance of these criteria with respect to the objective of the study was given weights based on studies by Aşchilean *et al.* (2017). This is detailed as follows:

Step 1: Identification of the problem that has to be solved: This is aimed at selecting the appropriate two-stage drying technique.

Step 2: Establishing the decision-making criteria: The criteria based on which the goal of the study was achieved were identified in (Table 3.2) and written in decision criteria matrix $\mathbf{C} = [C_j]$, where $j = 1, 2, \ldots, 8$. i.e, the number of criteria

Step 3: Establishing the decision-making alternatives: The alternatives, out of which the selection was made, were identified and written in the alternatives' matrix $\mathbf{A} = [A_i]$, where $i = 1,2,3$ i.e, the number of alternatives.

Step 4: Determining the relative weight of criteria by comparing the criteria in pairs. The relative importance of the criteria, $c = [c_{ij}]$ with respect to the objective was determined by performing a pairwise comparison (Hruška *et al.*, 2014). The relative importance of each criteria was determined based on extensive literature review and technical consultancy on the impact each criterion has on the two-stage dryer selection process. The weights assigned to each criterion were based on the Saaty scale as shown in Table 3.3. It is worth noting that when a comparison between two criteria is reversed, then the importance value equals the reverse of the direct comparison value, and also, a criterion compared with itself is always assigned the value 1. This makes the main diagonal entries of the pairwise comparison matrix equal to 1 (Hruška *et al.*, 2014). This was filled in a square matrix, A, of the size m, where m = number of decisional criteria.

Table 3.3: Fundamental scale of Satty (Saaty, 1980)

Values/Rates	Description
1	Equally preferred or it does not matter (equal importance)

2	Equally preferred, but with certain moderate differentiation tendencies
3	Moderately preferred
4	Preferred towards strongly preferred
5	Strongly preferred
6	Strongly preferred towards obviously preferred
7	Obviously preferred
8	Obviously preferred towards extremely preferred
9	Extremely preferred

Step 5: Developing the vector of weights. A vector $\boldsymbol{W} = [W_1, W_2, \dots W_m]$ which indicates the weight that each criterion was given in pairwise comparison matrix A, was determined using these two steps:

a) For each of the A's column, every entry in column *i* of A was divided by the sum of the entries in column i. This yields a new matrix, called $\mathbf{A}_{norm}$ (normalised). It should be noted that the sum of each column in the $\mathbf{A}_{norm}$ matrix must be 1, which is a condition that is required for the formulation of a normalised matrix (Aşchilean *et al.*, 2017).

b) The W_i was estimated as the average of the entries in row *i* of A_{norm}.

Step 6: Determining the consistency factor of the decision criteria matrix. Since weights of the pairwise comparison matrix are based on the decision maker's choice, the pairwise comparison matrix is subjected to consistency check to avoid any bias in the allocation of weights (Saaty, 1980). The consistency factor was determined using the following steps:

a) Determining the maximum Eigen value of the pairwise matrix using Equation 1.

$$\lambda_{max} = 1/m \sum_{i=1}^{n} \frac{i^{th} entry\ in\ AW^T}{i^{th}\ entry\ in\ W^T} \tag{1}$$

where:
λ_{max} = maximum Eigen value m =
number of attributes A =
pairwise comparison matrix
W = the estimate of the decision-makers weight

b) Determining the consistency index, CI using Equation 2.

$$CI = \frac{\lambda_{max} - m}{m-1} \text{I=λ\_max-m/m-1} \tag{2}$$

c) Determining the consistency factor. The Consistency Index was then compared to the Random Index (RI) for the appropriate value of m, used in decision-making as shown in Table 3.4. If (CI/RI) < 0.10, the degree of consistency is satisfactory, but if (CI/RI) > 0.10, serious inconsistencies may exist, and the AHP may not yield meaningful results.

Table 3.4: Values of the random index based on the matrix size (Aşchilean *et al.*, 2017)

Matrix Size	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RCI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

Step 7: Determining the relative weights of the alternatives based on criteria. Steps 4 and 5 were followed to develop square matrices of size *i* (equals to the number of alternatives). The number of matrices developed is equal to the number of criteria considered in the study. Step 8: Filling in the performance matrix, where the performance of the alternatives was identified for each criterion, and the data were written in the performance matrix **P** = [Pij].

Step 9: Finally, the total weight showing the significant level of each alternative was determined by multiplying the weight of each alternative related to each criterion with the weight of each criterion, and then calculated their sum. i.e, $P \times W^T$×W^T.

** The best alternative is the one for which the sum of the product of the weight of each alternative and the weight of each criterion has the highest value.

3.2.3 Screening of factors to establish an experimental design using the AHP method

The flow diagram in Figure 3.2 was developed to show the factors that affect each of the processing techniques applied in the study. With the AHP, these factors were screened and the ones which had highest weight was used to develop the experimental design.

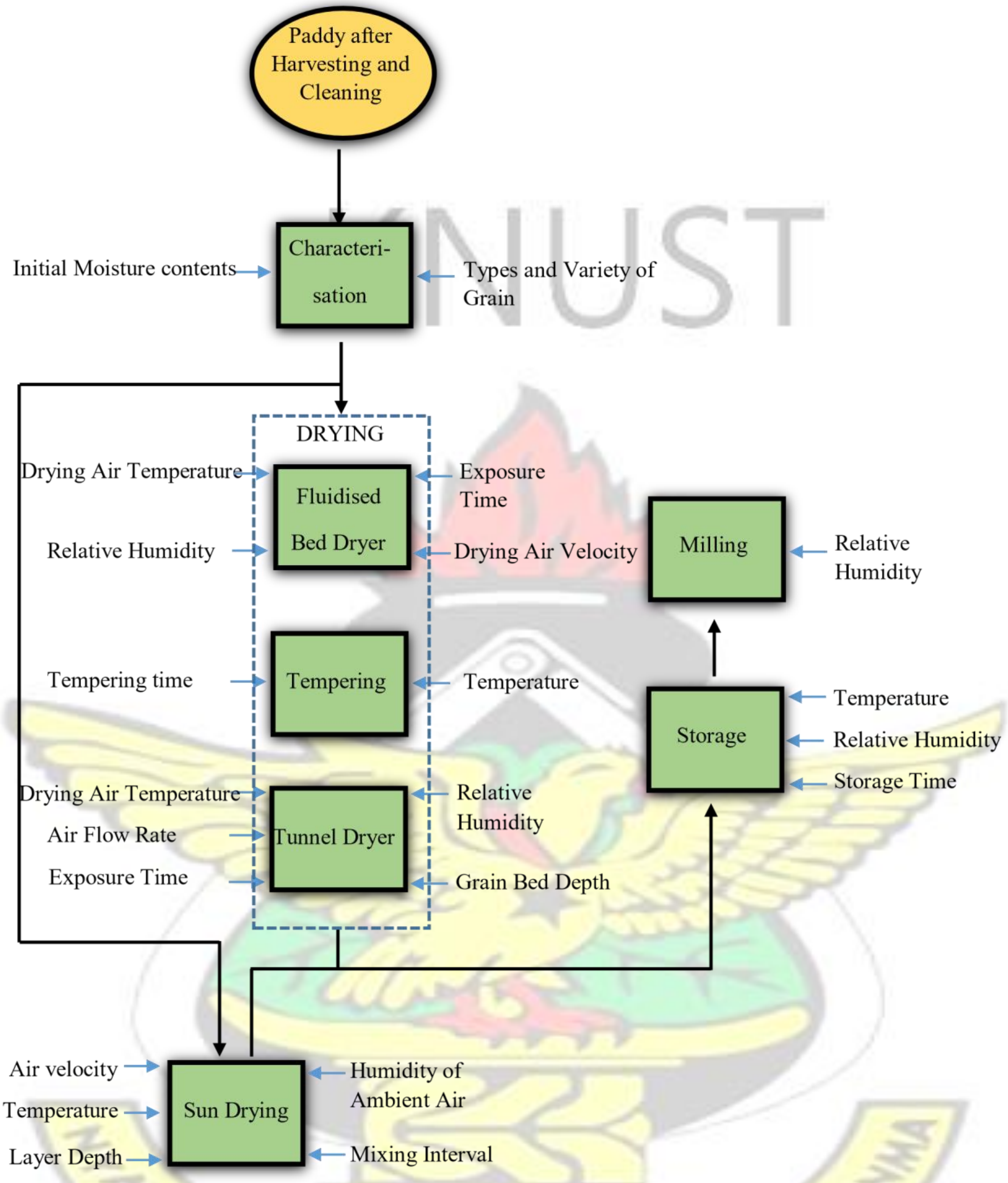

Figure 3.2: Process flow diagram indicating the unit operations and their influencing factors, involved in obtaining milled rice after harvesting and cleaning

Screening and ranking of the factors influencing the unit operations involved in obtaining milled rice after harvesting and cleaning was done using the AHP method and the first five factors that can be varied were selected to establish an experimental design. The list of factors from each unit operation from Figure 3.2 is shown in Table 3.5.

Table 3.5: List of factors considered for the second stage of the AHP

Factor’s symbol	Factor’s Name
F1	Temperature (FBD)
F2	Air Velocity (FBD)
F3	Initial Moisture Content
F4	Type and Variety of grain
F5	Tempering Time
F6	Storage time
F7	Drying air temperature (TD)
F8	Air flow rate (TD)
F9	Relative humidity (FBD)
F10	Relative humidity (TD)
F11	Temperature (Storage)
F12	Relative Humidity (Storage)
F13	Tempering Temperature

3.3 Experimental Methods

3.3.1 Experimental design

As shown in Table 3.6, a Central Composite Design (CCD), in which three independent variables were converted to dimensionless ones (x_1, x_2, x_3,), with the coded values at 3 levels: −1, 0, +1. The selection of factors was based on the results obtained through the AHP (as explained previously). The arrangement of CCD as shown in Table 3.6 and Table 3.7 was in such a way that allows the development of the appropriate empirical equations thus, second order polynomial multiple regression equations (Mason *et al.*, 2003).

Table 3.6: Independent variables and their levels for the central composite design used in the study

Variables	Symbol	Coded variable levels		
		-1	0	1
Drying air temperature in the fluidised bed dryer.	x_1	60	80	100
Drying air temperature in the tunnel dryer.	x_2	40	45	50
Storage time	x_3	1	2	3

Table 3.7: Arrangement of the CCD for the three independent variables used in the present study with specific treatments for each run

Run	Fluidised Bed Drying Temp (˚C)	Tunnel Drying Temp (˚C)	Storage Time (months)	Variety
1	60	40	1	1
2	60	40	3	1
3	60	50	1	1
4	60	50	3	1
5	100	40	1	1
6	100	40	3	1
7	100	50	1	1
8	100	50	3	1
9	46.36	45	2	2
10	113.63	45	2	2
11	80	36.59	2	2
12	80	53.41	2	2
13	80	45	0.32	2
14	80	45	3.68	2
15	80	45	2	1
16	80	45	2	1
17	80	45	2	1
18	80	45	2	2
19	80	45	2	2
20	80	45	2	2

where; Varieties 1 and 2 represent *Amankwatia* and *AGRA rice* varieties respectively.

The 2^{nd} order polynomial equation to represent the process of the study was in the form as shown in Equation 3

$y=\beta_0+\beta_1x_1+\beta_2x_2+\beta_3x_3+\beta_{11}x_{12}+\beta_{22}x_{22}+\beta_{33}x_{32}+\beta_{12}x_1x_2+\beta_{13}x_1x_3+\beta_{23}x_2x_3$=β_0+β_1x_1+β_2x_2+β_3x_3+β_11?x_1^2+β_22?x_2^2+β_33?x_3^2+β_12 x_1x_2+β_13x_1x_3+β_23x_2x_3

` **(3)**

The predicted response (y), which in this case is Head Rice Yield, was therefore correlated to the set of regression coefficients (β): the intercept coefficient (β_0), linear correlation coefficients (β_1, β_2, β_3), interaction correlation coefficients (β_{12}, β_{13}, β_{23}) and quadratic coefficients (β_{11}, β_{22}, β_{33}). MatLab R2018a was used for the design of the experiment, regression and graphical analyses of the obtained data.

3.3.2 Experimental Set-Up

The following materials were used to carry out the experiments for the study.

- Freshly Harvested Paddy
- Electronic Balance
- Stop Watch
- Oven
- Drying Tray
- Polyethylene Bag
- Fluidised Bed Dryer
- Tunnel Bed Dryer
- Milling Machine
- Anemometer

Using factors as specified by the experimental design, a two-stage drying was carried out on the two rice varieties using a fluidised bed dryer and a tunnel bed dryer (fixed bed). The following activities were undertaken:

i. Sample Collection and Conditioning;

The rice samples (*Amankwatia* and *AGRA* rice varieties) used for this experiment were obtained from the Council for Scientific and Industrial Research (CSIR) - Crops Research Institute (CRI) at Fumesua, Ghana. The paddy samples were harvested and threshed manually to reduce the development of cracks which arises during mechanical threshing.

Plate 3.1: Harvesting of *Amankwatia* from the field

The samples were cleaned from debris and the cleaned samples were stored in an airtight polyethylene bag and kept in a refrigerator until they were needed.

ii. Moisture content (MC) determination:

The initial moisture content (% wet basis) of the rice samples was determined using the standard oven method (ASABE, 1995). The Sartorius Electronic Balance (L 22005) was used to weigh 20 g of sampled paddy. This was done three times to obtain three replicates for both varieties used for the study. The weighed samples were dried in an oven at 130 °C for 24 h and then reweighed and the moisture content on wet basis was calculated using Equation 4 according to Smith *et al.* (1994).

$$MC = \frac{\text{Weight of wet sample} - \text{Weight of dry sample}}{\text{Weight of wet sample}} \times 100\text{C=Weight of wet sample} - \text{Weight of dry sample}/\text{Weight of wet sample} \times 100\ \% \qquad \textbf{(4)}$$

Where;

MC = Moisture content on wet basis

3.3.3 Drying experiments

The drying experiment was carried out at the Chemical Engineering Unit Operations Laboratory at the Kwame Nkrumah University of Science and Technology, Kumasi, Ghana.

Paddy samples (370 g) were weighed using an electronic balance (Sartorius Electronic Balance (L 22005)) before being used for the experiment.

A fluidised bed dryer (P. R. L. Engineering Ltd., UK, Model: FBD/L 72) as shown in Plate 3.2 was used in the first stage of the drying process, where the fresh paddy was dried to about 18 % moisture content (w.b). Before using the fluidised bed dryer, the dryer was preset to the desired drying temperature as specified in Table 3.7 and the airflow in the dryer set to a rate of 2.8 m/s. During the drying process, the drying sample was weighed every 30 sec using the Sartorius Electronic Balance (L 22005). This was done to estimate the weight reduction of paddy to a moisture content of 18 % (w.b) (Bunyawanichakul *et al.*, 2007) using Equation 5.

$$M_i = \left[1 - \frac{W_o(1-M_o)}{W_i}\right] \times 100\% \qquad \textbf{(5)}$$

where,

M_i = moisture content at ith time, %

M_o= initial moisture content, decimal

W_o= initial weight of sample, g

W_i = weight of sample at ith time, g

Plate 3.2: First stage drying of paddy using the fluidised bed dryer

The second stage of the drying process was carried out using the fixed bed dryer as shown in

Plate 3.3. Paddy samples were initially weighed using an electronic balance (Sartorius Electronic Balance (L 22005)), placed in trays and dried using the fixed bed dryer at temperatures as specified in Table 3.7. An air flow rate of 1.77 m/s was recorded in the dryer using an anemometer. Moisture reduction was monitored and recorded every 15 m until the desired moisture content of about 13 % (w.b) recommended for safe storage was reached (Discroll and Adanezak, 1987). The weight reduction was estimated using Equation 5.

Plate 3.3: A fixed or static bed dryer

3.3.4 Storage

The dried samples were kept in an airtight polyethylene bag and stored at ambient room conditions for durations of one, two and three months. The focus was to assess the quality of the dried paddy over a storage period as reports from Sharma and Kunze (1982) and Wongpornchai *et al.* (2004) suggested that, head rice yield is low in dried paddy immediately after drying, but increases as it is kept.

3.3.5 Milling

The milling machine shown in Plate 3.4 was used to mill the paddy varieties. The process was carried out at the Crop Research Institute (CRI) of the Council for Scientific and Industrial Research (CSIR), Fumesua, Kumasi-Ghana. It started in the month of April, 2019 and was carried out after the 1, 2 and 3 months of storage. The milling process involved three steps: dehusking, debraning / polishing and grading.

Plate 3.4: Milling of dried sample with Zaccaria PAZ-1/DTA Lab rice mill

a. Dehusking Step:

The grain moisture meter (Riceter J301) was used to check the moisture content of the samples at milling. Samples of 100 g each were taken and loaded into the first hopper located on top of the Zaccaria PAZ-1/DTA Lab rice mill as shown in Plate 3.5, for dehusking the dried paddy in the dehusking chamber to obtain brown rice (BR) in 75 s.

Plate 3.5: The section of the Zaccaria PAZ-1/DTA Lab rice mill for dehusking

b. Polishing/ Debraning Step:

A weighing scale was used to weigh the brown rice before it was loaded into the second hopper of the Zaccaria PAZ-1/DTA Lab rice mill in Plate 3.6, with the polisher preset at low-medium whiteness level, to obtain polished rice (white rice, WR) in 75 s. The weight of the polished rice was then taken to be used for the determination of head rice.

Plate 3.6: The section of the Zaccaria PAZ-1/DTA Lab rice mill for polishing / debraning

c. Grading Step:

The Grader on the Zaccaria PAZ-1/DTA Lab rice mill (Plate 3.7), was used to separate the broken rice kernels from whole rice after milling. The rotating drum of the grader was set at an angle of 30° for the separation. The whole rice and the broken rice were weighed and recorded. The head rice yield from the milled samples was determine based on Equation 6.

$$Head\ rice\ yield\ = \frac{\text{weight of head rice}}{\text{total grain weight}}$$ ead rice yield weight of

head rice/total grain weight rice yield weight of head rice/total grain weight

(6)

Plate 3.7: The section of the Zaccaria PAZ-1/DTA Lab rice mill for grading

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Selection of an appropriate two-stage drying technique

This section of the study highlights the results from the application of AHP to select the best two-stage drying technique out of the three alternatives. The selected two-stage drying technique was used to carry out the drying process considered in the study. By using the selected two-stage drying technique, a proper milling yield for the two rice varieties was assured.

4.1.1 Application of the AHP in the selection of the appropriate two-stage drying technique

Table 4.1 presents the pairwise comparison between criteria (decision criteria matrix) using the judgemental scale of Saaty (1980) as presented in Table 3.3 in the previous chapter. **Table 4.1: Pairwise comparisons between criteria**

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
C1	1.00	6.00	0.50	3.00	0.33	4.00	2.00	5.00
C2	0.17	1.00	0.14	0.25	0.13	0.33	0.20	0.50
C3	2.00	7.00	1.00	4.00	0.50	5.00	3.00	6.00
C4	0.33	4.00	0.25	1.00	0.20	2.00	0.50	3.00
C5	3.00	8.00	2.00	5.00	1.00	6.00	4.00	7.00
C6	0.25	3.00	0.20	0.50	0.17	1.00	0.33	2.00
C7	0.50	5.00	0.33	2.00	0.25	3.00	1.00	4.00

C8	0.20	2.00	0.17	0.33	0.14	0.50	0.25	1.00

where C1, …, and C8 are the criteria already clarified in Table 3.2 in the previous chapter.

The relative weight of the eight decision criteria was determined based on practical knowledge and general engineering principles with the main objective, which was to select an appropriate two-stage drying technique in mind. Some of these principles considered have been applied by researchers in various fields of engineering studies. For example, in the selection of an appropriate two-stage drying technique, the effectiveness of the drying system (which takes into consideration the drying rate of the system, cost or energy consumption by the system, its effectiveness in enhancing milling yield and colour of produce) is apparently more important to be considered than it requiring minimal labour to run it. For instance, in the comparison between C3 and C6, if the criterion *C3* is five times more preferred than the criterion *C6*, then the criterion *C6* is 1/5 times less preferred than criterion *C3*. Thus, if the criterion *C3* receives a judgemental value of 5, then the criterion *C6* shall have the mark 1/5. It is important to note that a criterion compared with itself obtains the judgemental value of 1. This is the reason why the value 1 is recorded on the matrix' diagonal (Aşchilean *et al.*, 2017).

Following up with step 5 as presented in the previous chapter, the pairwise comparison between criteria was then normalised and transformed in weights to know the level of significance each criterion had on the drying techniques. The final result as presented in Table 4.2. shows the normalised form of the decision criteria matrix.

Table 4.2: Normalised for decision criteria matrix

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**Av. W**
C1	0.13	0.17	0.11	0.19	0.12	0.18	0.18	0.18	0.16
C2	0.02	0.03	0.03	0.02	0.05	0.02	0.02	0.02	0.03
C3	0.27	0.19	0.22	0.25	0.18	0.23	0.27	0.21	0.23
C4	0.04	0.11	0.05	0.62	0.07	0.09	0.04	0.11	0.14
C5	0.40	0.22	0.44	0.31	0.37	0.27	0.35	0.25	0.33
C6	0.03	0.08	0.04	0.03	0.06	0.05	0.03	0.07	0.05
C7	0.07	0.14	0.07	0.12	0.09	0.14	0.09	0.14	0.11
C8	0.03	0.06	0.04	0.02	0.05	0.02	0.02	0.04	0.04
Total	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

From Table 4.2 the weights of each of the criteria considered for the selection process was calculated. This was done by finding the average values on each row in the $\mathbf{A}_{norm}$ matrix. This result is shown in the radar plot in Figure 4.1. The figure shows that in the selection of the appropriate two-stage drying technique, head rice yield is of utmost importance since it had a relative weight of 0.33 out of 1. This is followed by drying rate, colour, moulds/aflatoxins, energy/cost, labour, weather susceptibility and contamination with the relative weight of 0.23, 0.16, 0.11, 0.07, 0.05, 0.03 and 0.02 out of 1 respectively.

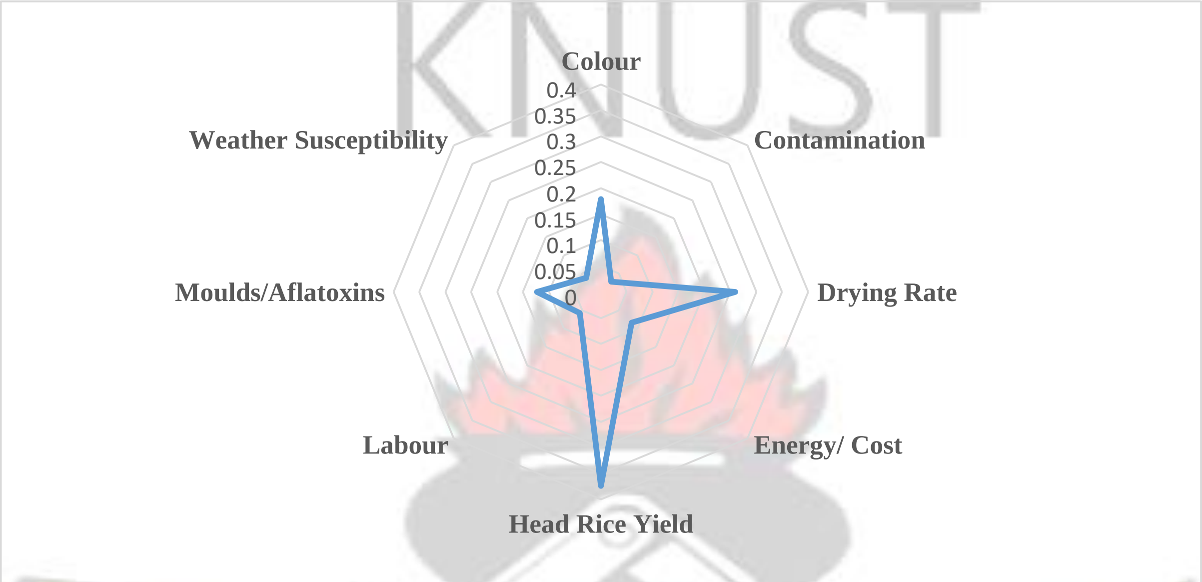

Figure 4.1: Relative weights of criteria

These results clearly indicate that in the selection of an appropriate two-stage drying system for processing paddy, HRY becomes an important criterion which has to be considered since HRY determines the quality of rice. Cracks in grain kernels is a major concern in the rice industry since consumers prefer whole grains. This decreases the economic value of rice since broken grains sell for roughly half the price of whole grain rice (Taechapairoj *et al.*, 2004; Chakraborty *et al.*, 2017). So it is necessary to select an effective drying technique that would minimise these breakages and enhance the HRY of milled rice, thus solving the problems farmers face especially in the rainy season and the outmost concern to the rice industry in producing optimal HRY (Khir *et al.*, 2019).

Furthermore, drying rate, colour and moulds/ aflatoxins are other important criteria which have to be considered in the selection of an appropriate two-stage drying system for processing paddy. Drying is very crucial after harvesting of paddy and it remains imperative to dry grains immediately following harvesting, that is within 24 h to maintain grain quality (IRRI, 2013). Therefore, an efficient drying system with a high rate of moisture removal is needed to avoid subjecting the grain kernels to yellowing and mould growth caused by the high moisture at harvest (Atungulu *et al.*, 2015). The other criteria are all considered appropriate in the process of selecting an appropriate two-stage drying system and as such, have their relative importance as shown in the results.

The consistency factor of the decision criteria matrix was further determined to assess the consistency of the developed decision criteria matrix. With the 8 criteria considered in the study, a value of 1.41 was selected as the Random Index (Saaty, 1980). The maximum Eigenvalue for the decision criteria matrix was calculated to be 8.29 using Equation 1, and this resulted in a Consistency Index of 0.042. Finally, a Consistency Ratio of 0.03 was determined which means that the decision criteria matrix for the study is consistent. i.e., the weights allocated for the various criteria are clearly defined. These results agree with studies by (Aşchilean *et al.*, 2017).

The comparative weights of the alternatives were done with a focus on the various criteria considered in the study. The results are shown in Tables 4.3a to 4.3h.

Table 4.3a: Weight of alternatives based on Colour

C1

	A1	**A**
A1	1.00	5.
A2	0.20	1.
A3	0.14	0.
sum	**1.34**	**6.**

Table 4.3b: Weights of alternatives based on contamination

C2

	A1	**A2**	**A3**
A1	1.00	7.00	7.00
A2	0.14	1.00	1.00
A3	0.14	1.00	1.00
sum	**1.29**	**9.00**	**9.00**

Table 4.3c: Weight of alternatives based on Drying Rate

C3

	A1	**A**
A1	1.00	3.
A2	0.33	1.
A3	0.14	0.
sum	**1.48**	**4.**

Table 4.3d: Weights of alternatives based on Energy/ Cost

C4

	A1	**A2**	**A3**
A1	1.00	0.20	0.14
A2	5.00	1.00	0.33
A3	7.00	3.00	1.00
sum	**13.00**	**4.20**	**1.48**

	A1	A2	A3
A1	1.00	3.00	7.00
A2	0.33	1.00	7.00
A3	0.14	0.14	1.00
sum	**1.48**	**4.14**	**15.00**

	A1	A2	A3
A1	1.00	0.20	0.33
A2	5.00	1.00	3.00
A3	3.00	0.33	1.00
sum	**9.00**	**1.53**	**4.33**

Table 4.3g: Weight of alternati based on Moulds/Aflatoxins

C7

	A1	A2	A3
A1	1.00	6.00	7.00
A2	0.17	1.00	3.00
A3	0.14	0.33	1.00
sum	**0.31**	**7.33**	**11.00**

Table 4.3e: Weight of alternatives based on HRY

C5

Table 4.3f: Weights of alternatives based on Labour

C6

Table 4.3h: Weights of alternatives based on Weather Susceptibility

C8

	A1	A2	A3
A1	1.00	3.00	7.00
A2	0.33	1.00	7.00
A3	0.14	0.14	1.00
sum	**1.48**	**4.14**	**15.00**

Normalising the relative weight between the two-stage drying alternatives according to each of the criteria in order to get the performance matrix of the three alternatives (two-stage drying techniques) in relation to the eight decision criteria are as shown in Tables 4.4a to 4.4h.

Table 4.4a: Normalised for alternatives based on Colour

C1

	A1	**A2**	**A3**
A1	0.75	0.79	0.64
A2	0.15	0.16	0.27
A3	0.10	0.05	0.09

Table 4.4b: Normalised for alternatives based on Contamination

C2

	A1	**A2**	**A3**
A1	0.78	0.78	0.78
A2	0.11	0.11	0.11
A3	0.11	0.11	0.11

A1	0.68	0.71	0.54
A2	0.22	0.24	0.38
A3	0.09	0.05	0.08

Table 4.4e: Normalised for alternatives based on HRY

C5

	A1	**A2**	**A3**
A1	0.11	0.13	0.08
A2	0.56	0.65	0.69
A3	0.53	0.22	0.23

Table 4.4c: Normalised for alternatives based on Drying Rate

C3

	A1	**A2**	**A3**

Table 4.4d: Normalised for alternatives based on Energy / Cost

C4

	A1	**A2**	**A3**

A1	0.08	0.05	0.09
A2	0.38	0.24	0.22
A3	0.54	0.71	0.68

Table 4.4f: Normalised for alternatives based on Labour

C6	**A1**	**A2**	**A3**
A1	0.68	0.72	0.47
A2	0.22	0.24	0.47
A3	0.09	0.03	0.07

Table 4.4g: Normalised for alternatives based on Moulds / Aflatoxins

	C7		
	A1	**A2**	**A3**
A1	0.76	0.82	0.64
A2	0.13	0.14	0.27
A3	0.11	0.05	0.09

Table 4.4h: Normalised for alternatives based on Weather Susceptibility

	C8		
	A1	**A2**	**A3**
A1	0.78	0.78	0.78
A2	0.11	0.11	0.11
A3	0.11	0.11	0.11

where;

A1 refers to FBD + TD

A2 refers to FBD + SD

A3 refers to TD + SD

Completing the performance matrix. The performance of the three alternatives was determined in connection with the eight decision criteria and the result is shown in Table 4.5

Table 4.5: Performance of the two-stage dryer alternatives based on decision criteria

	A1	**A2**	**A3**
C1	0.31	0.08	0.04
C2	0.33	0.05	0.05

C3	0.28	0.12	0.03
C4	0.03	0.12	0.28
C5	0.05	0.27	0.11
C6	0.27	0.13	0.03
C7	0.32	0.08	0.04
C8	0.33	0.05	0.05

Determining the level of significance of each alternative: The value of each alternative's level of significance was calculated by finding the product of the performance matrix (Table 4.5) and the relative weights of criteria (results in Figure 4.1). This yielded a vector which gives the priority value (on a scale of 0 to 1) from which the better alternative can be selected. The results from the calculations are presented in Figure 4.2. Based on the result, it was found out that the best two-stage drying process is the FBD and the TD, with a weight of 0.22. This was followed by FBD and SD, TD and SD with weights 0.18 and 0.09 respectively. Based on this, the twostage drying process which applied FBD and TD was selected and used for the experimental study.

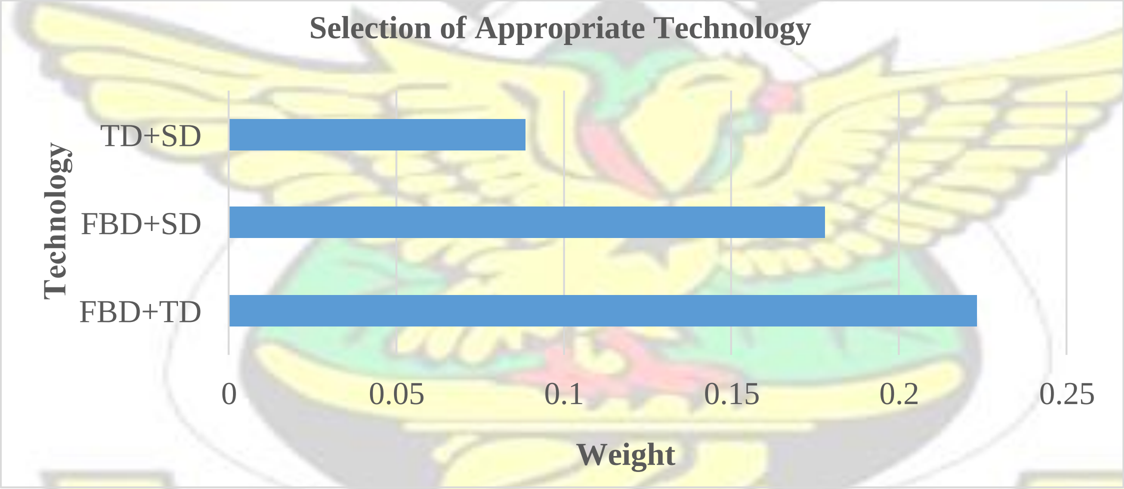

Figure 4.2: Level of significance of two-stage drying technology

4.1.2 Selection of factors to establish an experimental design using the AHP method

This section of the study highlights the results from the application of AHP to the objective which was to screen and rank factors (influencing the unit operations involved in obtaining a proper milled rice after harvesting and cleaning) based on their level of significance. The factors to be considered are as presented in Figure 3.2 of Chapter 3. The selected factors were used in the establishment of the experimental design. This experimental design was further used to carry out the drying experiment in the study.

4.1.2.1 Application of AHP in the selection of factors to establish the experimental design

Table 4.6 presents the pairwise comparison between factors (decision criteria matrix) using the judgemental scale of Saaty (1980) as presented in Table 3.3 in the previous chapter. **Table 4.6: Values of the comparisons between factors**

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13
F1	1.00	2.00	2.00	2.00	3.00	3.00	4.00	5.00	6.00	6.00	8.00	8.00	9.00
F2	0.50	1.00	1.00	1.00	2.00	2.00	3.00	4.00	5.00	5.00	7.00	7.00	8.00
F3	0.50	1.00	1.00	1.00	2.00	2.00	3.00	4.00	5.00	5.00	7.00	7.00	8.00
F4	0.50	1.00	1.00	1.00	2.00	2.00	3.00	4.00	5.00	5.00	7.00	7.00	8.00
F5	0.33	0.50	0.50	0.50	1.00	1.00	2.00	3.00	4.00	4.00	6.00	6.00	7.00
F6	0.33	0.50	0.50	0.50	1.00	1.00	2.00	3.00	4.00	4.00	6.00	6.00	7.00
F7	0.25	0.33	0.33	0.33	0.50	0.50	1.00	2.00	3.00	3.00	5.00	5.00	6.00
F8	0.20	0.25	0.25	0.25	0.33	0.33	0.50	1.00	2.00	2.00	4.00	4.00	5.00
F9	0.17	0.20	0.20	0.20	0.25	0.25	0.33	0.50	1.00	1.00	3.00	3.00	4.00
F10	0.17	0.20	0.20	0.20	0.25	0.25	0.33	0.50	1.00	1.00	3.00	3.00	4.00
F11	0.13	0.14	0.14	0.14	0.17	0.17	0.20	0.25	0.33	0.33	1.00	1.00	2.00
F12	0.13	0.14	0.14	0.14	0.17	0.17	0.20	0.25	0.33	0.33	1.00	1.00	2.00
F13	0.11	0.13	0.13	0.13	0.14	0.14	0.17	0.20	0.25	0.25	0.50	0.50	1.00

where F1, …, and F13 are the factors already clarified in Table 3.5 in the previous chapter

The relative weight of each of the thirteen factors was determined based on practical knowledge and general engineering principles with the main objective to screen and rank factors (influencing the unit operations involved in obtaining a proper milled rice after harvesting and cleaning) based on their level of significance in mind. Some of these principles considered have been applied by researchers in various fields of engineering studies. For instance, a report by Ghasemi *et al.* (2018) indicated that, although cracks can occur prior to harvesting on the farm during threshing, drying, storage and milling, among all these unit operations, a considerable loss of milled rice (percentage of broken kernels) is traced to the drying stage. Also high temperature drying causes damages that affect the quality of rice (Rehal *et al.*, 2017). Translating this in the selection and ranking of these factors, factors such as FBDT and air flow rate in the FBD are apparently more important to be considered than storage time. For instance, in the comparison between F1 and F6, if the factor F1 is three times moderately preferred than the factor F6, then the factor F6 is 1/3 times less preferred than factor F1. Thus, if the factor F1 receives a judgemental value of 3, then the factor F6 shall have the mark 1/3. It is important to note that a criterion compared with itself obtains the judgemental value of 1. This is the reason why the value 1 is recorded on the matrix' diagonal (Aşchilean *et al.*, 2017).

Following up with step 5 as presented in the previous chapter, the pairwise comparison between factors was then normalised and transformed in weights to determine the level of significance each factor had on each unit operation. The final result as presented in Table 4.7 shows the normalised form of the decision criteria matrix.

Table 4.7: Normalised decision matrix for factors

	F1	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**F9**	**F10**	**F11**	**F12**	**F13**	**Weight, W**
F1	0.23	0.27	0.27	0.27	0.23	0.23	0.20	0.18	0.16	0.16	0.14	0.14	0.13	0.2016
F2	0.12	0.14	0.14	0.14	0.16	0.16	0.15	0.14	0.14	0.14	0.12	0.12	0.11	0.1349
F3	0.12	0.14	0.14	0.14	0.16	0.16	0.15	0.14	0.14	0.14	0.12	0.12	0.11	0.1349
F4	0.12	0.14	0.14	0.14	0.16	0.16	0.15	0.14	0.14	0.14	0.12	0.12	0.11	0.1349
F5	0.08	0.07	0.07	0.07	0.08	0.08	0.10	0.11	0.11	0.11	0.10	0.10	0.10	0.0897
F6	0.08	0.07	0.07	0.07	0.08	0.08	0.10	0.11	0.11	0.11	0.10	0.10	0.10	0.0897
F7	0.06	0.04	0.04	0.04	0.04	0.04	0.05	0.07	0.08	0.08	0.09	0.09	0.08	0.0624
F8	0.05	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.05	0.05	0.07	0.07	0.07	0.0443
F9	0.04	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.03	0.03	0.05	0.05	0.06	0.0313
F10	0.04	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.03	0.03	0.05	0.05	0.06	0.0313
F11	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.03	0.0164
F12	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.03	0.0164
F13	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.0124
F13	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.0124

From Table 4.7, the weight of each of the factors was calculated. This was done by finding the average values on each row in the $\mathbf{A}_{norm}$ matrix. This result is shown on the radar plot in Figure 4.3. The Figure shows that temperature in the FBD and TD, storage time and variety of paddy have significant effect on the HRY and hence, worth the investigation on how these factors significantly affect the HRY

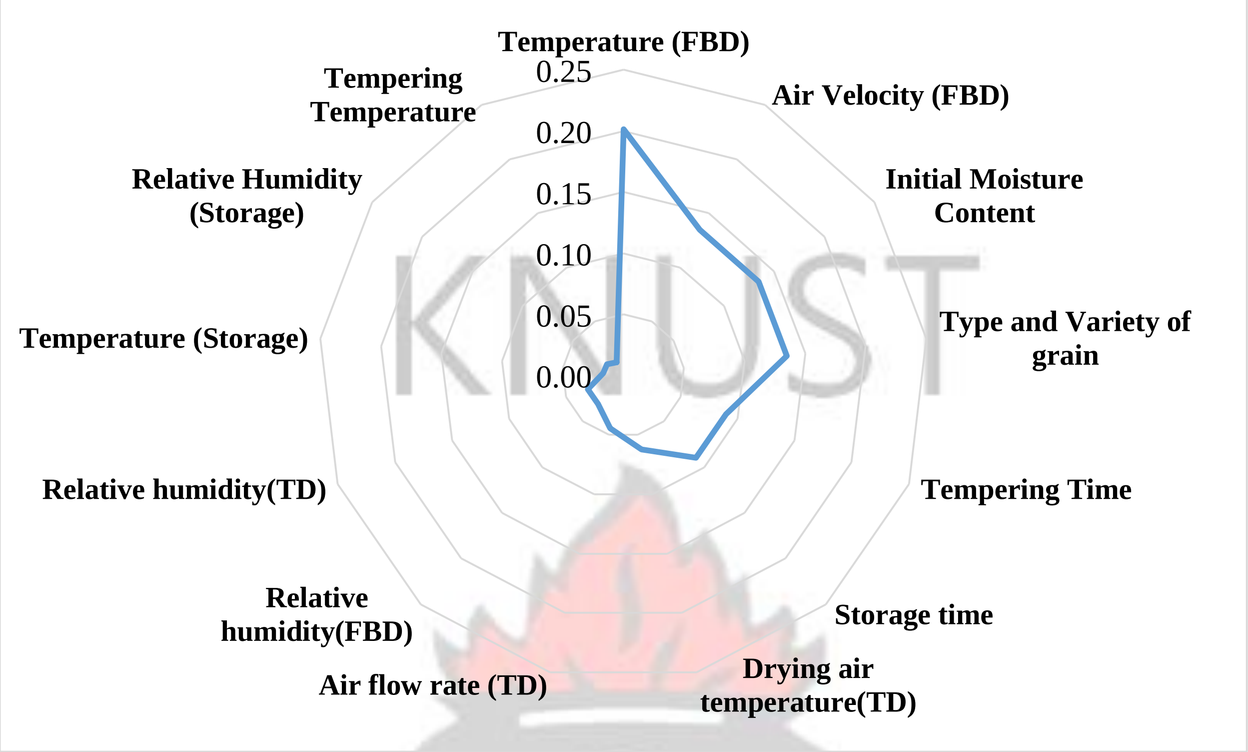

Figure 4.3: Level of significance of factors

The consistency factor of the decision criteria matrix was further determined to assess the consistency of the developed decision criteria matrix. With the thirteen factors considered in the study, a value of 1.41 was selected as the Random Index (Saaty, 1980). The maximum Eigen-value for the decision criteria matrix was calculated to be 13.53 using Equation 1, and this resulted in a Consistency Index of 1.59. Finally, a Consistency Ratio of 0.03 was determined which means that the decision criteria matrix for the study is consistent. i.e., the weights allocated for the various criteria are clearly defined. These results agree with studies by (Aşchilean *et al.*, 2017).

4.2 Performance modelling and determination of significant factors

The economic importance of maintaining a high head rice yield is critical during drying, storage and milling operations. As discussed under section 4.1.2, the focus was to select, in order of significance, factors having direct impact on HRY. Fluidised bed drying temperature, tunnel drying temperature, storage time and the variety of paddy were the factors considered in the experimental design. An experimental design (CCD design) with 20 runs and at three levels, which included six centre points was conducted and data from the drying and milling experiment are presented in Appendix 1; Table 1 and Table 2 respectively. The initial moisture content on wet basis for *Amankwatia* and *AGRA* rice varieties were 20 % and 20.17 % respectively. The responses from each experimental run is shown in Table 4.8.

Table 4.8: Responses (HRY) from the experimental runs

Run	FBDT (˚C)	TDT (˚C)	Storage Time (months)	Variety	Head rice yield (%)
1	60	40	1	*Amankwatia*	60.82
2	60	40	3	*Amankwatia*	66.38
3	60	50	1	*Amankwatia*	54.27
4	60	50	3	*Amankwatia*	58.34
5	100	40	1	*Amankwatia*	51.47
6	100	40	3	*Amankwatia*	55.34
7	100	50	1	*Amankwatia*	41.43
8	100	50	3	*Amankwatia*	45.56
9	46.36	45	2	*AGRA*	38.37
10	113.63	45	2	*AGRA*	34.00
11	80	36.59	2	*AGRA*	54.10
12	80	53.41	2	*AGRA*	40.87
13	80	45	0.32	*AGRA*	50.97
14	80	45	3.68	*AGRA*	63.56
15	80	45	2	*Amankwatia*	63.54
16	80	45	2	*Amankwatia*	63.48
17	80	45	2	*Amankwatia*	63.51
18	80	45	2	*AGRA*	58.32
19	80	45	2	*AGRA*	58.35
20	80	45	2	*AGRA*	58.37

From this table, it was observed that run 2 recorded a maximum response (Head rice yield) of 66.38 % when the FBDT, TDT, ST and rice variety were 60 °C, 40 °C, 3 months and *Amankwatia* respectively. Run 10 recorded the minimum response (head rice yield) of 34 % when the FBDT, TDT, ST and rice variety were 113.63 °C, 45 °C, 2 months and *AGRA* respectively. This result is in agreement with findings of Rehal *et al.* (2017) whose report indicated that high drying temperatures caused damage that affect the quality of rice. This low yield recorded at the high drying temperature could also be attributed to internal cracks as a result of moisture and temperature gradients (Chakraborty *et al.*, 2017).

4.2.1 Performance modelling and model diagnostics

A response surface methodology (RSM) generated regression model(quadratic), was created from results of the experimental runs with the chosen factors defining the independent variables (x) and their relationship with the dependent variable (y) thus, HRY (response) was determined using analysis of variance (ANOVA). The multiple linear regression equation showing the regression coefficients, the y-intercept, linear and quadratic coefficients of x_1 , x_2 and x_3 is shown in Equation 7. This regression model represents the performance of HRY (y_1), and how this parameter responds to changes in fluidised bed dryer temperature (x_1), tunnel dryer temperature (x_2) , storage time(x_3) and the varieties of paddy (x_4).

4.2.1.1 Regression model

$$\boldsymbol{y_1 = -261.91 + 2.737x_1 + 11.655x_2 + 2.3669x_3 - 31.209x_4 - 0.018327x_1^2 - 0.13338x_2^2 + 0.12308x_3^2 - 0.0065375x_1x_2 - 0.010187x_1x_3 + 0.22242x_1x_4 - 0.03075x_2x_3 + 0.073686x_2x_4 + 1.5433x_3x_4} \qquad \textbf{(7)}$$

Table 4.9 shows the characteristics of the developed equation (eqn. 7) with R-square value of 0.995, RMSE of 1.14 and Adjusted R-squared of 0.986. The ANOVA results with a p-value of 6.5E-0.6 (<0.05) indicates that the quadratic model is significant. The goodness of fit was validated using studies by Aghaie *et al.* (2009). The result obtained from this study corroborates with findings by Yousaf *et al.* (2017) whose regression model for HRY had R-square value of 0.96 and an Adjusted R-squared value of 0.96.

Table 4.9: Fitting characteristics of the regression model

Regression Model	**Fitting Characteristics**			
	RMSE	**R_2**	**AdjR^2**	**P-Value**
Head Rice Yield **(y_1)**	1.14	0.995	0.986	6.5E-0.6

More so, the linear regression model was fitted using the least squares method. An assumption of the least square estimation is that the residuals (errors) are random and normally dispersed. Residuals that are not normal would make the standard residuals of ordinary least squares estimates unreliable. The heteroscedastic and kernel density plots were used to assess the randomness and normally dispersed nature of the errors respectively.

The kernel density estimate of the residual vector was obtained using the kernel smoothing function estimate, *ksdensity* of Matlab (Mathworks Natick, NA) for univariate and bivariate data. If the residuals in the heteroscedastic plots show a trend, it suggests that the errors are not random and similarly a bow shape in the kernel density plots suggests that the errors are not normally dispersed. However, it is evident from the plots in Appendix 2; fig. 1 and fig. 2 that, the errors are random and normally dispersed.

4.2.2 Determination of the significant levels of factors on HRY using ANOVA Table 4.10. shows results obtained from the ANOVA table. ANOVA was used to estimate the significant effect of each factor and the correlation each independent variable has with the response surface. It can be seen from Table 4.10 that, the FBDT and TDT had high significant effects on HRY at p-values of 1.9E-0.5 (<0.05) and 5.5E-0.6 (<0.05) respectively. This result is consistent with findings of Akowuah *et al*. (2012) and Mounir and Allaf (2014). They reported that drying temperature had a significant effect (P≤0.05) on the HRY for the different post-drying durations studied. The FBDT and TDT negatively affected the HRY, in that an increase in these factors decreases the HRY, while storage time affected the HRY positively. It was interesting to note that, although storage time affected the HRY positively, it did not have any significant effect (p>0.05) on HRY. This result corroborates studies by Dokurugu (2009) which showed that storage time had no significant effect (p>0.05) on the quality of milled rice. HRY was negatively affected by interactions between; FBDT and ST, FBD and TDT, and on TDT and ST. Interactions between variety and the other three factors (FBDT, TDT and ST) affected HRY positively. All interactions had no significant effect (P>0.05) on HRY except interactions of variety with FBDT with a p-value of 6.5E-04 (<0.05), and with variety and ST with a p-value of 0.048 (<0.05).

Table 4.10: Analysis of variance probability table

	Estimate	SE	tStat	pValue
Intercept)	-261.91	31.529	-8.3068	0.00016503
x1	2.737	0.22616	12.102	1.9337E-05
x2	11.655	1.1563	10.079	5.5369E-05
x3	2.3669	4.2505	0.55686	0.59777
x4	-31.209	6.3101	-4.9458	0.0025887
x1x1	-0.018327	0.00075204	-24.37	3.1383E-07
x2x2	-0.13338	0.01203	-11.088	3.2056E-05
x3x3	0.12308	0.30134	0.40843	0.69713
x1x2	-0.0065375	0.0040276	-1.6232	0.15568
x1x3	-0.010187	0.020138	-0.50588	0.63098
x1x4	0.22242	0.031291	7.1082	0.00038963
x2x3	-0.03075	0.080553	-0.38174	0.71581
x2x4	0.073686	0.12515	0.58878	0.57749
x3x4	1.5433	0.62619	2.4645	0.048819

4.3 Process optimisation

Discussions under section 4.2 indicated that FBDT and TDT had high levels of significance on the response (HRY). A slight increase in these factor levels can be detrimental or can develop thermal stresses inside the kernel. This means that selecting the right operating conditions / factor levels can go a long way to reduce the impact these factors have on HRY. This section of the study focused on determining the factor levels that maximise the HRY.

4.3.1 Response contour plots

- Figure 4.4 presents the effect of FBDT and TDT on % HRY of *Amankwatia* rice variety at one-month storage time.

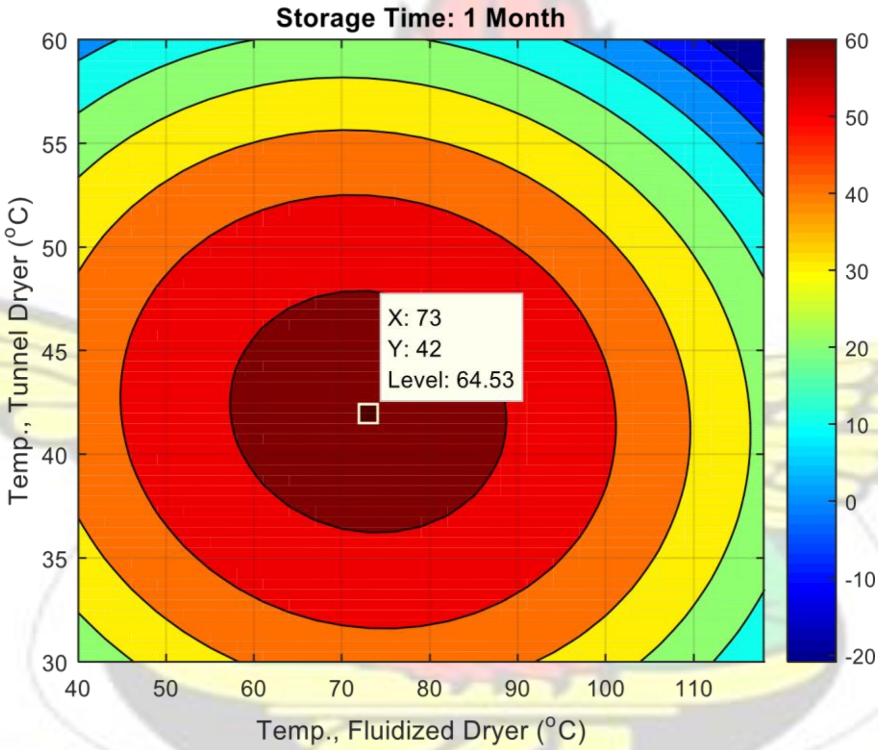

Figure 4.4: Head rice yield as a function of FBDT and TDT at one-month storage time of *Amankwatia* rice variety

From this figure, it was observed that a FBDT of 73 °C and TDT of 42 °C, at the end of 1 month storage time of *Amankwatia* rice variety recorded an optimal HRY of 64.53 %. It is interesting to note that, the optimum range of drying temperatures for *Amankwatia* in a FBD and TD were approximately within 58 °C ≤ FBDT ≤ 89 °C and 37 °C ≤ TDT ≤ 48 °C respectively. This result matches those of Dokurugu (2009) who dried *Jasmine* rice variety using a two-stage drying technique at 60 °C (FBDT) and 45 °C (TDT) which yielded an optimal head rice yield of 64.22 % at one month of storage. This result also revealed that drying temperatures below; 58 °C and 37 °C and above 89 °C and 48 °C in a FBD-TD combination will yield a lower head rice for *Amankwatia* rice variety.

- Figure 4.5 presents the effect of FBDT and TDT on % HRY of *Amankwatia* rice variety at two-months storage time.

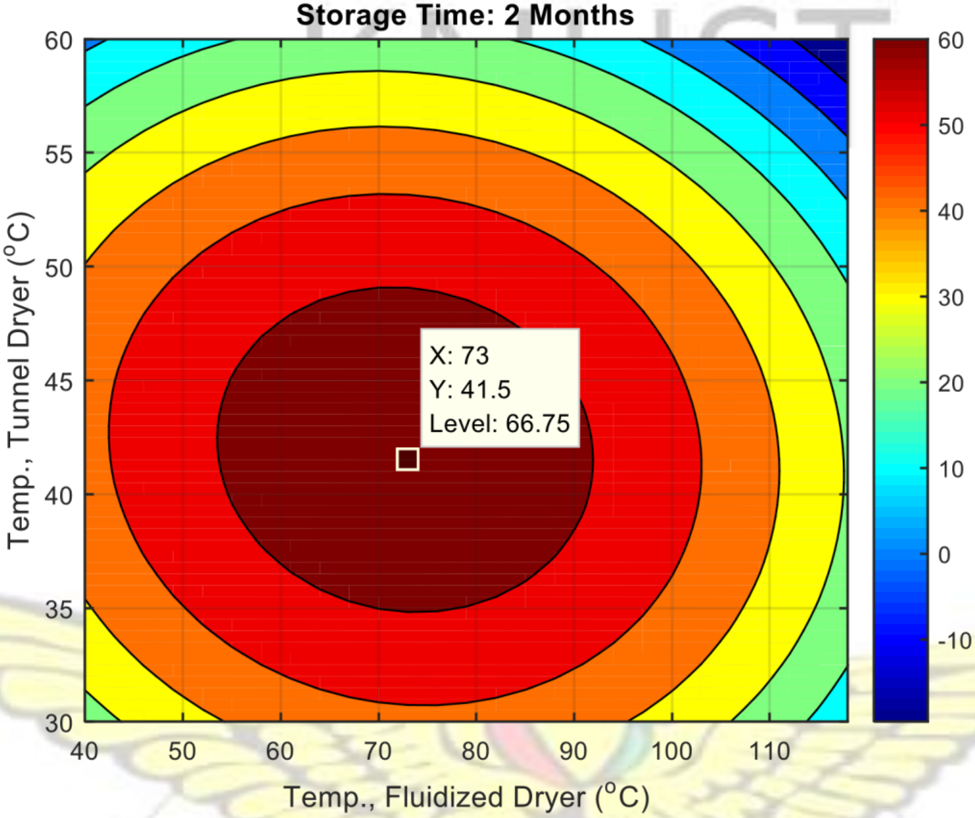

Figure 4.5: Head rice yield as a function of FBDT and TDT at two-months storage time of *Amankwatia* rice variety

As seen from this figure, a FBDT of 73 °C and TDT of 41.5 °C, at the end of the 2 months storage time of *Amankwatia* rice variety recorded an optimal HRY of 66.75 %. This result also revealed that the optimum range of drying temperatures for *Amankwatia* rice variety in a FBD and TD was approximately within 54 °C ≤ FBDT ≤ 92 °C and 35 °C ≤ TDT ≤ 49 °C respectively under two-months observation. Evidently, drying temperatures below 54 °C and 35°C and above 92 °C and 49 °C in a FBD-TD combination will yield a lower head rice for *Amankwatia* rice variety. These results agree with findings of Akowuah *et al.* (2012), which suggest that “as the drying temperatures increase, there is a corresponding decrease in HRY which varied with duration of storage”.

Figure 4.6 presents the effect of FBDT and TDT on % HRY of at three-months storage time of *Amankwatia* rice variety

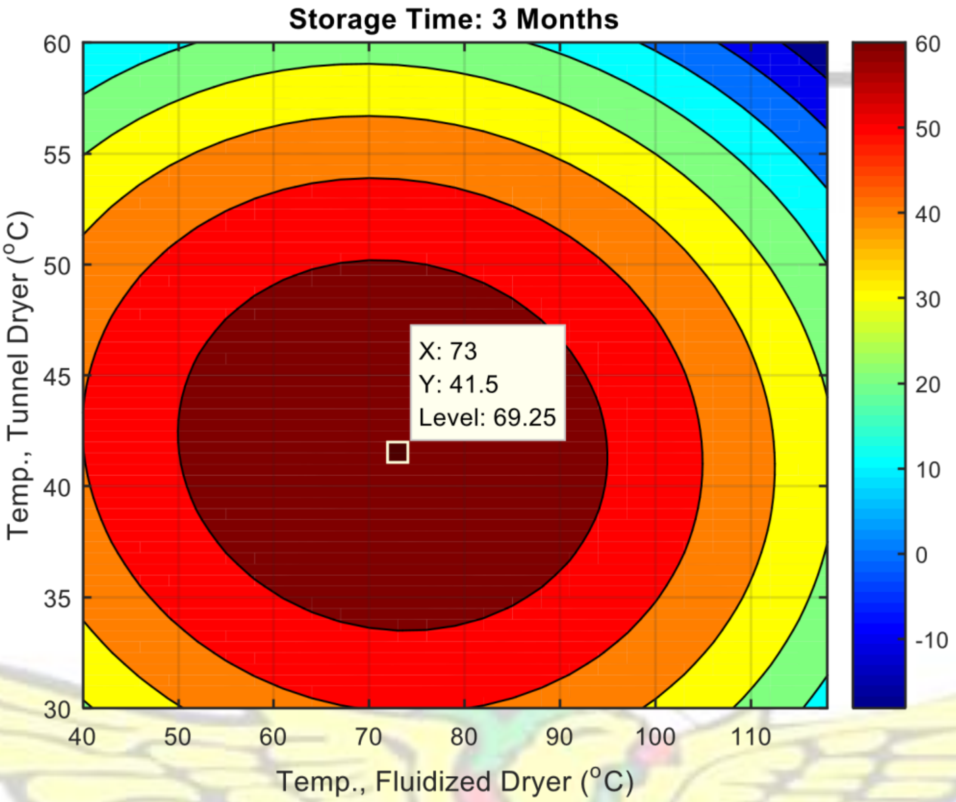

Figure 4.6: Head rice yield as a function of FBDT and TDT at 3-months storage time of *Amankwatia* rice variety

It is apparent from this figure that, a FBDT of 73 °C and TDT of 41.5 °C, at 3 months of storing *Amankwatia* rice variety recorded an optimal HRY of 69.25 %. This plot also revealed that the optimum range of drying temperatures for *Amankwatia* rice variety in a FBD and TD was approximately within 50 °C ≤ FBDT ≤ 95 °C and 34 °C ≤ TDT ≤ 50 °C respectively under three months' observation. This clearly indicate that drying temperatures below 50 °C and 34 °C and above 95 °C and 50°C in a FBD - TD combination will yield a lower head rice for *Amankwatia* rice variety. This result corroborates research findings of Akowuah *et al.* (2012), which suggested that drying paddy in a tunnel dryer using temperatures above 50 °C induce thermal stress in the kernel thereby yielding cracked kernels and eventually reducing the quality of milled rice.

Figure 4.7 presents the effect of FBDT and TDT on % HRY of *AGRA* rice variety at onemonth storage time.

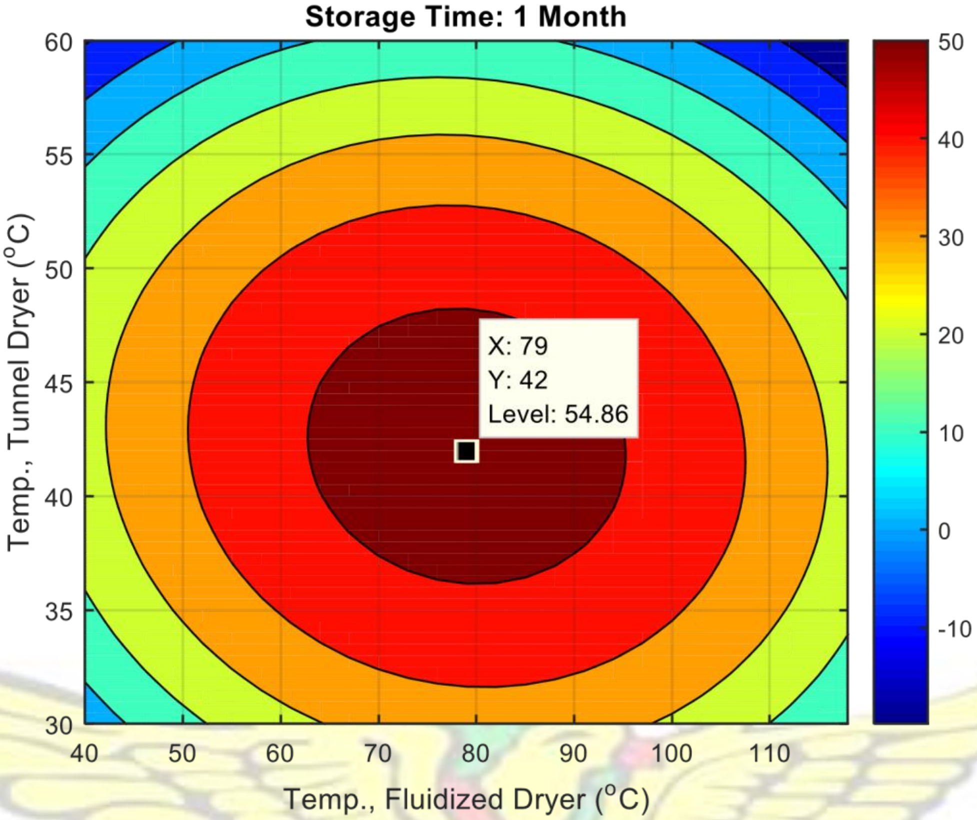

Figure 4.7: Head rice yield as a function of FBDT and TDT at one-month storage time of *AGRA* rice variety

From this figure, it was observed that FBDT of 79 °C and TDT of 42 °C, at 1 month of storing AGRA rice variety recorded an optimal HRY of 54.86 %. It is interesting to note that, the optimum range of drying temperatures for *AGRA* in a FBD and TD was approximately within 63 °C ≤ FBDT ≤ 94 °C and 36 °C ≤ TDT ≤ 48 °C respectively. This result also revealed that drying temperatures below 63 °C and 36 °C and above 94°C and 48 °C in a FBD-TD combination will yield a lower head rice for *AGRA* rice variety. These results corroborate research findings of Meeso *et al.* (2004) who indicated that drying at high temperatures in the first stage of a two-stage paddy drying led to the development of moisture gradients inside each grain kernel and resulted in cracking and breakage of the paddy kernels.

Figure 4.8 presents the effect of FBDT and TDT on % HRY at two-months storage time of *AGRA* rice variety.

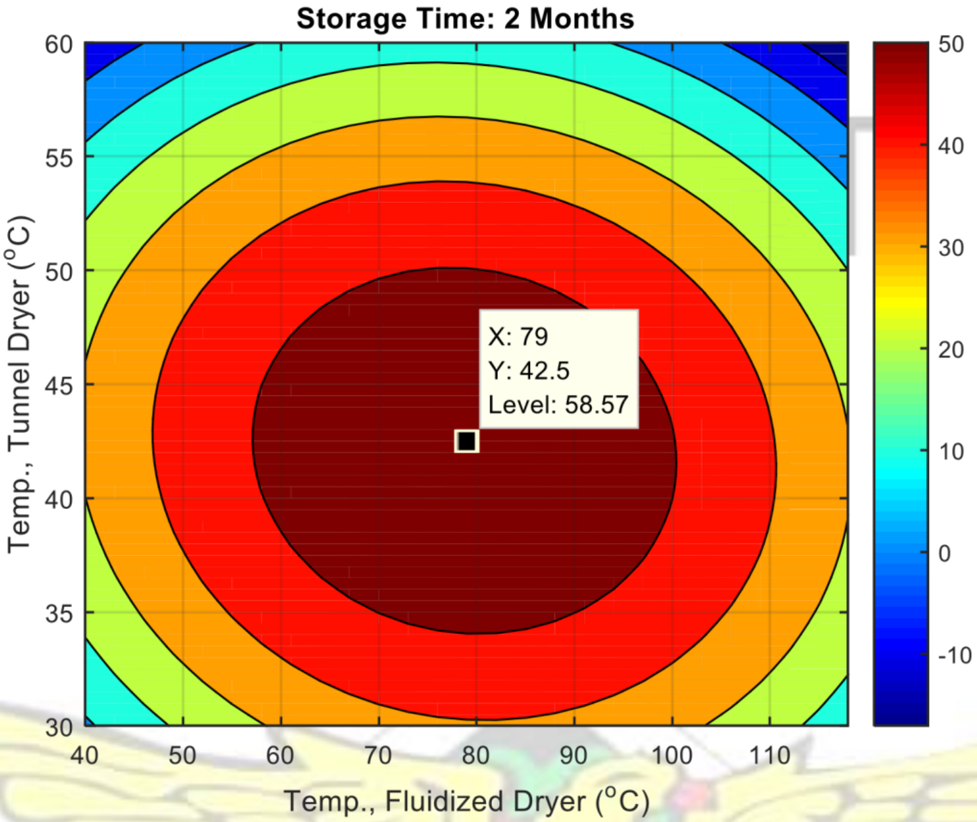

Figure 4.8: Head rice yield as a function of FBDT and TDT at two-months storage time of *AGRA* rice variety

As seen from this figure, a FBDT of 79 °C and TDT of 42.5 °C, at 2 months of storing *AGRA* rice variety recorded an optimal HRY of 58.57 %. This result also revealed that the optimum range of drying temperatures for *AGRA* rice variety in a FBD and TD was approximately within 58 °C ≤ FBDT ≤ 100 °C and 34 °C ≤ TDT ≤ 50 °C respectively under two months' observation. Evidently, drying temperatures below 58 °C and 34°C and above 100 °C and 50 °C in a FBD - TD combination will yield a lower head rice for *AGRA* rice variety. These results confirm the findings of Tirawanichakul *et al.* (2004) who reported that drying paddy in a fluidised bed at high temperatures ranging above 100 °C affected the head rice yield negatively.

Figure 4.9 presents the effect of FBDT and TDT on % HRY at three-months storage time of *AGRA* rice variety.

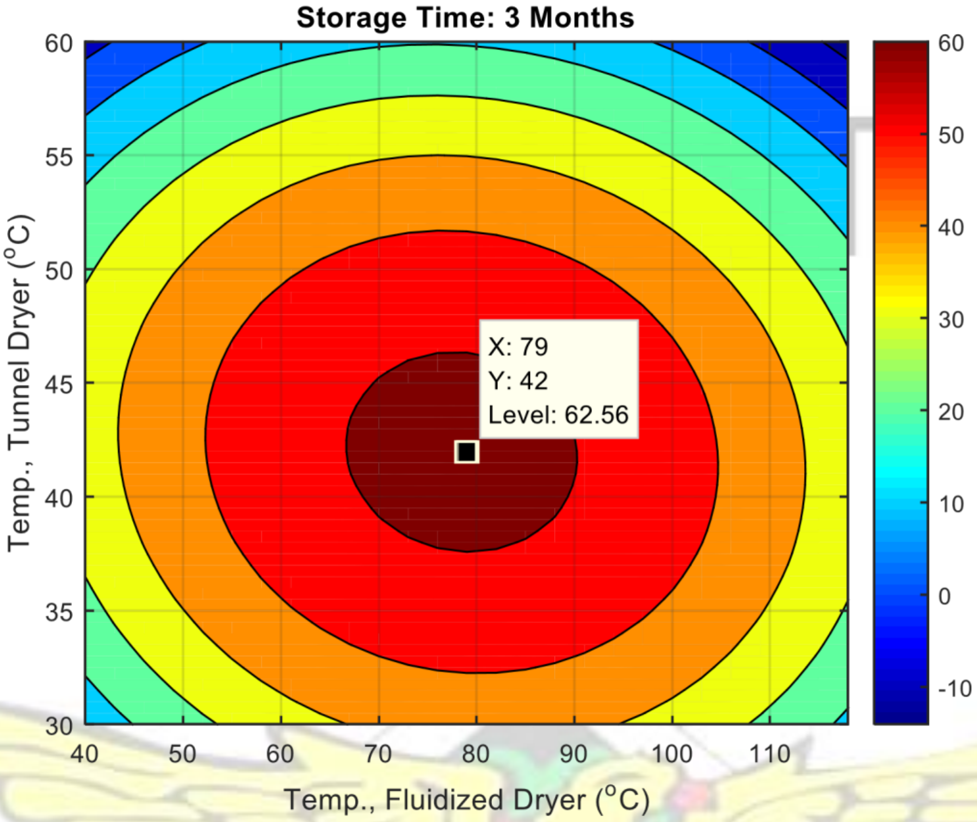

Figure 4.9: Head rice yield as a function of FBDT and TDT at three-months storage time of *AGRA* rice variety

It is apparent from this figure that, a FBDT of 79 °C and TDT of 42 °C, at 3 months of storing *AGRA* rice variety recorded an optimal HRY of 62.56 %. This plot also revealed that the optimum range of drying temperatures for *AGRA* rice variety in a FBD and TD was approximately within 68°C ≤ FBDT ≤ 90 °C and 38 °C ≤ TDT ≤ 46 °C respectively under three-months observation. This further validates results of Dokurugu (2009) who dried jasmine using drying temperatures of 80 °C and 45 °C and observed an optimal head rice yield of 62.20 % at three months of storage. These results clearly indicate that drying temperatures below 68 °C and 38 °C and above 90 °C and 46 °C in a FBD-TD combination will yield a lower head rice for *AGRA* rice variety.

4.3.2 Summary of the response analysis

Table 4.11. Presents the summary of the optimum values for the factor levels and their corresponding response on head rice yield of *Amankwatia* and *AGRA* rice varieties. It can be observed from this table that the optimal operating levels for *Amankwatia* and *AGRA* rice

variety are at three months of storage. At the end of the third month of storage, an optimum head rice yield of 69.75 % and 62.56 % were recorded for *Amankwatia* and *AGRA* rice varieties respectively. The optimum drying temperatures for *Amankwatia* rice variety were 73 °C and 41.5 °C in the fluidised bed dryer and tunnel dryer respectively. The optimum drying temperatures for *AGRA* rice variety were 79 °C and 42 °C in the fluidised bed dryer and tunnel dryer respectively. Comparing results for both varieties, generally, *Amankwatia* rice variety performed better than *AGRA* rice variety in terms of head rice yield. This noticeable decrease in head rice yield observed between the two varieties could be attributed to significance levels of variety and temperature.

Table 4.11: Head rice yield from optimum levels of independent variables

Storage Time (Months)	**Optimal factor/operating levels**		**Head Rice Yield (%)**
	Fluidised bed drying temperature (°C)	Tunnel Drying temperature (°C)	
Amankwatia rice variety			
1	73	42	64.53
2	73	41.5	66.75
3	73	41.5	69.25
AGRA rice variety			
1	79	42	54.86
2	79	42.5	58.57
3	79	42	62.56

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS 5.1 Conclusions

Based on the results of this study, the following conclusions have been made:

- The first objective was to perform a multi criteria analysis for selection of an appropriate two-stage drying technique. FBD and TD had the highest weighting of 0.2, followed by FBD and SD, and TD and SD with weights 0.18 and 0.09 respectively. Based on the study performed, fluidised bed dryer and tunnel dryer were selected as the best drying option for a proper milling yield of the two rice varieties (*Amankwatia and AGRA).*

- The second objective was to model the performance of the two stage drying process and determine the factors that significantly affect the head rice yield. A response surface methodology was used to model the performance of a two stage drying process. FBDT, TDT, and the rice variety had significant effects on head rice yield with p-values of 1.9E0.5 (<0.05) and 5.5E-0.6 (<0.05) and 2.5E-0.5 (<0.05). However, ST with p-value of 0.6 (>0.05) indicated that, ST had no significant effect on the HRY.

- The third objective was to determine the operating conditions that optimise the head rice yield. Response surface methodology was used to optimise the operating conditions of FBDT, TDT, variety and storage time on HRY. The results showed that the optimal operating conditions for *Amankwatia* rice variety which yielded an optimum HRY of 69.25 % were 73 °C, 41.5 °C and 3-months in the FBD, TD and storage time respectively. The optimal operating conditions for *AGRA* rice variety which yielded an optimum HRY of 62.56 % were 79 °C, 42 °C and 3-months in the FBD, TD and storage time respectively.

5.2 Recommendations

The following recommendations have been made based on the outcome of the study:

- Further studies using the same experimental design to investigate the impact of FBDT and TDT on the HRY of other rice varieties would be interesting.

- To achieve an optimum head rice yield during processing of *Amankwatia* and *AGRA* rice varieties, farmers and researchers could use the results (optimal operating conditions) of this study.

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APPENDICES

APPENDIX 1:

Table 1: Data from two stage drying of *Amankwatia* and *AGRA* rice varieties

Run 1		Run 2		Run 3		Run 4	
Time	**MC**	**Time**	**MC**	**Time**	**MC**	**Time**	**MC**
0	20	0	20	0	20	0	20
0.5	19.6	0.5	19.8	0.5	19.68	0.5	19.5
1	19.3	1	19.5	1	19.5	1	19.1
1.5	18.8	1.5	18.6	1.5	18.7	1.5	18.8
2	18.6	2	18.3	2	18.6	2	18.57
2.5	18.45	2.5	18.15	2.5	18.43	2.5	18.46
17.5	17.1	17.5	16.9	17.5	17.3	17.5	17.5
32.5	16	32.5	15.5	32.5	15.8	32.5	16.1
47.5	14.3	47.5	14.6	47.5	14.9	47.5	15.1
62.5	13.1	62.5	13.6	62.5	13.6	62.5	13.9
				77.5	13.2	77.5	13.4

Run 5		Run 6		Run 7		Run 8	
Time	**MC**	**Time**	**MC**	**Time**	**MC**	**Time**	**MC**
0	20	0	20	0	20	0	20
0.5	19.56	0.5	19.44	0.5	19.56	0.5	19.11
1	18.8	1	18.51	1	18.6	1	18.3
1.2	18.39	1.2	18.15	1.2	18.45	1.2	18.23
16.2	17.4	16.2	17.2	16.2	17.5	16.2	17.6
31.2	16.2	31.2	16.1	31.2	16.4	31.2	16.1
46.2	15.4	46.2	15.2	46.2	15.2	46.2	14.9
61.2	14.7	61.2	14.8	61.2	14.5	61.2	14
76.2	13.9	76.2	14.2	76.2	13.6	76.2	13.4
91.2	13.3	91.2	13.1				

Run 9		Run 10		Run 11		Run 12	
Time	**MC**	**Time**	**MC**	**Time**	**MC**	**Time**	**MC**
0	20.17	0	20.17	0	20.17	0	20.17
1	19.3	0.4	19.02	0.4	19.2	0.4	19.3
2	18.75	0.8	18.2	0.8	18.87	0.8	18.5
3	18.4	1.1	17.88	1.3	18.62	1.3	18.63
18	17.3	16.1	15.9	16.3	18.1	16.3	17.1
33	15.9	31.1	14.7	31.3	17.2	31.3	15.5
48	15	46.1	13.3	46.3	16.2	46.3	14
63	14.4			61.3	15.4	61.3	13.1
78	13.9			76.3	15		
93	13.4			91.3	14.6		
				106.3	14.2		
				121.3	13.9		

Run 13		Run 14		Run 15		Run 16	
Time	**MC**	**Time**	**MC**	**Time**	**MC**	**Time**	**MC**
0	20.17	0	20.17	0	20	0	20
0.4	19.33	0.4	19.6	0.4	19.25	0.4	19.36
0.8	18.76	0.8	18.97	0.8	18.6	0.8	18.7
1.3	18.5	1.3	18.49	1.3	18.08	1.3	18.1
16.3	17.3	16.3	17.4	16.3	17.4	16.3	17.5
31.3	16.2	31.3	16	31.3	15.9	31.3	15.7
46.3	15.3	46.3	15.2	46.3	14.9	46.3	15.1
61.3	14.8	61.3	14.6	61.3	14.1	61.3	14.2
76.3	14.3	76.3	14	76.3	13.2	76.3	13.4
91.3	13.2	91.3	13.3				

Run 17		Run 18		Run 19		Run 20	

Time	MC	Time	MC	Time	MC	Time	MC
0	20	0	20.17	0	20.17	0	20.17
0.4	19.4	0.4	19.6	0.4	19.5	0.4	19.6
0.8	18.8	0.8	19.01	0.8	18.8	0.8	19
1.3	18.16	1.3	18.41	1.3	18.32	1.3	18.39
16.3	17.2	16.3	17.4	16.3	17.5	16.3	17.4
31.3	15.9	31.3	16.3	31.3	16.1	31.3	16.2
46.3	15.3	46.3	15.4	46.3	15.6	46.3	15.3
61.3	14.4	61.3	14.6	61.3	15	61.3	14.9
76.3	13	76.3	14	76.3	14.1	76.3	14.2
		91.3	13.4	91.3	13.1	91.3	13.4

Table 2: Results from milling experiment

RUNS	**Initial Moisture content (% wb)**	**Initial Weight**	**Brown rice recovery**	**Milled rice recovery (Polished)**	**Grading**	**Grading**
	(before milling)	**(G)**	**(weight after dehusking)**	**(weight after debraning)**	**(Head rice recovery)**	**Broken**
1	13	100	72.3	67.3	60.82	6.48
2	13.5	100	76.4	74.7	66.38	8.32
3	12.4	100	68.4	60.7	54.27	6.43
4	12.5	100	70.4	63.7	58.34	5.36
5	13.4	100	67.4	58.3	51.47	6.83
6	14	100	69.2	61.9	55.34	6.56
7	13	100	66.1	56.1	41.43	14.67
8	12.5	100	66.2	56.4	45.56	10.84
9	13.6	100	64.1	52.5	38.37	14.13
10	13.6	100	63.7	51.9	34	17.9
11	13.6	100	68.1	59.7	54.1	5.6

12	13.4	100	65.2	54	40.87	13.13
13	13.4	100	66.3	56.8	50.97	5.83
14	14	100	75	71.9	63.56	8.34
15	13.6	100	74	69.6	63.54	6.06
16	13.4	100	72.4	67.5	63.48	4.02
17	13.3	100	73.3	68.6	63.51	5.09
18	13.3	100	69.9	62.6	58.32	4.28
19	13.4	100	71.3	64.9	58.35	6.55
20	13.4	100	71.6	66.5	58.37	8.13

APPENDIX 2: DATA FROM MODEL DIAGNOSTICS Residual for model

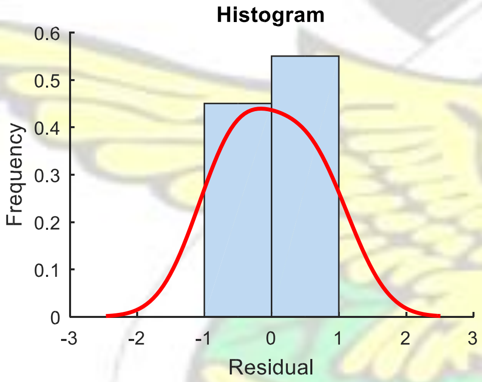

Fig. 1. Kernel density plots

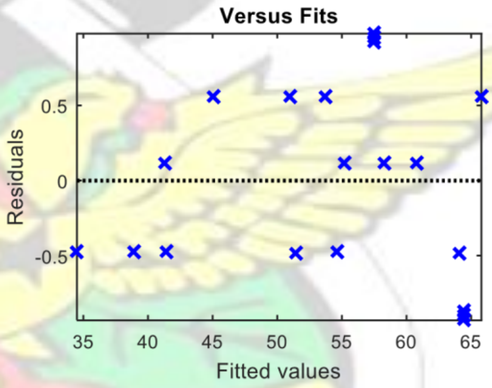

Fig. 2. Heteroscedastic plot