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ANALYSIS OF DRYING CHARACTERISTICS OF SORGHUM VARIETIES GROWN IN KENYA

(A case study of Elgeyo-Marakwet County)

BY

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ABSTRACT

Inefficient sorghum drying results in post-harvest losses that contribute to cases of hunger, malnutrition, poverty and food insecurity. One possible solution to reduce these losses is to design an affordable dryer for the sorghum farmers in Kenya. In order to do this, it was necessary to define the drying characteristics of the sorghum varieties grown, and develop thin layer drying equations that would be adopted when determining the design conditions for a sorghum dryer. This research was done to evaluate the drying characteristics of sorghum varieties grown in Kenya.

In the evaluation of sorghum varieties that are grown in Kenya- Elgeyo Marakwet County, four common sorghum grain varieties grown were found to be Serena, Seredo, Gadam and KARI/Mtama 1. From this study, it was established that 99% of the farmers in Elgeyo-Marakwet County practise the traditional field-drying/sun drying, whereas 1% dry sorghum in the house in hanging cobs. The farmers were both small scale and large scale farmers.

Thin layer drying of these four sorghum varieties were each studied under temperatures of 40°C, 50°C and 60°C in a convective laboratory dryer in order to analyse the drying conditions. The moisture content during the drying process was measured using the oven method and moisture meters until equilibrium moisture content was achieved. The drying rate was then determined by plotting the moisture ratio against time. From the data collected, drying curves of the sample varieties were analysed. The experimental results were fitted into seven pre-existing thin layer drying equations, and non-linear regression analysis was performed for each variety. The values of R^2, RMSE and χ^2 were evaluated and used to predict the most suitable model for each variety i.e. Highest R^2, Lowest RMSE and lowest $\chi^{2.}$

From the drying curves, a decay pattern was observed for all the sorghum varieties studied. The drying rate was fastest at a temperature of 60°C. Following the non-linear regression analysis of drying data of the four varieties, all the models chosen showed a high R^2 value (>90%) and RMSE range of 0.006 to 0.159. The χ^2 ranged from 0.0005 to 0.2079. The recurrent and best fit model was found to be the Logarithmic model for Gadam, Kari Mtama 1 variety, Serena and Seredo varieties. The thin layer drying equation for the Logarithmic model will form a basis in the design of an efficient and low-cost drying system for the sorghum farmers in Kenya.

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LIST OF SYMBOLS

φ	Relative humidity
$\dot{V}$	Volumetric flow rate
ν_0	Superficial velocity
ΔP	Pressure drop per unit height
ε	Bulk porosity, fraction
μ	Dynamic viscosity of air
ρ	Air density
∂M	change in moisture content
∂t	change in time
χ^2	chi-square.
^{o}C	Degrees Celsius

ABBREVIATIONS & ACRONYMS

ANOVA	Analysis of Variance
ASAL	Arid & Semi- Arid Land
ASABE	American Society of Agricultural and Biological Engineers
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
CEIC	Census and Economic Information Centre
EABL	East African Breweries Limited
EMC	Equilibrium Moisture Content
FAO	Food & Agriculture Organization
FAOSTAT	Food & Agriculture Organization Statistical data
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IFPRI	International Food Policy Research Institute
IRRI	International Rice Research Institute
KALRO	Kenya Agricultural & Livestock Research Organization
KARI	Kenya Agricultural Research Institute
KCSAP	Kenya Climate Smart Agriculture Project
KNBS	Kenya National Bureau of Statistics
M.C.	Moisture content
M.R.	Moisture Ratio
PHAP	Post Harvest & Agro-processing
RH	Relative Humidity
RMSE	Root Mean Square Error
SDGs	Sustainable Development Goals.
SS	Total Sum of squares

VPD	Vapor Pressure Deficit
U.N.	United Nations
d.b.	Dry basis
w.b.	Wet basis

1 INTRODUCTION

1.1 Background

The adaptability and diversity of grain sorghum has made it one of the top five cereals in the world (Awika, 2011). According to the Food Security Department of FAO (Food and Agriculture Organization), sorghum ranks fifth in cereals after rice, wheat, barley and maize with a global production of 58 million tonnes per year (FAOSTAT, 2020).

Sorghum is said to have originated in Eastern Africa before being adopted on a global level. 50% of world sorghum is in Africa, while the rest is being grown in other continents of the world (Poeydomenge, 2021). Following maize, sorghum is said to be the second most important cereal in Africa. The total production in Africa is 27 million tonnes per year. Compared to its neighbouring countries such as Ethiopia, Uganda and Tanzania, sorghum production in Kenya ranked last with a production of 0.32 tonnes/year (Njagi, Onyango, Kirimi, & Makau, 2019). However, the sorghum production has been on the rise, with an upward trend of 0.99 tonnes/hectare since 2014. It has mainly been grown for human consumption by producing ugali and porridge and recently there has been demand for sorghum for beer brewing here in Kenya (Chepng'etich, Nyamwaro, Bett, & Kizito, 2015). Sorghum is also commended for its health benefits such as a gluten-free alternative, antioxidant, cholesterol and diabetes reduction and prevention of cancer (Kahonge, 2014). Due to the increasing demand from those wanting to live a healthy lifestyle, many are looking into sorghum as an alternative cereal after maize and millet.

Drying is an important stage in the post-harvest processing of grains, as it determines the quality and quantity of the final product. Drying is also vital since its inadequacy affects the subsequent food processing stages and is the farmers' initial preservation method, which reduces the moisture content of the grain from 30% to an expected 10-12% (Mejia, 2000). According to a recent study, it is reported that grains such as maize and sorghum go through a significant proportion (~6 % to 14%) of post-harvest loss when threshing, drying, storing and processing (Nyambo, 2013).

In order to ensure good quality of the drying process and avoid losses, there is need to invest greatly and widely in improved post-harvesting technological systems that will prevent food loss and minimize waste which will serve as a gateway in ensuring both local and national food security (IFPRI, 2012). This can be done by analysing the characteristics, conditions and the process of sorghum drying in order to develop suitable design conditions necessary for the design of an efficient sorghum dryer.

1.2 Problem Statement

The Kenya National Bureau of Statistics predicts that with the current growth rate of 3.3 million p.a., the population of Kenya will be about 65 million by 2030 (CEIC, 2020). In Elgeyo-Marakwet county, the total population in 2019 was 454,480 and the projected growth rate is 2.1% per annum (KNBS, 2019), meaning that the population will be about 600,000 in the year 2030. With this population increase and demand for food, the cost of living also rises. The total global production of sorghum is 58 million tonnes per year. Compared to its neighbouring countries such as Ethiopia, Uganda and Tanzania, sorghum production in Kenya ranked last with a production of 0.32 tonnes/year (FAOSTAT, 2020). Furthermore, land available for agriculture is being substituted by residential houses. Unfortunately, the poverty level in this County is 57%, which is 11% higher than the national poverty level (Elgeyo-Marakwet, 2018). Post-harvest losses have been reported to be approximately 25% (Nyambo, 2013). Most of the residents depend on local farmers for their daily food, and agriculture is a means of support to many. There is therefore a need to protect the source of food production in whichever way possible. One way this can be done is through curbing post-harvest loss.

Post-harvest grain losses occur mostly due to poor drying after harvest, causing mould contamination, mycotoxins and insect infestation during storage. Drying being the first stage in the post-harvest process, plays a critical role in ensuring the quality of the grain. Inefficient drying affects the other post-harvest processes i.e. storing, processing, packaging and distributing (Kim, Kim, Kim, Lee, & Han, 2016). Besides, sorghum when mature cannot be harvested immediately due to its high amount of moisture content (25%-30%). If harvested then, the grain can either crack or produce heads that are difficult to thresh. On the other hand, leaving it in the farm for too long attracts birds and small animals which feed on the grain thus increasing losses (Sumner & Worley, 2017). Moreover, storage before drying increases the risk of mycotoxins in the sorghum, which is hazardous for human health (Tumbleson *et al.*, 2006).Thus, there are serious repercussions when the drying process of sorghum is not efficient.

The traditional method of open-air sun-drying where grain is laid on the ground and the sun naturally dries the grain, is still the prevalent method of drying sorghum in Kenya. However, this method is not only laborious but also time consuming and inefficient.

While the study of sorghum has been done by many researchers, the information available for sorghum drying characteristics, specifically for Kenyan varieties is limited. It is therefore necessary to develop thin layer drying equations for the available sorghum varieties. These fundamentals will provide a basis of designing an efficient and affordable system for drying sorghum for small scale farm holders by in Kenya. If this is achieved, post-harvest losses caused by drying such as slow drying rate, mould, birds, diseases and pests will be greatly minimized. Furthermore, high quality, nutritional sorghum will be produced and will pave way for quality sorghum grain and sorghum products suitable for both the marketplace and sustainable consumption. This in overall, will reduce the cases of hunger and malnutrition in Kenya.

1.3 Objectives

1.3.1 General Objective

The general objective of this research was to evaluate the drying characteristics of sorghum varieties grown in Kenya.

1.3.2 Specific Objectives

The specific objectives of this research were to:

1. Evaluate sorghum varieties and drying techniques adopted by farmers.
2. Investigate the characteristics of sorghum related to drying experimentally.
3. Develop thin layer drying equations, compare against pre-existing models and select the best fitting thin layer drying equation for each sorghum variety.

1.4 Justification for the Study

Drying determines the quality of the final sorghum grain. With the high poverty level, many small-scale farmers in Kenya cannot afford to buy specialized equipment for drying. Majority still adopt the traditional method of open sun drying, thus incurring losses. Losses occur through attacks by birds and animals when field/open-sun drying, and through infestation by mould, mycotoxins and pests if the sorghum is not dried well.

Sorghum diversification has increased over the years due to technological demand, yield and disease modifications. The sorghum varieties in Kenya have slightly different characteristics from the original grain sorghum (*Sorghum bicolour L. Moench),* which plays a role in analysing the drying conditions of the grain variants. In Kenya, KALRO has developed varieties and there has been ongoing research on hybrid varieties in order to curb the crop diseases (KALRO, 2021). Infonet-Biovison has also classified eight varieties based on the ecological zones, some of which are in Table 2.1.

KALRO-KCSAP project (funded by World Bank) has specific technologies, innovations, management and practices for the sorghum value chain aimed at achieving the climate smart technologies (Kisilu, Kamau, & Cheruiyot, 2019). However, mechanization so far has been on sorghum planters, weeding and harvesters, which are the pre-harvest processes. There is need to adopt technologies and innovations on the post-harvest processes as well, and this includes mechanization for the sorghum drying process.

Conducting this research will pave way for design of post-harvest technologies that are in line with the United Nations Sustainable Development Goals (SDGs) (U.N, 2015). For instance, SDGs 1 and 2, which are to reduce poverty and hunger, will be achieved by curbing post-harvest losses, which in this research focus on drying technology. Post-harvest loss in the drying process will be reduced, enabling farmers to have a higher production rate. Furthermore, properly dried sorghum grain will ensure quality grain is produced for food, which will be durable. Goal 3, aimed at ensuring good health and well-being, will be achieved when there is enough production of sorghum, which is of high nutritional value and is also medicinal.

In order to design an effective drying system, there is a need to set basis of thin layer drying equations that will be used for the design. This can be found when the drying characteristics of the sorghum are determined.

1.5 Scope of work

The study focused on determining drying characteristics of sorghum grown in Kenya. The sorghum varieties that were studied included Serena, Seredo, KARI Mtama 1 and Gadam, which are currently grown in Elgeyo-Marakwet County. Apart from the varieties, the other study variables were time, temperature and moisture content. The main characteristic determined was the moisture content of each grain. For the analysis of the drying process, only a thin layer sample was used in analysing the drying characteristics. From the results, thin layer drying model curves were plotted. Given that there are many pre-existing mathematical models that have been developed, 7 of these models were used. These models have been used in the modelling of sorghum grain before, hence were preferred. The models included the Lewis model, Page model, Modified Page model, Two-Term model, Logarithmic model, Henderson and Pabis model, and the Wang-Singh model.

2 LITERATURE REVIEW

2.1 Sorghum and its varieties

Grain sorghum is one of the most common cereal grains in the world. According to the Food Security Department of FAO, sorghum ranks fifth in cereals after rice, wheat, barley and maize (FAOSTAT, 2020). According to Croplife (2021), sorghum is the second-most predominant cereal in Africa after maize/corn. While sorghum is not as common as maize here in Kenya, its diversity and nutritional value make it a go-to grain for many as a staple food and also for health purposes.

Sorghum is used for both human and animal consumption in Kenya. Its nutritional value make it famous for porridge, bread and *ugali*, the staple food in Kenya. Sorghum is a good source of Vitamin B (20% of recommended Daily Value), fibre (10% of recommended Daily Value), magnesium, manganese and phosphorus. Compared to other cereal grains, sorghum ranks high in providing essential proteins to the body (Whole Grain Council, 2020). Commercially, sorghum is used as malt in the manufacture of beer (Kute, Kamidi, & Chirchir, 2000), as well as making porridge, *ugali* and as fodder for feeding animals. The famous Kenya brewing industry, EABL recently contracted smallholder sorghum farmers to produce more sorghum for the manufacture of some of their beers. In an article published by the Standard Newspaper, EABL Company sought to increase its sorghum intake from 10,000 tonnes to 30,000 tonnes (Gwengi, 2016). Already, white sorghum (Gadam) is being cultivated in Elgeyo-Marakwet Arror ward for the company. From these authors, it is evident that the demand for sorghum is on the rise. There have been successful attempts at making value addition products of sorghum which are being embraced. Fortified flours and sausages are examples of such. Sorghum is also praised for its health benefits such as a gluten-free alternative, antioxidants, and reducing cholesterol and diabetes (Kahonge, 2014). Thus, while sorghum is not as common as wheat and maize, it still is a grain that is beneficial, on demand and sustainable.

Sorghum has been traditionally produced in areas prone to drought and which experience a subsidized amount of rainfall annually. According to Noah & Waithaka (2005), sorghum excels in areas between 500-1700 m above sea level and with rainfall not less than 300 mm per annum. Thus, while it is known for being a drought-resistant crop, sorghum still needs rainfall/water for it to flourish and grow to maximum productivity. In Elgeyo-Marakwet county, sorghum is grown in the lowlands i.e. Kerio Valley, where the altitude ranges from 900-1500 m and rainfall is <850 mm per year.

A research done by Kenya Agricultural & Livestock Research Organization identified four sorghum varieties grown in Kenya which were: Kari Mtama 1, Gadam, Seredo and Serena varieties (KALRO, 2021). Without specifying which variety, KALRO (2021), pointed out that most of the varieties developed have been through open pollination. There is research ongoing on hybrid-bred varieties. Another research done by Infonet-Biovison (2019), revealed that there are eight sorghum varieties in Kenya namely: Serena, Seredo, KARI Mtama 1, IS76, Gadam, E1291, E6518, and BJ28. The classifications of the varieties was based on the ecological zones. Based on the scope of this research, the varieties' colour, yield and attributes were also defined in KALRO (2021) and Infonet-Biovision (2019). Although the yield quantity in KALRO (2021) was in ton/ha, after conversion, there was minimal difference with the research done by Infonet-biovision (2019). Another study by Mutahi (2012), highlighted on the 1000-kernel weight of the varieties, which had not been done by other authors. These characteristics are summarized in Table 2-1:

Table 2-1: Kenyan Sorghum Varieties and their characteristics (Infonet-Biovision,2018)

Variety	Colour	Yield (90 kg bags/acre)	Attributes	1000-kernel weight (g)
Serena	Brown	12	Adaptable widely	24.85
Seredo	Reddish Brown	12	Adaptable widely but tolerant to striga	27.76
KARI/Mtama 1	White	15	Tolerant to stem borers but attracts birds	24.20
Gadam	White-Greyish	8-20	Birds-resistant, tolerant to stem-borers, shoot fly and foliar diseases	19.86

Most of the research done on sorghum has been on grain sorghum (Sorghum bicolour L. Moench), which is prevalent in the tropical and arid/semi-arid regions worldwide (Mwadalu & Mwangi, 2013). A study on thin layer drying characteristics of grain sorghum was done by Ng'ang'a & Okoth (2003). In comparison to other researchers who used Sorghum bicolour L. Moench, they used three Kenyan varieties of grain sorghum which were Serena, Seredo and

KARI Mtama 1 whose findings showed that the Page equation fitted the drying characteristics of the varieties. Over the years, there have been diversification of sorghum varieties due to technological developments, yield demand and also disease variants (Okori, 2020).

2.2. Sorghum Drying

Once the sorghum is mature enough for harvest, it is field dried before threshing. Drying as a preservation method reduces the moisture content to a secure level so as to preserve the grain quality and minimize post-harvest loss (IRRI, 2016). The drying process defines the quality of the grain and also tends to affect the ensuing post-harvest processes (Keum, Kim, & Hong, 2002). Sorghum is said to be mature when the moisture content is at 30% (McKenzie & Richey, 2014). However, if the moisture content is >25%, it should not be threshed since the seeds are too soft. Threshing with moisture content at this level may lead to cracked seeds or unbeaten heads. While all the post-harvest processes are critical in ensuring food safety and quality, the authors emphasize on drying as a main process. McKenzie & Richey (2014), explain why drying is vital- as it precedes the threshing process. Furthermore, improper drying of sorghum means a greater moisture content which can lead to the growth of mould. Rausch (2014), explains that mould produces mycotoxins which damages and reduces the nutrients in the grain. The views of the authors above are convergent and agree that sorghum drying is an essential and critical process in ensuring good grain quality.

Studies have been done to analyse the drying methods and the factors influencing the drying of sorghum. Through observation, most of the farmers practice open drying. This is where they leave their sorghum in the fields exposed to the sun and wind to reduce the moisture. Some have referred to this as field drying, while for others it is known as open-sun drying (Rausch, 2014). Sadaka, VanDevender, Atungulu, & Gagandeep, (2015), in describing grain drying options, point out that the field drying method is the most widely used all over the world. Although the name varies, studies show that both are similar in terms of drying methods.

Some farmers choose to sun dry using the panicle method, where the sorghum is tied in bundles and placed on rooftops or hanged (ICRISAT, 2011). While it covers a low capacity, the grain is not dried efficiently. The outside stalks dry faster than the ones inside. If there is on-field drying beforehand, assuming perfect weather conditions, the moisture content will be lower during the mechanical drying, which eventually affects the drying process.

Besides field drying, other drying methods for grains include natural air drying, low temperature drying, high temperature drying and or dryeration. Natural air drying and low temperature drying is mostly interconnected to in-bin drying. Here, the sorghum is placed in a bin which has a fan attached. Contrary to low temperature drying, natural air drying does not require heat (Sadaka, 2018). However, this has been done on a large scale. In a study of mechanical damage for sorghum seeds, Muiru *et al.*, (2020), dried Kari Mtama 1 and Seredo varieties at 36°C in an oven, prior to threshing, which revealed that sorghum can be oven dried. McNeill & Montross, (2003) mention that sorghum can be dried using corn drying systems. He however, points out that using these systems to dry grain sorghum will take a longer duration, as smaller seeds have greater airflow resistance. In order to avoid this, Sadaka (2018), suggested that the bin depth of grain sorghum should be half of that used in drying of corn and centrifugal fans be adopted, since these fans have high airflow rates especially in high static pressures. While there are many sorghum drying methods, these authors only studied drying methods that were focused on sorghum drying on a large scale and not on small scale.

It is also critical that sorghum should not be over-dried. This is because, sorghum tends to shrink during the drying process. In order to compensate for this, setting a base moisture content is recommended, and a shrink factor be applied (Sadaka S. , 2018).This helps in handling post-harvest loss, and also improving the economic value of the grain. Sadaka (2018) demonstrated how to obtain the shrink factor for grain sorghum. However, this has not been done for other sorghum varieties.

2.3. Sorghum drying curves

Many researches have done experiments analysing the drying rates and have developed drying models from experimental curves. Alonso (2011), reports that grain drying undergoes two phases-the constant rate period and the falling rate period, with a critical moisture content point in between the two phases. Major cereal drying goes through the falling rate period. The curve is similar to a decay curve. However, Alonso (2011) failed to clarify that these conditions are for single particles which are dried under constant external conditions as written in the Grain Drying and Storage Book (Brooker, Bakker-Arkema, & Hall, 1992). According to Brooker et. al (1992), grain drying is not displayed during the constant-rate period unless harvested immaturely. It is in the falling rate phase where the grain drying occurs. This is because the grain surface has exceeded its saturation point and the increase in temperature increases the internal resistance, forcing the moisture to evaporate. Angula & Inambao (2019) report that the evaporation of moisture is as a result of water molecule migration due to the difference in mass and energy. It can be argued that the mass and energy difference is unclear as to whether it is internal, external or on the surface of the grain.

Kim *et al.*, (2016) performed an experiment to determine the drying rate of sorghum under temperatures of 40°C, 50°C and 60°C and relative humidity of 30%, 40% and 50%. Although they did not specify the sorghum variety and drying phases, from their results it was observed that the drying rate decreased exponentially. Isothermally, the drying rate increased as the relative humidity increased when the moisture ratio (MR) was 0.5 i.e. at half response time. When the relative humidity was held constant, increase in drying temperature decreased the MR. Thus, they concluded that both the drying temperature and relative humidity have an effect on the moisture content, with temperature having a greater effect.

Another study by Franke *et al.*, (2008), through experiments and drying curves analysed the performance of drying methods on the quality of sorghum bicolour L. Moench grain seeds. This was via natural drying, intermittent drying and stationary drying. The natural decay curve was the longest, while the intermittent drying curve was the shortest. They concluded that natural drying lead to a slow desorption process which reduced the seed quality. In intermittent drying, a higher rate of moisture was removed from the grain, which meant the seeds got vigour and high quality. Although the quality of the grain that was stationary dried was okay, the used layer thickness affected the sorghum grain negatively due to the exposure time and the air flow in the stationary dryer. In addition to the higher moisture removal rate, this intermittent process included the seed upturn, which played a role in even-drying while increasing the drying speed (Franke, Torres and Lopes, 2008). While the study displayed the three respective curves, the curves for the intermittent and stationary drying methods of sorghum were short, and therefore did not clearly indicate the drying phases as described by Brooker *et al.*, (1992).

2.4. Thin Layer drying models

Numerous researchers have adopted thin layer drying models in order to determine the drying kinetics of various fruits, grains and vegetables. This model involves drying a thin layer of a sample and taking into consideration the moisture content with respect to time.

Given that each grain has its own characteristics, following one theoretical model in determining the drying kinetics is illogical (Ertekin & Firat, 2017). Therefore, adopting an experimental approach by drying a thin layer of the grain has been approved by many researchers to be an effective way of determining the drying characteristics of grains. Furthermore, the design of efficient food dryers have adopted mathematical models that have been simulated using thin layer drying (Yi, Wu, Zhang, Li, & Luo, 2012).

Modelling of thin layer drying has been classified under 3 main categories, namely: Theoretical, Empirical and Semi-theoretical.

Theoretical models are based on Newton's law of cooling and Fick’s law of diffusion, but disprove the external moisture transfer resistivity (Akpinar, 2006). Furthermore, Meisami-asl *et al.*, (2010) point out that although theoretical models can be adopted for any material under various conditions, the diffusion, heat and mass transfer equations included, limit the adaptability of these models. In addition, these models only explain the moisture transferability in relation to internal resistance only. Thus, both Akpinar (2006) and Meisami-asl *et al.*, (2010) agree that theoretical models limit drying models by not taking into consideration external moisture transfer, which is important in drying, especially for artificial drying.

On the other hand, empirical models adopt experimental data, using it to develop mathematical equations for drying. Chinweuba *et al.*, (2016) mention that empirical models demonstrate a direct relationship between the moisture content and the drying time. However, their total dependence on experimental data omits some vital parameters and processes that take place during drying (Latiff *et al.*, 2019). Examples of some empirical models include the Thompson Model, Wang and Singh (Quadratic) model, and the Kaleemullah model (Chinweuba *et al.*, 2016). The Thompson model was successfully used in modelling the drying of shelled corn. The Wang and Singh model was adopted in developing drying equations for rice, parsley and bananas (Akpinar, 2006).

Semi-theoretical models are based on a mix of theoretical and experimental data. The model is derived from Fick’s 2nd law of diffusion and experiments of drying rates that are exclusive for the type of grain being dried. Semi-theoretical models have proven to be successful in the prediction of drying kinetics of many types of food. Some of the common semi-theoretical models that have been commonly used are shown in Table 2.2:

Table 2-2: Semi-Theoretical Thin Layer drying models

	Model	Equation	Reference
1	Lewis / Newton	$M.R. = e^{-k.t}$	(Bruce, 1985)
2	Page	$M.R. = e^{-k.t^n}$	(Page, 1949)
3	Modified Page I	$M.R. = e^{(-k.t)^n}$	(Overhults *et al.*, 1973)
4	Henderson and Pabis	$M.R. = a.e^{-k.t}$	(Henderson & Pabis, 1961)
5	Logarithmic	$M.R. = a.e^{-k.t} + c$	(Chandra & Singh, 1995)
6	Two-term	$M.R. = a.e^{-k_1.t} + b.e^{-k_2.t}$	(Henderson, 1974)
7	Wang and Singh	$M.R. = 1 + at + bt^2$	(Wang & Singh, 1978)

Kim *et al*., (2016) analysed the drying characteristics of sorghum and concluded that the Lewis model and the Simplified diffusion model were the most suitable in the drying of sorghum. On the other hand, Ng'ang'a & Okoth, (2003) conducted a similar experiment and concluded that the Page model was the most suitable in analysing the drying characteristics of sorghum. However, it can be argued that Ng'ang'a & Okoth, (2003) only compared 2 different equations, which gave a gap on the outcome of the other thin layer drying equations.

Bonner & Kenney (2012) did a similar experiment for Sorghum bicolour (L.) Moench and concluded that the Page model was the most suitable fit. Paulsen (1972) conducted an experiment for drying grain sorghum in Nebraska. However, he used the modified Thompson deep-bed drying model for designing different various dryer types, which is different from the thin layer drying model.

While the research for developing thin model drying of sorghum has been done, majority has been for the *Sorghum bicolour (L.) Moench*. There is still a gap for the different sorghum varieties grown, specifically in Kenya.

2.5. Sorghum dryers

The understanding of drying characteristics of sorghum are the foundation of designing a dryer and also determining optimized drying conditions for the drying process of sorghum (Sandeepa, Rao, & Rao, 2013). While open-air grain drying is dominant worldwide, the intense labour involved and unpredictable weather conditions inclined researchers and engineers to improve efficiency in drying. This has resulted in artificial drying methods, which are fast and efficient (Franke, Torres, & Lopes, 2008). The energy used in artificial drying may be electrical, mechanical or also solar if the solar energy has to be stored or connected to another machine. The drying equipment is dependent on the drying method used. This can be in-bin drying, fixed bed drying or batch drying.

2.5.1 In-bin dryers

The drying is done in the bin. This method uses low temperature to dry the grain. Driscoll and Srzednicki (1996) state that for in-bin drying, the air should not be heated to more than 6^{o}C. Sadaka (2018), specifies that less than -12°C should be used in in-bin drying that uses the natural air-drying method. Thus, based on these two authors, it can be argued that there are in-bin dryers that apply different drying methods. Brooker, Bakker-Arkema, & Hall (1992), broke down the types of in-bin driers into:

- Full bin: This is where the bin is filled with grain, drying takes place then the grain is cooled, aerated and stored in the same bin.
- Dryeration: The grain in the bin is dried at a high temperature up to about 3% above the recommended moisture content. The grain is then tossed into a tempering bin while still hot. Once the drying stresses become even, the grain is then cooled using ambient air and the stored heat, removing the remaining 3% moisture content. The result is a high quality grain with a low predisposition of breaking.
- On-floor batch in-bin, which works under the same principle as the flatbed dryer in Asia, where the grain is laid out on a flat perforated screen/floor and forced heated air from an axial fan below, is used for drying and cooling a batch of grain.
- Full bin with stirrer. The stirring gives room for more uniform drying in the grain. The devices, called stir augers, vertically mix the grain by rotary motion. This helps minimize the moisture gradient caused in the process. Brooker, Bakker-Arkema, & Hall, (1992) point out that the augers solve the problem of compaction that lead to decreased air flow. Sadaka (2018) adds that augers or recirculated are advantageous since they help increase the drying rate.

McClure *et al.*, (2015) point out that the preferred in-bin drying method for sorghum is the batch in-bin dryer. Their argument was based on sorghum grain having greater air resistance than other grains such as corn.

Sadaka (2018), gives no preference to sorghum dryers. He however, mentions that while any dryer can be used, it is important to ensure that adjustments such as the bin diameter/grain depth, and the fan size are made. He provided a table based on calculations, which indicated the typical drying depths for grain sorghum given bin capacity, fan horsepower and moisture content.

Table 2-3: Safe drying depths for grain sorghum with typical bin and fan combinations (Sadaka S. , 2018)

Bin Diameter	**Fan Horsepower**	**Moisture Content of Grain in Bin**			
		11%-13%	**14%-15%**	**16%-17%**	**18%-20%**
		Safe Depth of Grain (ft.)			
18	5	20	16-18	10-12	6-8
21	7.5				
24	10				
27	10				
30	15				
33	20				

2.5.2 Fluidized bed dryer

Fluidized bed dryers are designed according to the type of solid being dried, its material characteristics and fluidization conditions. The studies done on sorghum in fluidized bed were insufficient. However, Sandeepa *et al*., (2013) did a study on drying sorghum bicolour using the fluidized bed dryer. In this study, heated air was used in the drying process by feeding it to the fluidization column through the air chamber. From their study, they found that the Page model was the best fit thin layer drying model, and that the effective diffusion coefficient was in the same range that had been tested for other grains. From their study, they concluded that the drying kinetics for sorghum under a fluidized bed dryer were in the same range as the sorghum grain dried using other methods. However, the efficiency of this dryer in comparison to other dryers was not determined, and the other methods were not clearly identified. The studies done on sorghum in fluidized bed were insufficient.

2.5.3 Recirculating Batch dryer

Batch drying is a form of heated air drying, where high temperature is required. The drying process ends once the required moisture content is met. The process is called recirculating because the grain is turned over and over until it is completely dry (Sanford, 2019). In the bin, the grain constantly circulates from the tempering to the drying section until it is dry. One batch has a retention time of about 1 hour (Gummert, 2013). This study by Gummert was conducted on rice rather than grain sorghum. Soltani *et al*., (2020) note that batch and continuous flow dryers are the most preferred methods for drying grain sorghum. Sanford (2019), points out that, while the recirculating batch dryers are efficient, their disadvantage is that they are labor intensive and require supervision.

2.6. Problems in drying and storage of sorghum

When the moisture content is between 20-25%, the sorghum can then be threshed. However, if not consumed immediately, more drying is required for the sake of safe storage. The safe level of storing sorghum is usually when the moisture content is 10-12% (Mejia, 2000). Furthermore, the grain must be dried so as to prevent infestation by insects and grain germination. Poorly dried sorghum means a greater moisture content which leads to the rapid growth of mould due to the increase in grain temperature. Rausch (2014), explains that mould produces mycotoxins, damages the grain, and reduces the nutrients in the grain (low starch, sugar and high amount of fatty acids) in addition to producing asphyxiating odour harmful to human health.

Dillahunty *et al.*, (2000) demonstrated the relationship between the moisture content and colour by using heat. According to them, if the drying heat is in excess, it increases the grain temperature which causes discoloration. Consequently, discoloration becomes a sign of adjusting the temperature levels. Furthermore, high temperatures during sorghum drying may cause a fire hazard. McNeill & Montross (2003) advise that grain dryers should be modified in order to avoid such fires.

Of the four varieties in this research, the yield and the attributes are affected in the post-harvest process. The attributes play a huge factor in on-farm drying, where the grain is left in the field to dry before being harvested. With this, there is always the risk of attacks from birds, pests and climatic conditions. While some of the varieties have been modified to prevent attack from birds and other pests, the research to completely eradicate this issue is ongoing (KALRO, 2021).

2.7. Conceptual Framework

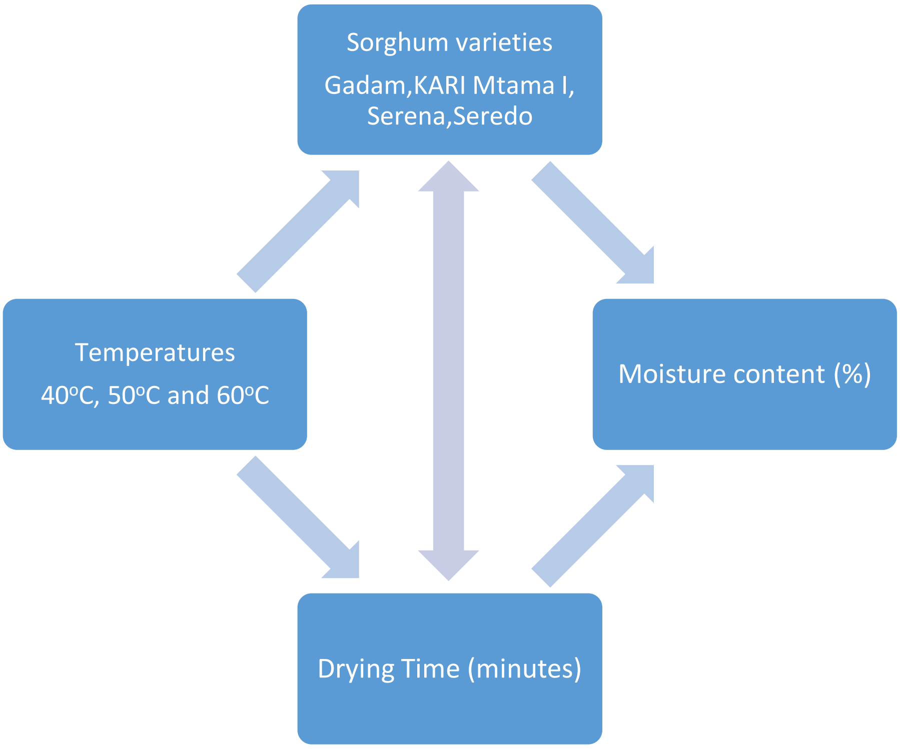

Figure 2.1: Conceptual Framework

2.8. Conclusion of Literature review and Research gaps

All in all, there have been numerous studies on the drying of grain. However, compared to other cereals such as corn and wheat, the studies done on sorghum are few. Also, the sorghum varieties have increased over the years, each with its own physical and biological properties. Majority of the sorghum studies have been on grain sorghum (Sorghum bicolour L. Moench), with a few studies on different sorghum varieties.

Experiments have been done to establish the drying patterns of sorghum. According to the literature review, the drying curves followed an exponential decay pattern, which was dependant on the drying method used. Thin layer drying models have proven to be the most suitable method in predicting the drying characteristics of grains and foods in general. There have been numerous studies on this mathematical model. This has been done by finding the relationship between the moisture ratio and the drying rate at a given temperature. Some scholars have considered relative humidity in this, while others have not. Although the studies for developing thin model drying of sorghum have been done, there is still a gap for the different sorghum varieties grown, specifically in Kenya.

Following the sorghum drying kinetics, dryers have been fabricated and designed. From the review, the studies done on this that were specifically for sorghum were limited. However, other sorghum drying equipment have mostly been used on a large scale. Other researchers have justified this by mentioning that any grain drier may also be used in sorghum drying, but with adjustability of parameters.

The literature review has also shown that sorghum grown in the west is mainly used as fodder or bird feed, making it attractive to birds. However, it is grown for human consumption in Kenya, where farmers are dependent on natural drying methods. There is on-going research on making hybrid varieties that will drive out pests and birds.

All in all, the literature review has revealed that studies on sorghum drying, and determination of the drying characteristics of various sorghum varieties are limited. There is also limited information on where the adaptability of thin layer drying models have been used in designing a sorghum dryer, hence the necessity of this research.

3 THEORETICAL FRAMEWORK

3.1 Factors Dictating Sorghum Drying Characteristics

The basics of analysing the drying kinetics of sorghum varieties are rooted in various equations and scientific laws. They include:

a) Moisture content
b) Temperature
c) Relative Humidity
d) Pressure
e) Grain structure,
f) Airflow resistance

Drying being a process of expatriating moisture, the first equation to consider is the moisture content.

3.2 Moisture Content

Moisture content is the amount of water/moisture in a substance. Drying reduces the moisture content to a safe level so as to preserve the grain quality. Mature sorghum has a moisture content of about 30% (McKenzie & Richey, 2014). However, harvesting and threshing at this moisture is futile since the seeds are too soft, leading to cracked seeds or unbeaten heads. Thus, most farmers leave their sorghum in the fields exposed to the sun and wind to reduce the moisture. The safe level of storing sorghum is usually when the moisture content is 10-12% (Mejia, 2000).

Lowering the moisture content of a grain increases its shelf life (Tonui, 2014). The increase in moisture content is directly proportional to the drying rate. Thus, drying can be said to be effective when the moisture content has decreased, and this can be done by increasing the air temperature required in the process.

Moisture content can be measured either on a dry basis or a wet basis. The wet basis is a ratio of the amount of water to the total weight of the grain sample, whereas the dry basis is a ratio of the amount of water in the grain to the dry weight of the sample i.e. the solids. While measuring the moisture content can be simple, it can also be confusing. Moisture content results vary due to the diverse methods of measurement e.g. direct methods and indirect methods; and also variability (Metergroup, 2017). These variability sources include the level of dryness, properties of the sample, the oven vapour pressure and the ideal oven temperature and drying time.

Moisture content is the amount of water/moisture contained in the grain in this case. Expressed as a percentage, the moisture content is usually given on a wet-basis (Mrema, 2011).

The moisture content of a grain is given by:

$$M.C(\%) = \frac{Weight\ of\ moisture}{Weight\ of\ sample} \times 100$$

(3.1)

If the mass/weight of the moisture is unknown, the moisture content can be determined by:

$$M.C.wb(\%) = \frac{Mi - Mf}{Mi} \times 100$$

(3.2)

where:

$M.C_{wb}$ is the Moisture content wet basis.

M_i is the initial mass of sample before drying

M_f is the final mass of sample after drying

Sorghum grain is hydroscopic thus it loses or gains moisture until an equilibrium is reached with the water vapour in the air (Findura, 2018). When this equilibrium is reached, it is known as equilibrium moisture content (EMC). EMC is highly dependent on temperature and the relative humidity of the air. Mrema (2011), tabulates the EMC of various grains at 27 degrees as in Table 3-1:

Table 3-1 Equilibrium Moisture Content values at 27°C and 70% RH

Equilibrium moisture content (EMC) values at 27°C and 70% relative humidity	
Crop	**EMC**
Maize	13.5
Wheat	13.5
Sorghum	13.5
Millet	16.0

Brooker *et al*., (1992) explain that EMC is important in drying since it is impossible to dry grain to a moisture content lower than the EMC associated with the drying air. If attempted, the relative humidity has to decrease and the temperature of the drying is increased, or vice versa.

This has been further explained through the modified Henderson equation as shown:

$$1 - RH = e^{[-k(T+C)(100X^{n}]}$$

(3.3)

where:

RH is the relative humidity

X is the dry basis moisture content (fractional)

T is the temperature, in Kelvin

k, n, C are the experimental constants for grain.

For sorghum, K=0.8532 X 10^5, n=2.4751 and C=113.725 (Mujumdar & Beke, 2003)

3.3 Moisture ratio

The interpretation and analysis of moisture content in food and grains was a bone of contention until a settled agreement came about by using the moisture ratio. The moisture ratio brought uniformity in the analysis of moisture content (Smith, 1918)

The drying that occurs by thin layers where each and every grain is fully exposed to the drying air. In this process, the moisture ratio is a function of temperature, relative humidity and time. Moisture ratio is dimensionless. It gives the moisture content at any time with respect to the initial moisture content of the sample (Obajemihi & Asipa, 2020).It can be represented in the form:

$$MR = \frac{MC - MC_e}{MC_o - MC_e} \text{ and MR = f (T, h, t);}$$

(3.4)

where:

MR is the moisture ratio

T is the air temperature (°C)

h is the air relative humidity (%)

t is the drying time

MC is the moisture content of the grain at any level and at any time, % dry basis (% d.b)

MC_e is the equilibrium moisture content (% d.b)

MC_o is the initial moisture content of the wet grain (% d.b)

3.4 Temperature

As mentioned above, moisture content can only be decreased by increasing the temperature. Sigge *et al.*, (1998) determined that increasing temperatures increase the drying rates, as a result, the grain is dried. However, very high drying temperatures reduce the quality of the grain (Shouse, Hanna, & Petersen, 2010). High temperature reduces the grain's nutritional value by reducing the protein solubility, enzymatic activity and moisture-binding capacity. On the contrary, low drying temperature has minimal effect on the factors affecting quality of the grain. Peplinski *et al.*, (1994), on a research on corn properties, indicated that the quality factors of corn such as density, germination, stress-cracking, and breakage, were minimally affected when exposed to low drying temperatures but varied greatly in heated air temperatures.

Conclusively, there is need to monitor the temperature of the sorghum grain while drying. Each variety has its own moisture content, which determines the drying temperature (Okori, 2020).

3.5 Relative humidity

Relative humidity can be defined as the ratio of the amount of water vapour pressure in the air to the maximum amount of saturated water vapour pressure that can be present at a given temperature (expressed as a percentage). (Earle & Earle, 1983)

$$\varphi = \frac{p}{p_s} \times 100 \tag{3.5}$$

where:

φ is the relative humidity (%)

p is the partial pressure of water vapour in the air

p_s is the saturated pressure of the water vapour

In drying, the relative humidity plays a critical role in determining the equilibrium moisture content. The equilibrium moisture content is the balance between the air and the grain, and determines the rate of sorption/desorption in the grain. Furthermore, the level of biological activity in the grain is determined by the relative humidity, e.g. mould does not flourish at relative humidity that is less than 65% (Nellist, 1998). Thus, if the grain is stored at 65% relative humidity, it will be improbable to deteriorate because it will inhibit the growth of mould and bacteria.

3.6 Vapour Pressure

Pressure determines the movement of moisture to and from the grains by the principle that water (moisture) moves from high pressure zones to low pressure zones (Earle & Earle, 1983). Vapour pressure is a key factor in drying, given that it determines the relative humidity, as seen in the previous section. The vapour pressure deficit (VPD) is the driving force for moisture loss from the grain while the vapour pressure differential is the difference in pressure between the water vapour in the atmosphere and the vapour in the grain (Wollaeger & Runkle, 2015). Of importance is the vapour pressure differential between the air and the surface of the grain. Alonso (2011), argues that sorghum grains lose or gain moisture due to the VPD between the grain and the air. When the vapour pressure of the grain is higher than the pressure in the area surrounding the grain, there will be a reduction in moisture content in the grain, and vice versa. The rate at which a grain gains or loses moisture is affected by the resistance to movement of moisture vapour set up by surface layers of the grain.

Thus, it can be said that without the vapour pressure difference, the movement of moisture from the sorghum grain cannot happen.

3.7 Grain structure

The grain structure is important in drying because it affects the sorption and desorption process in grain drying. Knowledge of the structure of the grain is important when interpreting the drying rate in terms of the biological structures of the grain e.g. the testa, endosperm, and the embryo (Bala, 2016). Bala (2016), elaborates by saying that moisture migrates from the innermost layer to the surface of the kernel. This flow depends on the endosperm's internal characteristics, the permeability of the testa, pericarp and aulerone layer. The heat and moisture flow determines the extent of damage to the layers. This has to be taken into consideration because of the need to curb post-harvest drying.

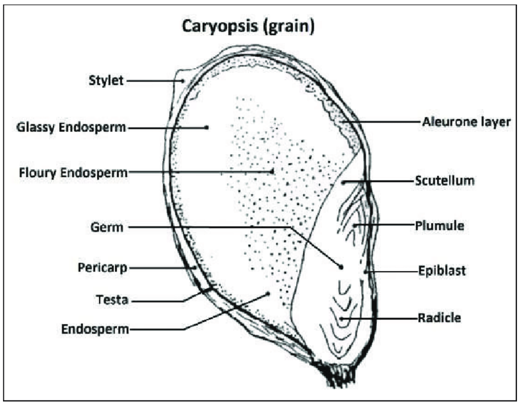

Figure 3.1: Sorghum grain structure ((Umwungerimwiza, 2015)

3.8 Airflow Resistance

Any drying system uses heated air to eliminate moisture from the grain. Ventilated systems reduce/eliminate the temperature gradient by using air. Thus, designing a drying system requires the study of airflow resistance to the grain in order to choose the fan and bin specifications (Górnicki & Kaleta, 2015).

Górnicki & Kaleta, (2015) liken airflow resistance to pressure drop per unit depth bed. This drop is dependent on factors such as bed depth, moisture content, airflow rate, bulk density, foreign objects, and the physical characteristics such as grain structure and weight of the grain. Besides, the airflow and pressure relationship come in handy when designing mathematical models and pressure patterns, together with the airflow distribution. Sorghum, which is smaller in size than maize, has a high moisture content and is more resistant to air flow than maize. The average grain size of sorghum is 20 – 25 in 1000-kernel weight (g) (Infonet-Biovison, 2019). Thus, the drying time is longer given the same drying conditions. Sumner & Worley, (2017), explain that since the airflow resistance of sorghum is 2.5 times higher than that of corn, the static pressure required to dry sorghum is more than that needed to dry corn/maize. Pressure increases with depth. In drying, the depth of the grain bed is dependent on the superficial velocity and pressure. Nellist (1998), explains that for a given superficial velocity, the pressure required to generate the flow of air, increases with the depth of the grain bed. Contrariwise, an increase in pressure is required to increase the superficial velocity.

Nellist (1998), further explains that the superficial face velocity into the bed can be equated to the volumetric flow rate by:

$$\dot{V} = v_0 \times A_s \tag{3.6}$$

where:

$\dot{V}$ is the Volumetric flow rate (m3/s)

$v_0$is the Superficial velocity (m/s)

A_s is the Cross-sectional area of the floor occupied by the grain

There have been several equations by researchers who have developed models that predict airflow resistance in grain. One of the most generalized equation was by Shedd (1953), who determined that:

$$Q = c\Delta P^d$$

(3.7)

where:

Q is the airflow rate, (m^3/s-m^2)

ΔP is the pressure drop, (kPa/m)

And c, d are the constants for the grain

Presented on a non-linear logarithmic plot, the Shedd's equation can determine the pressure drop over a small range of airflow rates. The simplicity of this equation has gained popularity in many researchers, who have inputted it in their mathematical models. However, its generality is limited when it comes to determining a wide airflow range (Górnicki & Kaleta, 2015).

For drying bulk grain, Gorniki (2015) noted that the Ergun model has been the most comprehensive model used for the airflow resistance calculations. Its inclusivity of both the laminar and turbulent flow of air has commended its use. The Ergun model also takes into consideration the porosity, particle diameter and air properties that are omitted in the Shedd's equation.

$$\Delta P = 150\frac{v_0\mu}{d_e^2}\frac{(1-\varepsilon)^2}{\varepsilon^3} + 1.75\frac{\rho v_0^2}{d_e}\frac{(1-\varepsilon)}{\varepsilon^3}$$

(3.8)

where:

ΔP is the pressure drop per unit height (Pa/m)

ν_0 is the superficial velocity (m^3/m^2.s)

d_e is the equivalent particle diameter (m)

ε is the bulk porosity, fraction

μ is the dynamic viscosity of air (Pa.s)

ρ is the air density (kg/m^3)

3.9 Drying Rate

Heat is required in drying in order to remove moisture from the grain. In addition, a stream of air is required to migrate the evaporated moisture. In order to effectively accomplish this, the drying rate has to be analysed. This rate is dependent on the factors mentioned previously, i.e., the moisture content, grain temperature, ambient temperature, relative humidity and airflow resistance. It measures the rate at which the internal moisture in the grain evaporates, with respect to the heat transmitted in the grain. The dimension for the drying rate is $\frac{Mass}{Time}\frac{(kg)}{(h)}$ The factors affecting the drying rate are related through the modified Henderson equation (Burmeister, 1998). According to this equation shown below, efficient dying calls for an equilibrium moisture concentration.

$$100\ M_{ed} = \{ln(1-\varphi_r)/[-K(T+C)]\}^{1/N} \tag{3.9}$$

where:

M_{ed} is 100 M_w/M_d

M_w is the Mass of water

M_d is the Mass of dry grain

M_{ed} is the Equilibrium moisture concentration (dry basis)

φ_r is the Relative humidity

T is the Temperature

For a wet basis equation:

$$(\mathrm{M_{ew}}),\ M_{ew} = 100\frac{M_w}{(M_w+M_d)}$$

(3.10)

The constants K, C, and N vary depending on the grain because of variation in desorption when drying. For sorghum, ASHRAE records the values of K, N and C as follows:

- K=0.000085320
- N=2.4757
- C=113.725

However, the constants have changed over the years, depending on the model used.

3.10 Diffusion

Diffusion in this case is the movement of moisture from a region of high concentration (grain) to a low concentration (air) along a concentration gradient. According to Fick's 2nd law of diffusion, the concentration is variant and changes with time. This perfectly describes the drying kinetics of phenomena, which are normally under an unsteady state.

Fick's 2nd law has been adopted in determining moisture diffusivity and drying constants in foods and grains.

$$\frac{\partial M}{\partial t} = \nabla^2 D_e M$$

(3.11)

where:

∂M is the change in moisture content (dry basis)

∂t is the change in time (s)

D_e is the Effective diffusion coefficient (m^2/s),

M is the Mass transfer (concentration) gradient.

4 MATERIALS AND METHODS

4.1 Study Area

The Serena, Seredo, Gadam and KARI Mtama I sorghum varieties were obtained from Elgeyo-Marakwet County which lies in the coordinates 0.67° N, and 35.51° E. The area has diverse agro-ecological zones. From the highlands to the Kerio Valley. Temperatures range between the lows of 15° C in the highlands to highs of 30° C at the bottom of the valley. Rainfall ranges between 850 mm in the valley to 1500 mm in the highlands. The poverty levels are relatively high and there is relatively high food and nutrition insecurity leading to poor growth and stunting among children below five years (Elgeyo-Marakwet, 2018). Sorghum, which grows generally in warm areas is concentrated in the valley zones of Elgeyo-Marakwet County which is the Marakwet-West zone. A detailed map is as shown:

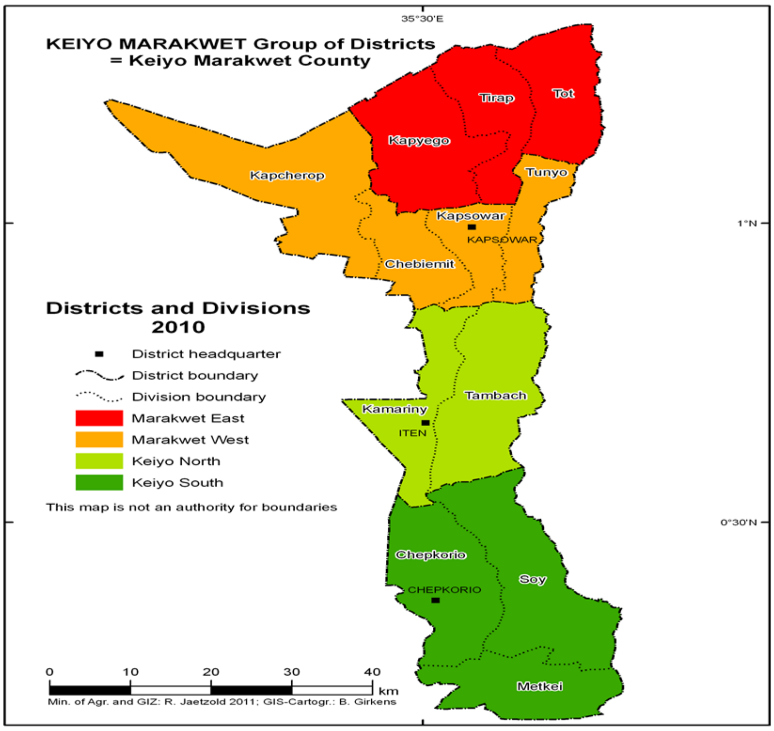

Figure 4.1: Map showing the zones of Elgeyo-Marakwet County

In Marakwet-West zone, sorghum grows in the Arror and Sengwer Wards. Due to limited resources, Arror ward was selected. Sorghum is grown both on a large scale and on a small scale in Arror ward. The climate favours the growth of different sorghum varieties, which made it a suitable study area.

The drying experiment was conducted in the Food and processing laboratory, Department of Environmental & Bio-systems Engineering Kabete Campus, at the University of Nairobi. This laboratory had the required apparatus and instruments for the drying experiment.

4.2 Research Design Methodology.

4.2.1 Sorghum varieties and drying techniques.

Prior to determining experimentally the drying characteristics of the sorghum varieties, it was necessary to obtain the background information of the research, so as to obtain fundamental design considerations. Given the scarce population and limited information known about sorghum farming in Arror, a simple random sample of 52 farmers was used. Subjects within the study area were selected using the sample selection equation below: (Mugenda & Mugenda, 2003)

$$n = \frac{z^2 . p . q}{d^2} \tag{4.1}$$

where:

n is the sample size required

z is the confidence level at 95% (1.96)

p is the estimated proportion of sorghum farmers in Arror area (85%)

q is the estimated proportion of non-sorghum farmers in Arror area (1-p) (15%)

d is the margin of error (0.1)

Hence, the sample size calculated was:

$$n = \frac{1.96^2 \times 0.85 \times 0.15}{0.1^2} = 48 \text{ farmers.} \tag{4.1.1}$$

Allowing for 10% attrition, the sample size was set at 52 farmers.

A field survey was conducted by closed-ended questionnaires and face to face interviews in order to establish the sorghum varieties and drying techniques that the farmers use. The closed-ended questionnaire method was selected given its affordability and capability of capturing the necessary information in a short time. Face to face interviews were selected for some of the farmers who were illiterate, given that Arror is in a remote area. A questionnaire sample is attached in Appendix 1. The data captured in the questionnaire included determining the sorghum varieties being grown, the acreage, and the drying techniques used by the farmers. From the field work, samples of the sorghum varieties that are grown in the area were collected for further research.

4.2.2 Sorghum Drying Characteristics

Experimental Procedure

From the field survey, sorghum samples collected were of 4 varieties namely; Serena, Seredo, Gadam and KARI Mtama 1. For the laboratory experiment, due to limited resources, a 2kg bag for each variety was purchased. These were taken to the University of Nairobi Laboratory in order to experiment on the drying characteristics of sorghum. Each sample was sorted to remove unwanted particles, cleaned and 250 g for each was put in a sealed container. While only 250 g was required for each sample, the 2kg catered for the cleaning process and spillage. The container was then put in a freezer at temperatures of -4°C for 24 hours to prevent the grains from germinating prior to determining the initial moisture content. After 24 hours, the sample was removed, thawed to thermal equilibrium and the initial moisture content was measured for the samples.

Data collection in the laboratory was collected using the following apparatus in Table 4.1, some which are shown in Appendix 2:

Table 4-1. Research Equipment and Instruments used

Equipment/Instrument	Model Number/Manufacturer	Function
1. Sartorius analytical laboratory scale	L610- Sartorius	Measuring the weight of the samples in grams
2. FarmPro Moisture Analyzer	V2.2 Supertech Agroline Denmark	For measuring moisture content of grain ~10g in percentages %
3. Gallenkamp Laboratory Bench oven	S3-Gallenkamp Germany	Laboratory oven with temperature range of 0-300°C
4. Glass vacuum Desiccator with desiccant (blue silica gel	1351-180 CNWTC	To prevent moisture loss during transition of removing samples from the oven and measuring the moisture content.
5. Calculator	Sharp EL531X-	For calculating the weight change.
6. Wet and dry bulb Mason’s hygrometer with Celsius and Fahrenheit readings	13/222/3- Brannan	For measuring the relative humidity. Ranges: -5 to +50°C, with error of +/- 1°C
7. Timer/Wrist watch-	WR30M	For recording time in 00:00 minutes.

The initial moisture content was determined before the drying process. This was done using the standard oven drying method -weighing scale and moisture meters for accuracy. The average moisture content was recorded after three runs of the moisture meters. The average kernel weight of the grains was found by measuring a small amount of the grain in a tin, and then subtracting the weight of the tin. This was done on average 5 times. Subsequently, 40g of each sample was weighed on a Sartorius precision laboratory balance/weighing scale and evenly distributed into dual-meshed trays with square openings of 0.2 x 0.2 cm^2 and the grain was laid in a depth of 10mm. The deeper the depth, the longer the drying time. For better precision, the samples were put into three trays, each labelled according to the moisture content measurement.

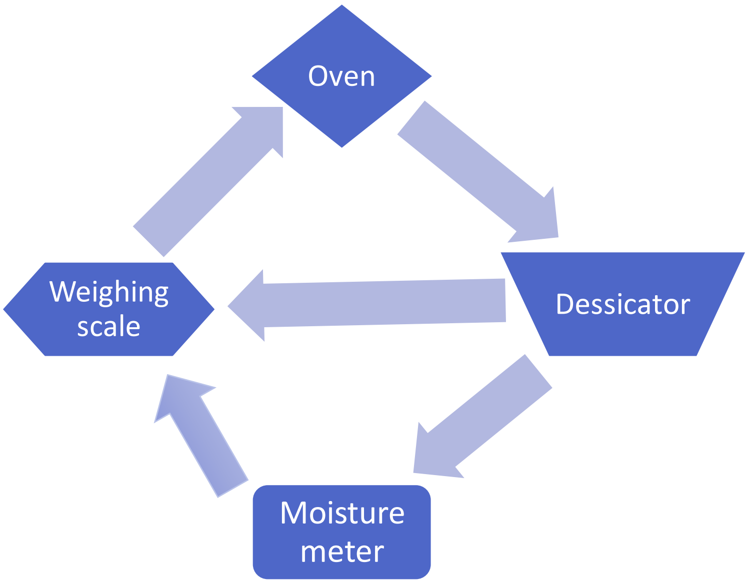

Figure 4.2. Schematic process of drying of the sorghum varieties

A calibrated laboratory oven dryer was pre-heated for one hour prior to putting the samples in it. This was to ensure uniform heat distribution and precise temperature required for the drying process. The three samples of a similar variety were then put in the oven at air temperatures of 40°C, 50°C, and 60°C and were left to dry. The drying conditions were regulated by the temperature control knob, which maintained the prescribed temperature throughout the drying process. After every 30 minutes, the samples were weighed and moisture loss recorded until the grain became dry and the weight change was <0.1 g i.e. equilibrium moisture content (Mutuli & Mbuge, 2015). The drying rate was then determined by plotting the moisture content recorded against the time.

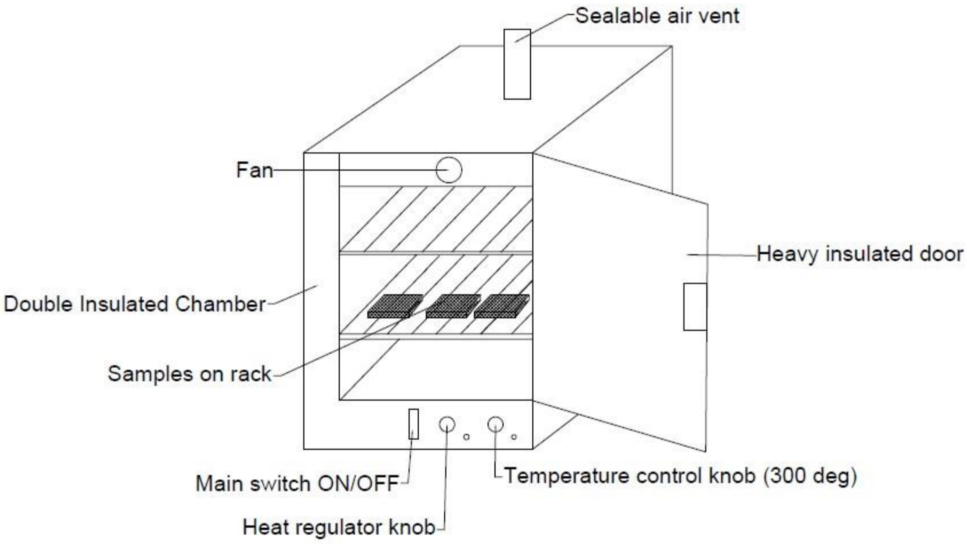

Figure 4.3. Diagram of sorghum sample varieties in the oven

4.2.3 Drying Curves of the sorghum varieties

The moisture content recorded against time was used in calculating the moisture ratio as in the equation below:

$$MR = \frac{MC - MC_e}{MC_i - MC_e} \tag{4.2}$$

where:

MR is the moisture ratio

MC is the moisture content of the grain at any level and at any time (% d.b)

MC_e is the equilibrium moisture content (% d.b)

MC_i is the initial moisture content of the wet grain (% d.b)

Drying curves of the sample varieties were plotted on graphs of moisture ratio against time. This was done separately for the 3 moisture recording instruments used.

4.2.4 Thin layer Drying Equations for the varieties

The equations formed through plotting the drying curves recorded above were compared against pre-existing thin layer drying equations, and non-linear regression analysis was performed for each variety. The selected thin layer drying equations were based on previous successful models that were conducted on grains. Microsoft Excel Solver analysis tool was used to analyse the data quantitatively using graphs and non-linear regression analysis. The drying rate was determined by plotting the moisture ratio recorded against the times. This moisture ratio is a ratio of the moisture content at any given time. The drying curves were plotted separately for each variety, and for each moisture recording instrument used.

The resultant curves produced were then analysed using the Solver Analysis tool in Excel. These experimental results were compared against pre-existing thin layer drying equations, and non-linear regression analysis was performed for each variety. Seven pre-existing models that were in Table 2.2 were chosen based on their prominence in previous studies for sorghum models. The statistical values of coefficient of determination (R^2), Root Mean Square Error (RMSE) and reduced chi-square (χ^2) were evaluated and used to predict the most suitable model for each variety.

The coefficient of determination (R^2), also known as correlation coefficient, has been proven by previous researchers as reliable in determining the best future outcomes to be predicted in the model (Akpinar, 2006). It was chosen in this study since it demonstrated the relationship between the predicted value and the experimental value. An R^2 that was closest to 1 showed a greater relationship, and vice versa (Ertekin & Firat, 2017). The formula is as shown in equation 4.2

$$R^2 = 1 - \frac{SS\ Res}{SS\ Total} \tag{4.2}$$

where SS Res is the Residual sum of the squares, and SS Total is the total sum of squares.

On the other hand, the Root Mean Square Error (RMSE) measured the difference between the predicted and the actual/observed value. It was chosen in this study due to its accuracy in predicting and aggregating residuals into one measure (Ertekin & Firat, 2017). The equation used in predicting thin layer drying models is shown in Equation 4.3.

$$\text{RMSE}=\sqrt{\sum_{i=1}^{n}\cdot\left(\frac{M.R_{predicted,i}-M.R_{observed,i}}{n}\right)^2} \tag{4.3}$$

where M.R. is the moisture ratio and n is the number of observations. The RMSE value had also been proven to be effective in mathematical modelling for drying grain (Wang & Singh, 1978). The closer it was to zero, the better the model. The formula used was as shown below in Equation 4.4.

$$\chi^2 = \sum_{i=1}^{n} . \left(\frac{M.R_{observed,i} - M.R_{predicted,i}}{N - n} \right)^2$$

(4.4)

The reduced chi-square χ^2 value analysed the match suitability between the predicted and the experimental value, i.e. the goodness of fit. Lowest value of χ^2 is chosen, as this was proven to provide the best goodness of fit (Yang, Fon, & Lin, 2007).

5 RESULTS AND DISCUSSION

Following the field work and laboratory work, data was collected and the results and discussion are as follows:

5.1 Sorghum varieties and drying techniques

The data collected on sorghum varieties and drying techniques was captured from 7 villages in Arror Ward. These were Cheborom, Kaimuchuk, Kambaa, Kasonok, Kamugus, Kaitwen and Kapcheptugen. The questionnaire based survey distributed in these villages gave the results in this chapter. The crop for drying was grain. For the sorghum varieties, the top five sorghum varieties grown are summarized in figure 5.1 below:

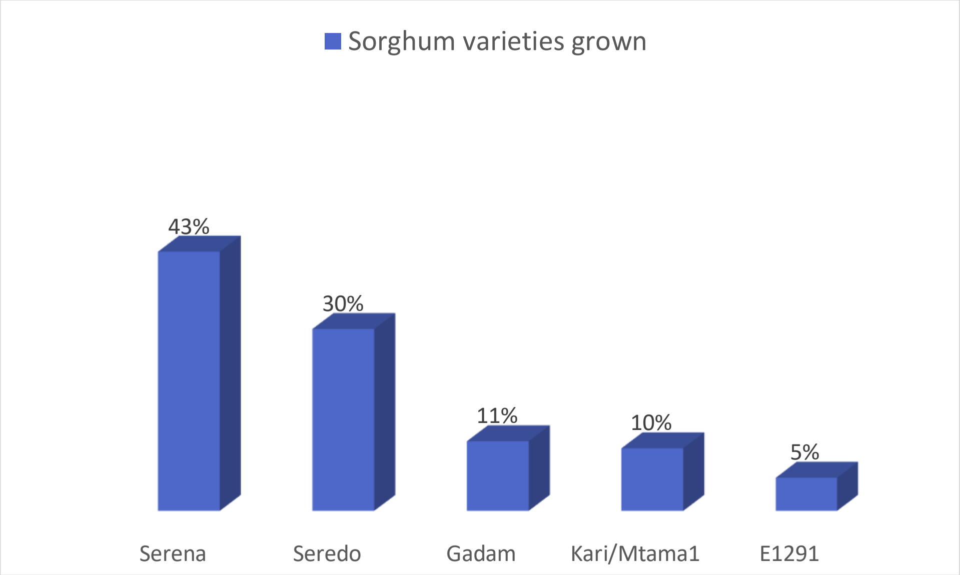

Figure 5.1: Chart showing the sorghum varieties and their production in Elgeyo-Marakwet County.

As seen above, the Serena variety had the highest production, compared to the other varieties (43%). The total bags produced was 290 bags/90 kg bag. This could be because of its low-cost and availability in the area. Its' prominence in the market of Arror also showed it is used by many for food. Although the Seredo variety is similar to the Serena sorghum variety, it had a lower production of 205 bags due to its taste and nutritional value. Gadam variety was had a production of 78 bags/90 kg bag, which was 11%. This was because it was mostly used in large scale farms, and was mainly grown for commercial use. Kari Mtama 1 production was 70 bags/90kg bag. E1291 had the least production. This may be because of lack of availability and cost, compared to the Serena variety.

From the questionnaire, the sorghum production accommodated both for home use and for commercial use. The results further revealed that the commercial sorghum was supplied to Kenya Seed Company and East African Breweries Ltd for research and also for brewing purposes.

As for the sorghum drying, 99% of the farmers said they practise open sun- drying. The average drying days were 5 days and the average drying hours were 7 hours/day. Given that the climate is hot, sun drying is the most efficient. Only one percent of the farmers practised indoor drying, where the sorghum is tied in stalks and dried in a warm room, which in this case was the kitchen area. The drying time in indoor drying was found to be 7 days. While this was a low percentage, it brought out the aspect that the farmers still use the traditional sorghum drying method as mentioned by Sadaka, VanDevender, Atungulu, & Gagandeep, (2015) who said that open sun-drying/field drying is the most common drying method in the world. However, from the laboratory drying experiment, the average drying time was reduced to an average of 3 hours, which immensly shortened the drying time in comparison to the traditional method.

The farmers revealed the challenges they faced while harvesting sorghum. These included:

- Birds and chicken feeding on the grain.
- Weather variations e.g. rains, wind
- Animals which destroy the grain e.g. monkeys, cows, goats
- Labour-costs are high if labourers are needed
- Lack of drying materials

In the laboratory drying, these challenges mentioned were non-applicable due to the shelter indoors, oven accessibility and low labour demand. The sorghum drying challenges faced by farmers in Elgeyo-Marakwet County revealed that there is still post-harvest loss in sorghum drying. Furthermore, although the farmers incur the losses by experiencing these challenges, they had not found an alternative to sorghum drying.

5.2 Sorghum Drying Curves

The results for each variety are discussed below:

5.2.1 Gadam

Gadam sorghum was observed to be white in colour and spherical in shape. The average initial moisture content was found to be 22%. Given that the moisture content was not initially measured in the field, the initial moisture content was lower than the average expected moisture content. According to the ASABE standards for measuring the moisture content, the oven method that used a weighing scale proved to be the most accurate. The graph below was plotted as the moisture ratio, against time. The moisture ratio was calculated using equation 3.4 in the theoretical framework.

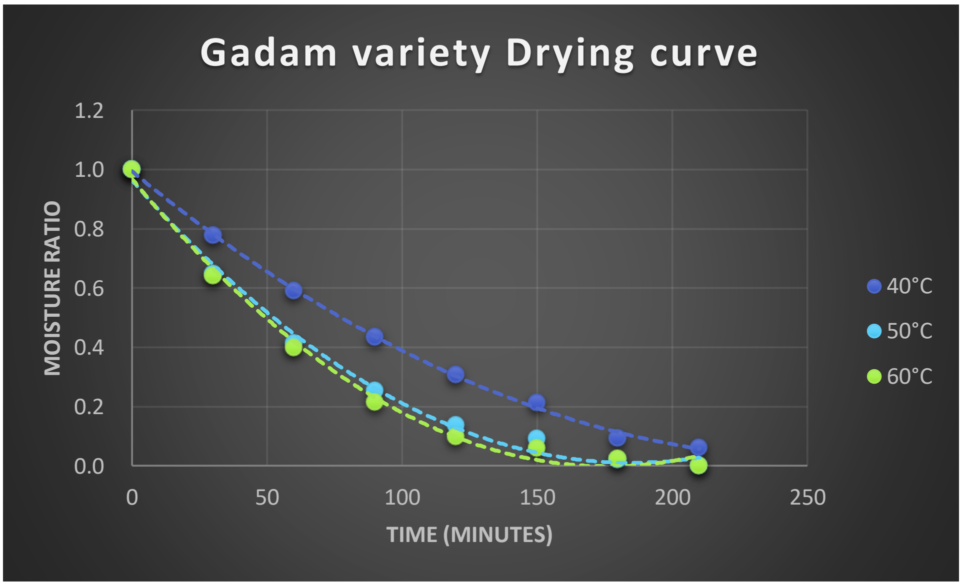

Figure 5.2: Drying curve for Gadam sorghum variety at 40 to 60 degrees Celsius

From figure 5.2 above, the readings showed that the rate of drying at 60°C took the shortest duration due to its high temperature, followed closely when the temperature was at 50°C. However the rate of drying at 40°C took a longer duration due to its low temperature. Given that this was the first trial, the errors were attributed to the oven temperature reading, which appeared faulty. The falling rate period began about 1 hour after drying, where the critical moisture ratio was 0.4, a phenomenon that was described by Alonso, (2011).

5.2.2 Kari Mtama 1

Kari Mtama 1 grain is pinkish-white in colour, and had a smooth pericarp compared to the other sorghum varieties analysed. The average initial weight of the grain purposed for drying was 40.02 g. The average initial moisture content of the Kari Mtama 1 variety was found to be 20.2%. Given that the moisture content was not initially measured in the field, the initial moisture content was lower than the average expected moisture content. The relative humidity was 81% at the start of the experiment.

As performed for the Gadam samples in section 5.2.1, the Kari Mtama 1 samples were also categorically analysed and the results were plotted and are as shown.

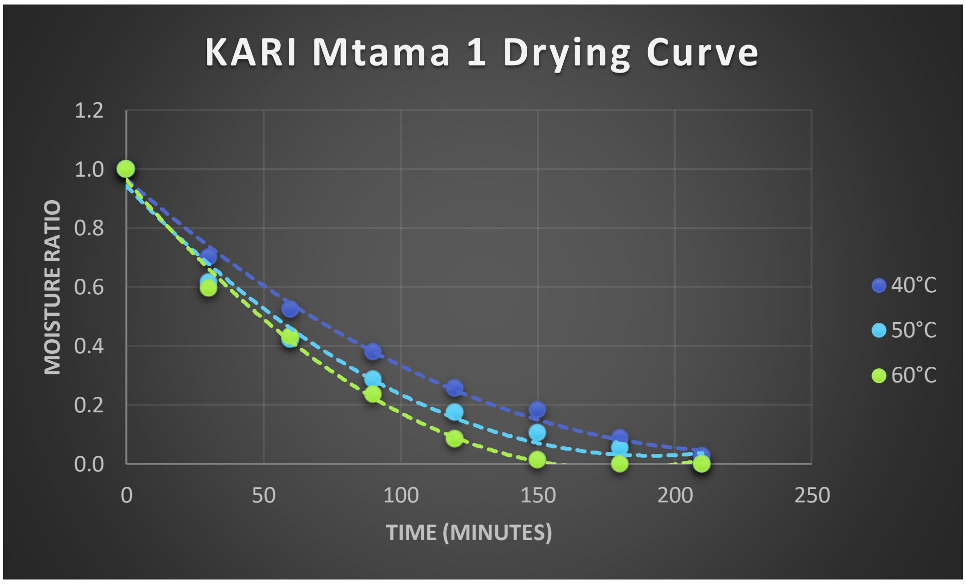

Figure 5.3: Drying curve for KARI Mtama 1 sorghum variety at 40 to 60 degrees Celsius

The constant rate period was during the first hour, and the moisture was critical at this stage. However, as the drying continued, higher temperatures increased the drying rate, while reducing the drying time. As seen, the falling rate period phase began at around minute 90, and the equilibrium moisture content for 60°C was observable after 2.5 hours. The drying curve was a good representation of the drying curve of the grain and confirmed the results from previous research and literature review of a decay pattern (Alonso, 2011), (Mutuli & Mbuge, 2015).

5.2.3 Serena

Serena grains are brown in colour, but with intense drying appears reddish-brown. The resemblance with Seredo variety is close. However, the grain size differs. The average initial weight of the Serena grain purposed for drying was 40.01 g. After drying, the colour of the Serena sorghum variety became slightly darker. The average initial moisture content of the Serena variety was found to be 19.4%. Given that the moisture content was not initially measured in the field, the initial moisture content was lower than the average expected moisture content.

As performed for the Gadam samples in section 5.2.1, the Serena sorghum variety samples were also categorically analysed and the results were plotted and are as shown.

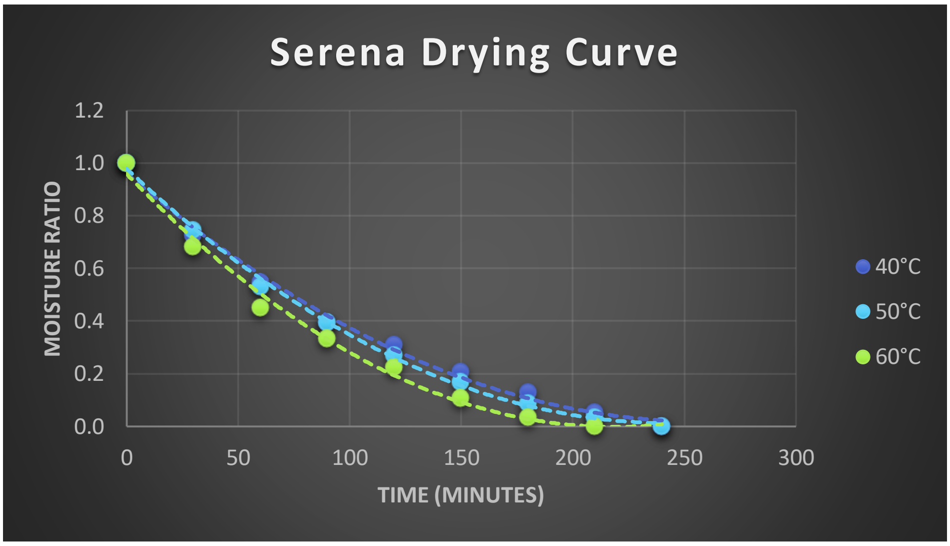

Figure 5.4: Drying curve for Serena sorghum variety at 40 to 60 degrees Celsius

While the drying rate was fastest at 60°C, the drying curves are in close proximity to each other and reveal an even exponential trend. This could be because of minimal errors during the data collection. The falling rate period rate began right after the 1-hour duration, and by the 3.5 hour, the equilibrium moisture content was reached.

5.2.4 Seredo

Seredo grains are a mix of beige and red in colour. Compared to the other varieties, Seredo grain size is slightly larger. The average initial moisture content of the Seredo variety was found to be 22.5%. Given that the moisture content was not initially measured in the field, the initial moisture content was lower than the average expected moisture content.

The Seredo sorghum variety samples were also categorically analysed and the results were plotted and are as shown.

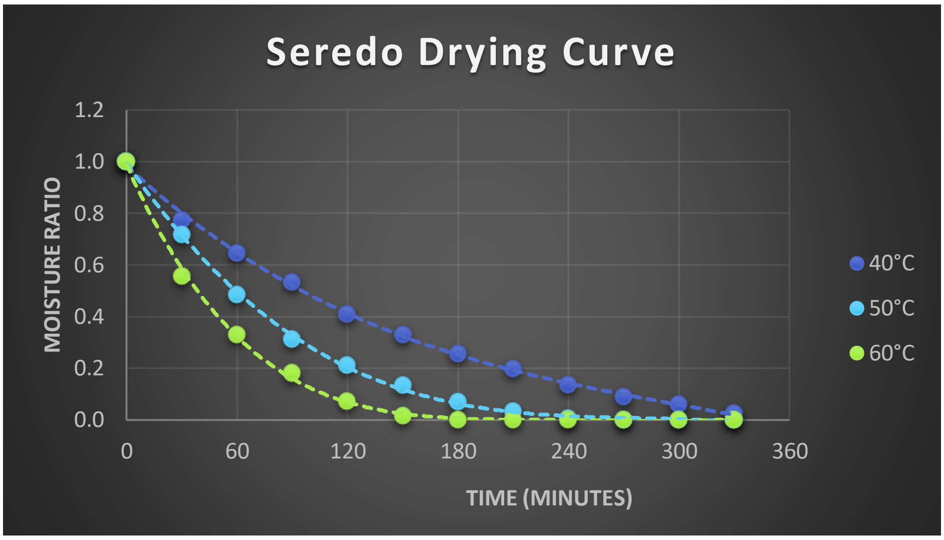

Figure 5.5: Drying curve for Seredo sorghum variety at 40 to 60 degrees Celsius

As shown in Figure 5.20 above, the drying showed that the moisture loss was greatest during the first hour. This is the constant rate period. The drying rate at 40°C took the longest duration for the weight difference to be <0.1g. In contrast, by hour 3, the equilibrium moisture content had been attained at a temperature 60°C.

Other graphs were also analyzed to evaluate the drying of the sorghum varieties with respect to specific temperatures. The results are as shown in Figure 5.6 to Figure 5.8

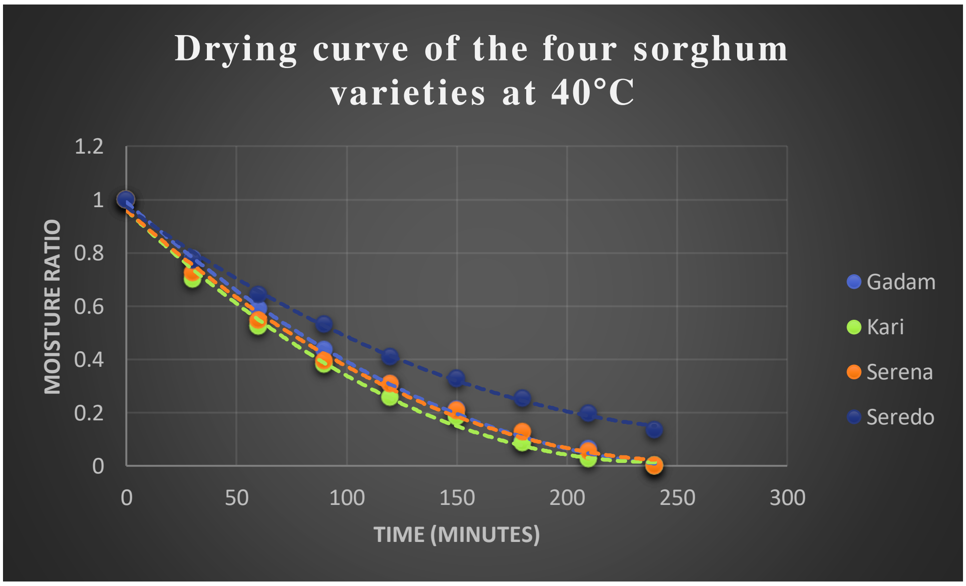

Figure 5.6: Drying curve showing Gadam, Kari Mtama 1, Seredo and Serena sorghum varieties at 40°C

At 40°C, the Seredo variety took the longest duration to dry, followed by the Gadam variety. Thus, it can be said that the drying rate through Seredo was the lowest at 40°C, compared to the other 3 varieties. One of the reasons may be because of its initial moisture content, which was the highest at the start of the experiment (22%). The other 3 varieties had a very low variability.

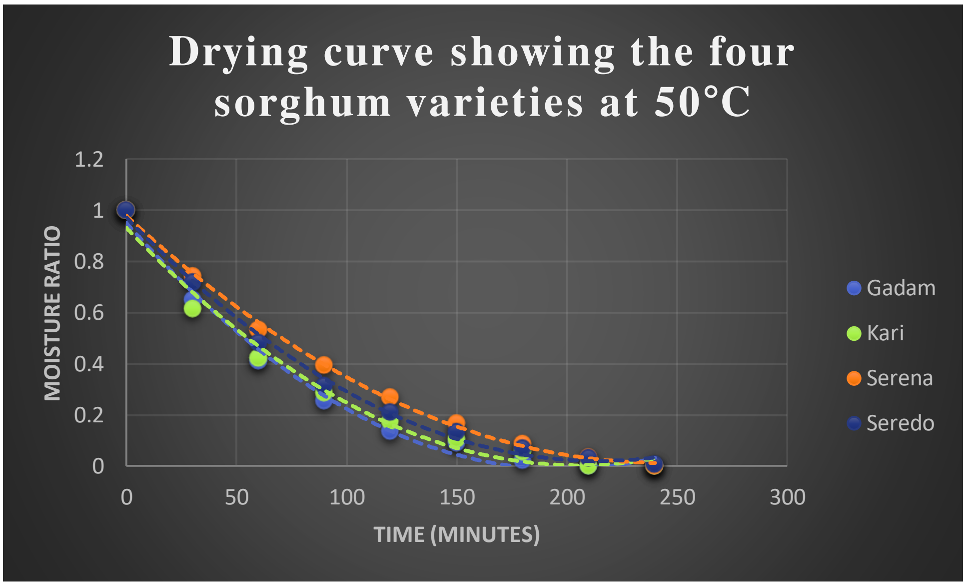

Figure 5.7: Drying curve showing Gadam, Kari Mtama 1, Seredo and Serena varieties at 50°C

At 50°C, all the varieties demonstrated a fairly similar curve. However, the Serena variety had the slowest drying rate. This may be due to the factors such as relative humidity and air resistance, which affected the drying rate as mentioned by Burmeister, (1998).Figure 5.8 below (60°C) also demonstrated a similar pattern to Figure 5.7.

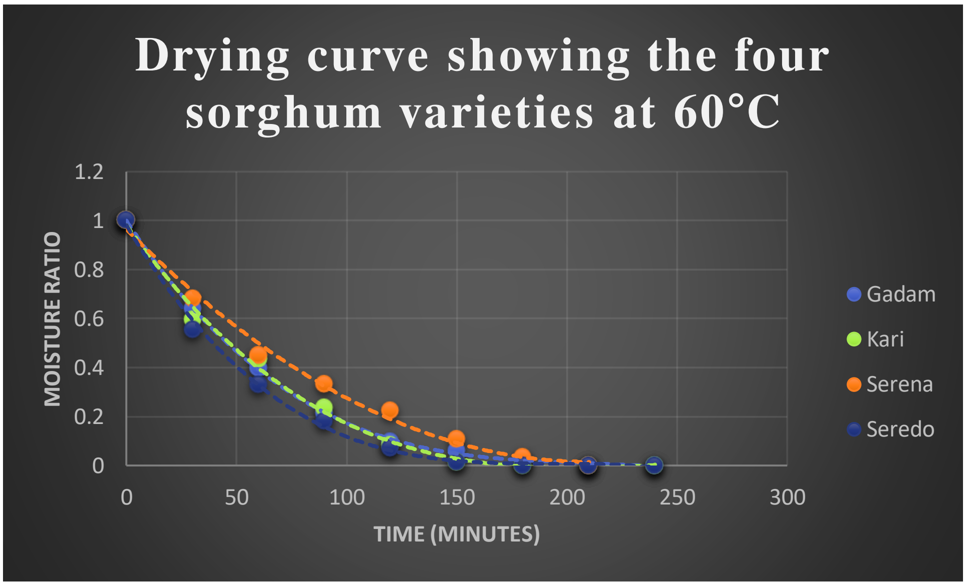

Figure 5.8: Drying curve showing Gadam, Kari Mtama 1, Seredo and Serena sorghum varieties at 60°C

The drying curves plotted all displayed a decay curve, which has been the adaptable curve in drying experiments done by many researchers. The curves appeared to have two phases, the constant rate period and the falling rate period (Alonso, 2011). The critical moisture ratio was at about point 0.4, where after it was observed that the ultimate grain drying was at the falling rate period. In comparison to previous drying curves done on sorghum, such as Kim *et al.*, (2016) and Franke *et al.*, (2008), the experimental results displayed a similar decay pattern, whose main interpretation is that higher temperatures display higher drying rates, and vice versa.

Even with the line of best fit, not all points were aligned. This was possibly due to errors in the study such as:

1. Power outage at some point during the experiment, which caused the oven temperature to fluctuate, and also made it difficult to read the reading from the weighing scale.
2. The oven temperature scale was located above the meniscus reading, which may have altered some results.
3. Grain spillage when transferring the trays from the oven to desiccator/moisture meters.

5.3 Thin Layer drying models

The results of the statistical analysis of the model, fitted from seven pre-existing thin layer drying models in Table 2.2 are shown in the sections below:

5.3.1 Gadam: Statistical analysis and models' coefficients

Table 5-1 : Gadam Statistical results for the curve fitted drying models at 40°C, 50°C and 60°C

Temp (˚C)	**Model**	**Coefficients**				**Statistical Results**			
		k	**n**			**R^2**	**RMSE**	**χ^2**	**Res. Error**
40	Lewis	0.0117	1.0000			0.9801	0.0628	0.0769	0.2303
50	Lewis	0.0198	1.0000			0.9833	0.0668	0.1484	0.6410
60	Lewis	0.0194	1.0000			0.9882	0.0472	0.0454	0.1392
		k	**n**						
40	Page	0.0012	1.4591			0.9913	0.0353	0.0186	0.0573
50	Page	0.0022	1.4321			0.9880	0.0448	0.0421	0.2202
60	Page	0.0068	1.2102			0.9991	0.0104	0.0028	0.0226
		k	**n**						
40	Mod-Page	0.0117	1.0000			0.9801	0.0628	0.0769	0.2303
50	Mod-Page	0.0198	1.0000			0.9833	0.0668	0.1484	0.6410
60	Mod-Page	0.0194	1.0000			0.9882	0.0472	0.0454	0.1392
		k		**a**					
40	Hend&Pabis	0.0126		1.1534		0.9739	0.0713	0.0625	0.1823
50	Hend&Pabis	0.0211		1.2325		0.9770	0.0970	0.1265	0.5367
60	Hend&Pabis	0.0204		1.1509		0.9843	0.0571	0.0363	0.0951
		k		**a**	**c**				
40	Logarithmic	0.0046		1.5725	-0.5950	**0.9985**	**0.0123**	**0.0024**	**0.0073**
50	Logarithmic	0.0120		1.0704	-0.1023	**0.9987**	**0.0153**	**0.0066**	**0.0475**
60	Logarithmic	0.0176		1.0845	-0.0202	**0.9940**	**0.0243**	**0.0114**	**0.0372**
		k1	**a**	**b**	**k2**				
40	2-term	0.0136	1.3241	-0.3241	64.3512	0.9808	0.0495	0.0400	0.1333
50	2-term	0.0226	1.5399	-0.5399	117.7509	0.9791	0.0577	0.0777	0.4143
60	2-term	0.0215	1.3410	-0.3410	138.4380	0.9944	0.0272	0.0109	0.0446
			a	**b**					
40	Wang-Singh		-0.0071	0.0000		0.9983	0.0153	0.0040	0.0122
50	Wang-Singh		-0.0103	0.0000		0.9909	0.0408	0.0353	0.1725
60	Wang-Singh		-0.0113	0.0000		0.9955	0.0298	0.0229	0.1678

The results in Table 5.1 above for the Gadam variety showed that the highest R^2 and lowest RMSE and χ^2values were satisfactorily described by the Logarithmic model. While the Page model also had high values of R^2 and low RMSE and χ^2values, the ANOVA (Analysis of Variance) tool in Microsoft Excel chose the best fit model based on evaluation of the F ratio. The ANOVA results revealed that the F ratio is smaller than the Fcritical value, thus the score differences were explained by chance, which by observation and least residual error, favoured the Logarithmic model because of its higher score in the whole data set. (Sloan, 2016). The F ratio was 0.001116 and the Fcritical value was 4.4939 with a 1 degree of freedom. The Logarithmic model equation was:

$$M.R. = a.e^{-k.t} + c \tag{5.1}$$

and the constants k, a and c were found to be 0.0046, 0.0120, 0.0176 for k, 1.5725, 1.0704, 1.0845 for a, and -0.5950, -0.1023, -0.0202 for c, at 40°C, 50°C, and 60°C respectively. Thus, it can be said that the Logarithmic model can be used to model the thin layer drying of Gadam sorghum grain.

5.3.2 KARI Mtama 1: Statistical analysis and models' coefficients

The following Table 5.2 captured the statistical analysis results for the Kari Mtama 1 variety.

Table 5-2 KARI Mtama 1 Statistical results for the drying models at 40°C, 50°C and 60°C

Temp	Model	Coefficients				Statistical Results			
		k	**n**			**R^2**	**RMSE**	**χ^2**	**Res. Error**
40	Lewis	0.01544	1.000			0.9724	0.0841	0.2684	0.8367
50	Lewis	0.01531	1.000			0.9973	0.0172	0.0093	0.0466
60	Lewis	0.02666	1.000			0.9364	0.1278	0.5946	1.1204
40	Page	0.00076	1.57324			0.9749	0.0667	0.0701	0.2518
50	Page	0.00892	1.10851			0.9948	0.0239	0.0083	0.0241
60	Page	0.00037	1.86382			0.9535	0.0911	0.0749	0.2444
40	Mod-Page	0.01544	1.000			0.9724	0.0841	0.2684	0.8367
50	Mod-Page	0.01531	1.000			0.9973	0.0184	0.0093	0.0466
60	Mod-Page	0.02666	1.000			0.9364	0.1278	0.5946	1.1204
				a					
40	Hend&Pabis	0.01662		1.24714		0.9639	0.1080	0.2182	0.7056
50	Hend&Pabis	0.01563		1.04494		0.9970	0.0265	0.0107	0.0421
60	Hend&Pabis	0.02836		1.27937		0.9263	0.1532	0.4666	0.9987
				a	**c**				
40	Logarithmic	0.00733		1.18274	-0.22672	**0.9967**	**0.0189**	**0.0046**	0.0122
50	Logarithmic	0.01252		1.01317	-0.05034	**0.9968**	**0.0185**	**0.0032**	0.0048
60	Logarithmic	0.01273		1.16878	-0.15979	**0.9935**	**0.0264**	**0.0125**	0.0389
		k1	**a**	**b**	**k2**				
40	2-term	0.017685	1.503056	-0.503059	1	0.9585	0.0805	0.1573	0.5834
50	2-term	0.015899	1.083625	-0.083626	1	0.9946	0.0249	0.0099	0.0384
60	2-term	0.031467	1.951661	-1.240425	1	0.9408	0.0942	0.2644	0.7461
			a	**b**					
40	Wang-Singh		-0.00791	1.56E-05		0.9926	0.0370	0.0194	0.0499
50	Wang-Singh		-0.010188	2.75E-05		0.9866	0.0471	0.0269	0.0749
60	Wang-Singh		-0.01174	3.44E-05		0.9913	0.0322	0.0115	0.0243

For Kari Mtama 1 variety in Table 5.2 above, high R^2 and lowest RMSE and χ^2values were analysed statistically and the models which matched the values were the Lewis, Logarithmic and the Wang-Singh model. In determining the best model between these, the ANOVA data analysis tool was used. The ANOVA results revealed that the F ratio is smaller than the Fcritical value, thus the score differences were explained by chance, which by observation and least residual error, favoured the Logarithmic model, as in the Gadam variety, due to the higher score in the whole data set. (Sloan, 2016) . Thus, it can be said that the Kari Mtama 1 variety is satisfactorily described by the Logarithmic model given its high values of R^2 and low RMSE and χ^2values.

5.3.3 Serena: Statistical analysis and models' coefficients

Table 5.3 captured the statistical analysis results for the Serena variety as follows:

Table 5-3 : Serena Statistical results for the curve fitted drying models at 40°C, 50°C and 60°C

Temp	**Model**	**Coefficients**				**Statistical Results**			
		k				**R^2**	**RMSE**	**χ^2**	**Res. Error**
40	Lewis	0.0124				0.9872	0.0525	0.0866	0.3419
50	Lewis	0.0145				0.9748	0.0778	0.1793	0.5561
60	Lewis	0.0170				0.9783	0.0739	0.1788	0.5642
		k	n						
40	Page	0.0018	1.3733			0.9854	0.0469	0.0360	0.1272
50	Page	0.0010	1.5118			0.9872	0.0474	0.0314	0.1044
60	Page	0.0014	1.4963			0.9769	0.0598	0.0543	0.1875
		k	n						
40	Mod-Page	0.0124	1.0000			0.9872	0.0525	0.0866	0.3419
50	Mod-Page	0.0145	1.0000			0.9748	0.0778	0.1793	0.5561
60	Mod-Page	0.0170	1.0000			0.9783	0.0739	0.1788	0.5642
		k		a					
40	Hend&Pabis	0.0133		1.1539		0.9828	0.0687	0.0791	0.2868
50	Hend&Pabis	0.0156		1.2360		0.9660	0.0977	0.1383	0.4373
60	Hend&Pabis	0.0182		1.2088		0.9719	0.0959	0.1527	0.4777
		k		a	c				
40	Logarithmic	0.0062		1.2175	-0.2752	**0.9948**	**0.0237**	**0.0063**	**0.0122**
50	Logarithmic	0.0084		1.1728	-0.1654	**0.9996**	**0.0069**	**0.0011**	**0.0051**
60	Logarithmic	0.0083		1.1854	-0.2334	**0.9948**	**0.0181**	**0.0072**	**0.0168**
		k1	a	b	k2				
40	2-term	0.0139	1.2844	-0.2844	1.0000	0.9785	0.0540	0.0615	0.2434
50	2-term	0.0167	1.4846	-0.4846	1.0000	0.9711	0.0669	0.0865	0.3249
60	2-term	0.0195	1.4624	-0.4624	1.0000	0.9694	0.0677	0.1081	0.3831
			a	b					
40	Wang-Singh		-0.0074	1.40E-05		0.9924	0.0359	0.0184	0.0485
50	Wang-Singh		-0.0062	7.24E-06		0.9790	0.0786	0.1164	0.7178
60	Wang-Singh		-0.0091	2.08E-05		0.9904	0.0390	0.0193	0.0491

The results in Table 5.3 above for the Serena variety showed that the highest R^2 values were satisfactorily described from the Logarithmic model at 40°C, 50°C and 60°C (0.9948, 0.9996 & 0.9948).

In addition, the lowest RMSE values and χ^2 range of all the temperatures fell under the Logarithmic model. The lowest χ^2 for the temperatures also fell in the Logarithmic model. Given that only one model fit the data, there was no variance analysis. Thus, it can be said that the Logarithmic model can be used to model the thin layer drying of Serena sorghum grain.

5.3.4 Seredo: Statistical analysis and models' coefficients

Table 5.4 captured the statistical analysis results for the Seredo variety and is discussed as follows:

Table 5-4 : Seredo Statistical results for the curve fitted drying models at 40°C, 50°C and 60°C

Temp	**Model**	**Coefficients**				**Statistical Results**			
		k	**n**			**R^2**	**RMSE**	**χ^2**	**Res. Error**
40	Lewis	0.0083	1.0000			0.9929	0.0308	0.0290	0.1138
50	Lewis	0.0200	1.0000			0.9545	0.1086	0.6737	2.0783
60	Lewis	0.0263	1.0000			0.9787	0.0749	0.1947	0.6758
		k	**n**						
40	Page	0.0026	1.2130			0.9937	0.0293	0.0142	0.0402
50	Page	0.0005	1.6671			0.9779	0.0677	0.0930	0.5786
60	Page	0.0022	1.5063			0.9780	0.0597	0.0422	0.1777
		k	**n**						
40	Mod-Page	0.0083	1.0000			0.9929	0.0308	0.0290	0.1138
50	Mod-Page	0.0200	1.0000			0.9545	0.1086	0.6737	2.0783
60	Mod-Page	0.0263	1.0000			0.9787	0.0749	0.1947	0.6758
		k		**a**					
40	Hend&Pabis	0.0087		1.0839		0.9909	0.0395	0.0282	0.0934
50	Hend&Pabis	0.0214		1.3950		0.9422	0.1477	0.4766	1.7740
60	Hend&Pabis	0.0279		1.2383		0.9727	0.1107	0.1654	0.5804
		k		**a**	**c**				
40	Logarithmic	0.0054		1.1440	-0.1789	**0.9977**	**0.0140**	**0.0026**	**0.0047**
50	Logarithmic	0.0117		1.0860	-0.0595	**0.9992**	**0.0105**	**0.0015**	**0.0056**
60	Logarithmic	0.0162		1.0683	-0.0798	**0.9988**	**0.0047**	**0.0019**	**0.0077**
		k1	**a**	**b**	**k2**				
40	2-term	0.0089	1.1308	-0.1308	58.4686	0.9886	0.0353	0.0241	0.0824
50	2-term	0.0301	62.5286	-61.6400	0.0308	0.9513	0.0761	0.1607	0.9652
60	2-term	0.0302	1.6881	-0.6881	204.0269	0.9731	0.0638	0.0920	0.4226
			a	**b**					
40	Wang-Singh		-0.00573	8.5236E-06		0.9952	0.0286	0.0196	0.0790
50	Wang-Singh		-0.00819	1.6861E-05		0.9892	0.0479	0.0502	0.2592
60	Wang-Singh		-0.01275	4.1192E-05		0.9884	0.0463	0.0235	0.0688

The results in Table 5.4 above for the Seredo variety showed that the highest R^2 values were satisfactorily described from the Logarithmic model at 40°C, 50°C and 60°C (0.9977, 0.9992 & 0.9988).

In addition, the lowest RMSE values and χ^2 range of all the temperatures fell under the Logarithmic model. The lowest χ^2 for the temperatures also fell in the Logarithmic model. Given that only one model fit the data, there was no variance analysis. Thus, it can be said that the Logarithmic model can be used to model the thin layer drying of Seredo sorghum grain.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

In determining the drying characteristics of sorghum varieties, the following can be concluded:

1. In line with Specific Objective 1, following the evaluation of sorghum varieties that are grown in Kenya- Elgeyo Marakwet County, the current sorghum grain varieties grown are Serena, Seredo, Gadam and KARI/Mtama 1. The drying techniques adopted by the farmers was 99% who practise the traditional field-drying/sun drying, and 1% dry sorghum in the house in hanging cobs.
2. In line with Specific Objective 2, the drying kinetics showed that high drying temperatures result in faster drying rates. When drying the sorghum in an oven, the optimum temperature for drying is 60°C.The highest initial moisture content was in the Seredo variety, which was 22.5%. Generally the initial moisture content of the sorghum varieties ranged from 19% - 23%. The equilibrium moisture content was 11% for the varieties sampled, except for the Serena variety, which had an equilibrium moisture content of 10.6%. The initial moisture content plays a role in the drying characteristics and the drying rate. For a low initial moisture content, the drying rate would take less time compared to the grain with a high initial moisture content. The drying curves showed an exponential curve for the varieties, which confirmed the decay curve trend for drying as from previous drying studies. It was evident from the drying curves, that the higher the temperature the faster the drying rate, and the lower the temperature, the slower the drying rate.
3. In line with Specific Objective 3, the regression analyses done on the seven thin layer drying models predicted the following models suitable for the varieties.

   Table 6-1 summarizes the suitable models and the respective equation for each variety.

Table 6-1: Summary of Thin Layer drying models for Sorghum varieties in Kenya

Variety	Thin-layer drying model	Equation
Gadam	Logarithmic model	$\mathrm{M.R} = \mathrm{a.e}^{-\mathrm{k.t}} + \mathrm{c}$
Kari Mtama 1	Logarithmic model	$\mathrm{M.R} = \mathrm{a.e}^{-\mathrm{k.t}} + \mathrm{c}$
Serena	Logarithmic model	$\mathrm{M.R} = \mathrm{a.e}^{-\mathrm{k.t}} + \mathrm{c}$
Seredo	Logarithmic model	$\mathrm{M.R} = \mathrm{a.e}^{-\mathrm{k.t}} + \mathrm{c}$

Following the non-linear regression analysis of the 4 varieties, all the models chosen showed a high R^2 value (>90%) and RMSE range of 0.006 to 0.159. The χ^2 ranged from 0.0005 to 0.2079. The recurrent and best fit model was found to be the Logarithmic model. This can be attributed to the constants a, and c, which added an empirical value to best fit the data.

The Logarithmic model has successfully been used in drying of green peppers (Doymaz & Ismail, Drying and rehydration behaviors of green bell peppers, 2010), pineapples (Kingsly, Balasubramaniam, & Rastogi, 2009), Morus Alba (Doymaz, 2004), beans (Kayisoglu & Ertekin, 2011) and peaches (Kingsly, Goyal, & Manikantan, 2007).

Overall, the objectives of the research i.e. evaluation of the drying characteristics of sorghum varieties in Elgeyo Marakwet County and development of the thin layer drying models were met.

6.2 Recommendations

The results for the four sorghum varieties demonstrated that the Logarithmic model is the best fit model used for drying sorghum. This means that this model can be implemented in designing a sorghum dryer based on the results of this research.

Given that this was an initial study, further recommendations can be included in order to refine the research in future. These include:

1. The experiment of the sorghum drying can be done not only under varied temperatures, but also with varied relative humidity in order to refine the data.
2. A suitable drying oven with controls for temperature and relative humidity as discussed in point 1 above, will ensure further accuracy and avoid unnecessary human error.
3. An additional study can be done on the airflow resistance of the varieties. This can be done by determining the pressure drop across the grain column and the velocity of the grain
4. An additional study to be done to assess the effects of drying system on the quality of sorghum grains being dried.

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8 APPENDIX

Appendix A1: Sample questionnaire

Sustainable post-harvest and agro-processing technologies for improved livelihoods among rural communities in Elgeyo Marakwet County, Kenya

Table 8-1: Personal Details in Questionnaire

Name of farmer: **(Jina la mkulima):**	**Telephone number (Nambari ya simu):**
County (Kaunti):	**Ward (Wadi):**
Location (Kata):	**Sub-location (Kata ndogo):**
Village (Kijiji):	**Signature:** **(Sahihi)**

1. Do you grow sorghum? (Je, unapanda mtama?)
   - ○ Yes (Ndio)
   - ○ No (La)
2. What sorghum varieties do you grow? Put a √ where it applies.
   Je, unapanda mtama ya aina gani? Weka alama √ kati ya hizi.

Table 8-2 Sorghum varieties grown - Questionnaire

Name (Jina)	**Colour (Rangi)**	**Yes/No** **(Ndio/La)**
Serena	Brown (Rangi ya hudhurungi)	
Seredo	Brown but larger than Serena	
Gadam	Grayish-white (for malt) (Nyeupe)	
KARI/Mtama 1	White (Nyeupe)	
E 1291	Brown (Hudhurungi)	

3. Field size grown for sorghum. How many acres of sorghum do you harvest?
   (Je, ni hekari ngapi ya shamba unayopanda mtama?)………………………………….

4. Quantity produced (Number of bags, 1 bag=90 kg)?
   (Unavuna kiasi gani? (Kwa gunia ya kilo tisini
   90kg)…………………………………………………….

5. What do you use the sorghum for?
   Kusudi ya mtama kwako ni kwa sababu ya?
   - Food-Ugali/Porridge. (Chakula cha nyumbani – ugali ama uji.)
   - Fodder for animals (Chakula cha mifugo)
   - Brewing/ Selling to brewers (Kutengeneza bia au unauzia wa kutengeneza bia)
   - Other: Please specify. (Ingine:

     Elezea)…………………………………………………………………..

6. Household demand: How much sorghum do you use or sell per week?

   (Matumizi ya nyumbani: Je, ni kiwango kipi unatumia au kuuza kwa wiki?)

   …………………………………………………………………………………

7. What sorghum drying techniques do you use? (Unatumia mbinu ipi kuukausha mtama wako?)
   - Open air sun drying? (Kuanika kwa Jua)
   - Solar drying? (sola)
   - Machine? (Mashine ya kukausha)
   - Other? Please explain (Ingine: Elezea)

     …………………………………………………………………………

     …………………………………………………………………………

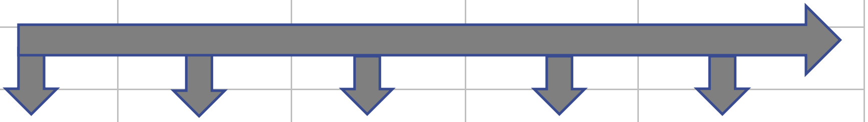
8. How long does it take to dry the sorghum after harvest? (Mtama huchukua muda ipi kukauka baada ya kuvuna?)
   ………………………………………………………………………………
9. Approximate Drying time (sunshine hours)? (Masaa ya kukausha kwa jua?)

   ………………

10. From the harvesting to the final product, approximately how much sorghum grain would be lost? (Tangu kuvuna hadi mwisho wa matumizi, linganisha kiwango cha mtama ambao unapungua kulingana na pahali inapopungua.)

Table 8-3: Post harvest Loss Subsections

Process where kilos are lost (Njia ya upungufu wa mtama)	**Threshing (Kupiga)**	**Cleaning (Kusafisha)**	**Drying (Kukausha)**	**Storage (Kuhifadhi)**	**Transportation (Usafirishaji)**
Kilos Lost (Kilo zinazopungua)					
Less than 1 kg (Chini ya kilo 1)					
1 kg (Kilo 1)					
2 kg (Kilo 2)					
5 kg (Kilo 5)					
More than 5 kg. (Zaidi ya kilo 5)					



11. What other issues or problems do you encounter when drying/processing sorghum?

(Ni mambo yepi mengine au shida unazokumbana nazo wakati wa kukausha au kutengeneza bidhaa kutokana na mtama?) …………………………………………

Appendix A2: Sorghum varieties

Figure 8.1: The four sorghum varieties used for the study

Appendix A3: Research samples and instruments:

Figure 8.2: Research samples and instruments used

Wet and dry bulb Mason’s hygrometer with Celsius and Fahrenheit readings

Figure 8.3: Wet and dry bulb Mason's Hygrometer

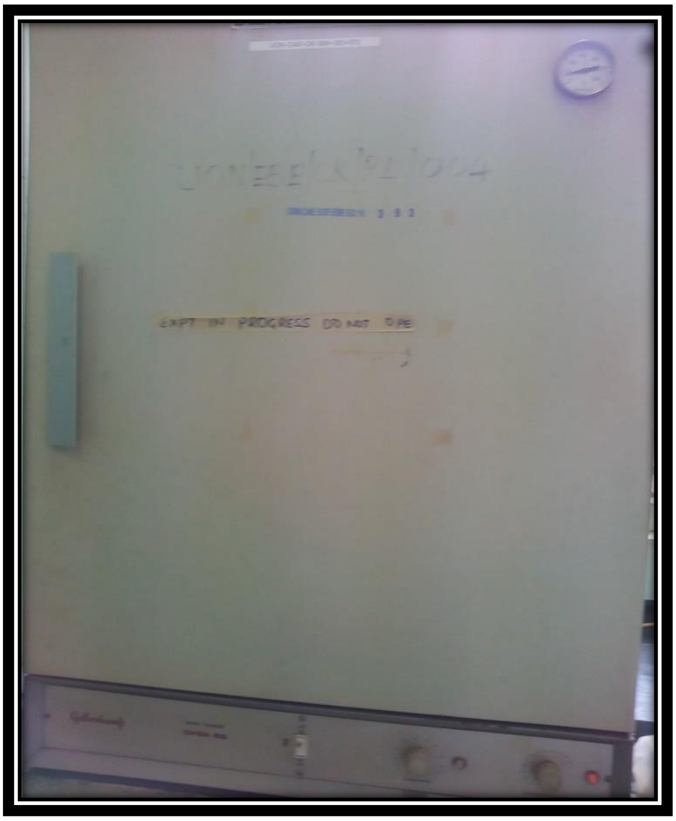


Figure 8.4: Gallenkamp Laboratory Bench oven

Figure 8.5: Sorghum Samples in oven just before removal

Weighing samples on the Sartorius precision laboratory balance

Figure 8.6: Weighing of the samples

FarmPro Moisture Analyzer

M.C. reading on the FarmPro Moisture meter

Recommended 9 ml portion for putting in the FarmPro moisturemeter

Figure 8.7: FarmPro Moisture Meter

Agratronix MT-16 Grain moisture tester showing M.C. reading in %

Figure 8.8: Agratronix MT-16 Grain moisture tester

Figure 8.9: Desiccator with desiccant (blue silica gel) at the bottom.