# EFFECTS OF DRYING TEMPERATURES ON DRYING KINETICS, PHYSICAL, FUNCTIONAL, NUTRITIONAL, AND ANTI-NUTRITIONAL PROPERTIES OF AMARANTH SEEDS AND CHEMOMETRIC ANALYSIS

by

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# Effects of Drying Temperatures on Drying Kinetics, Physical, Functional, Nutritional, and Anti-nutritional Properties of Amaranth Seeds and Chemometric Analysis

*A dissertation submitted to the Department of Food Technology, Central Campus of Technology, Tribhuvan University, in partial fulfillment of the requirements for the degree of B. Tech. in Food Technology*

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## Approval Letter

**This *dissertation* entitled *Effects of Drying Temperatures on Drying Kinetics, Physical, Functional, Nutritional, and Anti-Nutritional Properties of Amaranth Seeds and Chemometric Analysis* presented by Prekshya Timsina has been accepted as the partial fulfillment of the requirements for the B. Tech. in Food Technology**

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## Abstract

The aim of this work was to study the drying kinetics of amaranth seeds at three different temperatures and its effects on physical, functional, nutritional and anti-nutritional properties. The amaranth seeds were collected from Kathmandu organics, a grocery store in Kathmandu, Nepal. Three different drying temperatures 40, 50 and 60 °C were selected for the drying of amaranth seeds in a cabinet dryer.

When comparing the fresh with the samples of dried amaranth, it was observed that the drying operation led to reductions of 8.5% in proteins, 2.0% in ashes, 4% increase in crude fiber, and fat content was changed by approximately 3%. Amaranth seeds dried at 60 °C showed maximum retention of the phytochemical constituents and maximum reduction of anti-nutritional factors. In this study, moisture data of 40, 50, and 60°C were fitted to six drying models to provide an appropriate kinetic model and drying temperature for the drying process. The average value of coefficient of determination $R^2$, $\chi^2$ and RMSE revealed values varied between 0.9724-0.9973, 0.0362-0.1567 and 0.0176-0.0533, respectively. The Midilli *et* al. model obtained the highest $R^2$ and least $\chi^2$ and RMSE at all temperatures and better reflected the drying mechanism of amaranth seed and was determined to be the best fit for determining the proper drying temperature and drying kinetics for amaranth seeds. The effective diffusivity calculated using Fick's diffusion equation varied from $1.1592 \times 10^{-8}$ $m^2/s$ at 40 °C to $1.9716 \times 10^{-8}$ $m^2/s$ at 60 °C. The activation energy and $D_0$ for cabinet drying of amaranth seed at temperature from 40 to 60 °C were found to be 22.99 kJ/mol and $7.86 \times 10^{-5}$ $m^2/s$, respectively.

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## List of Abbreviations

| Abbreviations | Full form |
|---|---|
| AIA | Acid insoluble ash |
| ANOVA | Analysis of variance |
| db | Dry-basis |
| wb | Wet-basis |
| AOAC | Association of Official Analytical Chemists |
| GAE | Gallic acid equivalent |
| ppm | Parts per million |
| LDPE | Low density polyethylene |
| QE | Quercetin equivalent |
| TFC | Total flavonoid content |
| TPC | Total phenolic content |
| NFE | Nitrogen-free extract |
| DCP | Digestible crude protein |
| TOM | Total organic matter |

# Part I

# Introduction

## 1.1 General introduction

Amaranth is a herbaceous, dicotyledonous plant with a big inflorescence and an upright stalk. The crop's extreme geographic flexibility to a wide range of climatic circumstances is a result of all of this (Topwal, 2019). Grain amaranth's distinct agronomic, nutritional, and functional qualities make it a promising crop for improving peoples' nutrition, particularly in underdeveloped nations. It grows quickly, produces a lot, can withstand stress, is nutrient-dense, and has nutraceutical qualities. Amaranth grain is high in fiber, lipids, proteins, and calories (Muyonga *et al.*, 2008). Amaranth's high protein content, balanced amino acid profile, and gluten-free makeup make it a nutritious food that may appeal to customers who are health-conscious (Soriano-García and Aguirre-Díaz, 2019).

Due to its numerous nutritional advantages, researchers have recently determined that amaranth is a pseudo-cereal with a dual character, possessing both food-like qualities and health-promoting properties (Baraniak and Kania-Dobrowolska, 2022). While its grains are eaten as other cereals, the leaves are utilized as vegetables and animal feed (Burgos and Armada, 2015). This seed's superior nutritive composition makes it ideal for combining with cereal by-products to enhance their nutritious value (Singh and Punia, 2020). Amaranth grains have greater antioxidant activity and phytochemical content than oat, barley, wheat, corn, millet, and rice, making them a viable alternative to traditional cereals and a possible source of health-promoting bioactive components (Akin-Idowu *et al.*, 2017).

Amaranth can be utilized as grain, fresh, dried, or ensiled fodder in cattle nutrition (Rezaei *et al.*, 2013; Seguin *et al.*, 2013). After the emergence of bovine spongiform encephalopathy and the subsequent restriction of meat-and-bone meals in the nutrition of all farm animal species in Europe, the use of amaranth grain is particularly intriguing (Mlakar *et al.*, 2009). Research suggests that this plant may be a viable alternative to traditional feed for rabbits (Molina *et al.*, 2015), pigs (Kambashi *et al.*, 2014), chickens (Písaříková *et al.*, 2006), and ruminants (Abbasi *et al.*, 2012), particularly in tropical and subtropical locations.

Drying is a critical and energy-intensive unitary step in the post-harvest processing of crops. It is carried out to reduce the moisture content of agricultural goods after harvest.

Lowering the water content is critical for extending the shelf life of biological goods by lowering water activity to a level low enough to limit microbial growth, enzymatic reactions, and other spoiling processes (Mujumdar and Law, 2010). Drying is required for the processing and storage of grains. Furthermore, seeds with a high moisture content are more likely to develop mold and become infected by insects, leading them to degrade and reduce their quality (Barrozo *et al.*, 2014). As a result, seeds with a low moisture content are required for safe long-term storage. Optimizing the operating parameters, conditions, and overall quality of the final product requires mathematical modeling and simulation of drying curves under different conditions (Meisami-Asl *et al.*, 2009). Modeling is the application of a system of equations intended to provide an exact description of the drying system (I. Doymaz, 2007). In order to fit the drying kinetics of agro-food products, semi-empirical models are normally used (I. Doymaz, 2007); but the parameters of these models vary rapidly with the drying air conditions, making it challenging to use them to calculate the drying rate when the drying conditions have huge ranges of variation.

The most common method for carrying out drying modeling is to use thin layer models, which are semi-theoretical models based on Fick's rule of diffusion. Many studies have recently published reports on the effects of drying temperature and drying techniques on the drying modeling and moisture diffusivity of various products (Ahmat *et al.*, 2015; Duan *et al.*, 2011).

## 1.2 Statement of problem

Amaranth is an under-utilized crop that has a lot of promise to meet human and animal dietary demands. Despite having few calories, amaranth is thought to minimize malnutrition and promote optimal health because of its high content of protein, fat, and fiber in addition to important vitamins and minerals. In both urban and rural environments, amaranth can have a major impact on the food and nutrition security of vulnerable communities (Ruth *et al.*, 2021).

These plants share all of the features to be used in functional foods (Ishimoto and Monteiro, 2010), and their nutritional and functional properties are quite comparable, such as lower blood cholesterol and gluten-free (Almeida and Sá, 2009). Including these grains in the diet has the potential to enrich it while also providing health advantages, particularly for people with celiac disease who are intolerant of gluten (Almeida and Sá, 2009; Ishimoto

and Monteiro, 2010). In spite of having a high potential for use in animal feed, which can enhance cultivation and output for farmers by lowering production costs or providing additional sources of income, this crop has not been explored (Schmidt *et al.*, 2023).

The natural drying technique is easy to use and requires little financial outlay from the manufacturer. This approach has the benefit of using the sun's germicidal power without generating any pollution. But it's a gradual process that is totally dependent on the weather (Costa *et al.*, 2021). Amaranth seeds are frequently collected with a greater water content—roughly 40%—on a big scale. In this case, artificial drying techniques are needed to quickly lower the content of seed water and ensure that the harvest is well preserved (Costa *et al.*, 2021).

Incorrect processing prior to storage at the home or commercial level might result in product deterioration and a loss of nutritional content. Consuming rich cereals high in plant secondary metabolites (anti-nutrient factors) such as phytates, tannins, saponins, oxalates, trypsin inhibitors, nitrates, and proteases may not successfully treat malnutrition as well. Thus, there was a need to carry out this research in order to accurately model the drying kinetics, better understand the behavior of the seeds during the drying process, and investigate how different processing temperatures alter their physical, functional, nutritional, and anti-nutritional properties; so that to optimize the usage and absorption of grain amaranth.

Before being used in functional foods, these grains are dried and milled into flours. Because they might play an important part in food security, the seeds are saved after harvesting for future use and probable germination when the season arrives. Here, the seeds should be dried properly for longer storage stability, lesser physical damage and nutritional loss, and protect the germination capability of the seed so that it can be reused. In each of these processes, the most crucial stage is drying. So, detailed study on the effects of different temperatures on various aspects was required. Therefore, in this study temperature range was selected from the previous studies of grains where minimal physical damage and low reduction in germination was observed. And this study provides an overall effect of drying at three different temperatures.

## 1.3 Objectives

### 1.3.1 General objective

The general objective of this work was to study the effect of different drying temperatures on drying kinetics as well as physical, functional, nutritional, and anti-nutritional properties of amaranth seeds.

### 1.3.2 Specific objectives

1. To study the changes in physical characteristics of amaranth seeds induced by varying drying temperatures.
2. To study the impact of different drying temperatures on the functional properties of amaranth seeds.
3. To analyze the nutritional composition of amaranth seeds at different drying temperatures.
4. To evaluate the levels of anti-nutritional factors and phytochemical constituents in amaranth seeds subjected to varying drying temperatures.
5. To explore the drying kinetics of amaranth seeds under varying temperatures.
6. To fit the best mathematical model for drying of amaranth seeds.

## 1.4 Significance of study

Developing nations require a sufficient and nutrient-rich food supply. Malnutrition has become a major issue when it comes to food poverty, coupled with food accessibility and availability (Sohaib *et al.*, 2018).

Amaranth can withstand a shortage of water, develop quickly, and be grown in various types of soil, amaranth is one of the most promising crops that has lately gained attention (Capriles *et al.*, 2006; Caselato-Sousa and Amaya-Farfán, 2012). While most other grains, including wheat, rice, and corn, have low levels of lysine, amaranth has a high protein concentration. It is used to make gluten-free goods since it does not trigger allergic reactions in the intestinal mucosa and has been utilized in underdeveloped nations to combat protein deficiency (Escudero *et al.*, 2006; Guerra-Matias and Arêas, 2005). Amaranth is considered

to be the most advantageous feed grain for poultry in harsh climatic locations, such as drought-prone areas, as long as appropriate processing can be included into the feed production system (Hosseintabar-Ghasemabad *et al.*, 2024).

Innovative approaches to enhancing the value of food products and making use of underutilized crops are crucial in the quickly evolving socio-economic landscape. Functional additives boost the nutritional value of baked goods and other food products, making them more appealing to customers.

Mathematical modeling of the drying process and equipment design that allows for the selection of optimal operating conditions are the two most significant parts of thin-layer drying technology. Thus, the study would be useful to explore the thin-layer modeling approach as an essential tool in estimating the drying kinetics from the experimental data, describing the drying behavior, improving the drying process, and eventually minimizing the total energy requirement.

This study shows how different drying temperatures impact the drying kinetics of amaranth seeds, which helps to optimize the drying process for commercial or domestic uses. This is crucial for maintaining the nutritional quality of the seeds, especially in seed storage and food processing. By studying the effect of drying temperature on anti-nutritional properties such as phytates, it is possible to determine the reduction rate of these factors, thus improving the overall nutritional quality of amaranth seed products. Overall, studying the effect of different drying temperatures on physical, functional, nutritional, and anti-nutritional properties, as well as drying kinetics of amaranth seeds, contributes to a deeper understanding of the processing parameters that influence the quality and functionality of amaranth-based products.

### 1.5 Limitations of the study

1. Sample of mixed (white and red) variety was collected.
2. The effect on color parameters at different drying temperatures could not be studied.
3. Controlled drying condition with respect to air velocity, relative humidity couldn’t be maintained.
4. Effects on microbial properties and storage stability were not studied.

# Part II

## Literature review

### 2.1 An overview background of amaranth

All species of Amaranth belong to the genus *Amaranthus spp*., which is called Amaranthaceae (Achigan-Dako *et al.*, 2014; Peter and Gandhi, 2017). Amaranth is derived from an old Greek word meaning "flower," which also means "eternal" or "not wilting," "unfading," or "everlasting life" (Rastogi and Shukla, 2013; Reyad-Ul-Ferdous *et al.*, 2015). Amaranth is a member of the Amaranthoideae sub-family (Peter and Gandhi, 2017). Its domestication dates back to the sixth century BC, among Aesop's fables, who depicted Amaranth as a transient flowering plant that, in contrast to roses, had enduring beauty. Amaranth is a blooming plant that grows readily in home gardens and has an eye-catching inflorescence. Based on research, the Amaranthaceae family has between 60 and 75 species of Amaranth that are distributed globally, with only a small number being cultivated. These species are native to temperate, subtropical, and tropical temperature zones (Rastogi and Shukla, 2013; Topwal, 2019).

Amaranth is currently widely distributed around the world. It is grown and consumed in Africa, Mexico, Central America, Indonesia, Malaysia, the Philippines, China, Nepal, and India (Peter and Gandhi, 2017). While certain species of grain are thought to be native to South and Central America, other grain kinds are native to Europe, Asia, Africa, and Australia (Rastogi and Shukla, 2013; Topwal, 2019). Amaranth species are mostly known for its grain-purpose species in Western, Central, and South America. However, certain cultivars are cultivated for their leafy qualities. Amaranth was first grown by the powerful Aztecs 6000–8000 years ago in central Mexico. It was not only an important part of the Aztecs' diet, but also of their deity worship and human sacrifice customs (Achigan-Dako *et al.*, 2014; Randhawa *et al.*, 2015).

One of the few edible crops with potential uses for many purposes that has been rediscovered is amaranth. This is due to its wide range of industrial applications. In comparison to the most common staple crops, it has offered aesthetic value in the form of edible grains, green vegetables, fodder, and nutritional supplies (Achigan-Dako *et al.*, 2014; Aderibigbe *et al.*, 2022).

Amaranth is a grain that is rich in bioactive chemicals and is free of gluten and high protein. This is why regular eating of amaranth grains has been linked to a number of health advantages. Because amaranth contains squalene and has a low glycemic index, it can help decrease blood cholesterol and glucose levels. It is a good addition to a balanced diet (Reyes-Moreno *et al.*, 2019). Amaranth contains bioactive peptides that have been shown to have anti-hypertensive and anti-inflammatory qualities. The polyphenol content of the grain also adds to its high antioxidant capacity. While processing often degrades a grain's nutritional value, improved processes in amaranth have shown that processing may actually increase a grain's nutritious value while also increasing its adaptability to a variety of culinary applications (Reyes-Moreno *et al.*, 2019).

**Fig. 2.1** Amaranth plant

**Fig. 2.2** Amaranth seeds

## 2.2 Morphology of Amaranth

The genus *Amaranthus* is defined by the following traits: herbaceous habit with a prostrate to upright stem, and a short-lived perennial or annual life cycle (occasionally). The leaves have smooth margins, a notched or concave tip, and they alternate between being round and linear. With intricate dichasia crammed into inflorescences, flowers are flawed. Amaranth plants can be classified as dioecious (*A. palmeri, A. rudis*, and *A. tuberculatus*) or monoecious (*A. albus, A. blitum, A. caudatus, A. graecizans, A. hybridus, A. powellii, A. retroflexus,* and *A. viridis*). Three to five tepals and stamens are present in the terminal and/or axillary inflorescence. Most monoecious species self-pollinate and are wind-pollinated. Utricle or pyxidium is fruit (Assad *et al.*, 2017).

## 2.3 Nomenclature of amaranth

The taxonomic nomenclature of *Amaranthus* is as follows:

| | |
|---|---|
| Kingdom: | Plantae |
| Sub-kingdom: | Tracheobionta |
| Super-division: | Spermatophyta |
| Division: | Magnoliophyta |
| Class: | Magnoliopsida |
| Sub-class: | Caryophyllidae |
| Order: | Caryophyllales |
| Family: | Amaranthaceae |
| Genus: | *Amaranthus* L. |
| Species: | *Amaranthus cruentus* L. |

Source: Wolosik and Markowska (2019)

## 2.4 Amaranth: A food solution for food and nutrition insecurity

Globally, there has been improvement in lessening nutrient-related issues, particularly in poorer nations. Hunger, malnutrition caused by climate change, including rural poverty, and a lack of nutrition education, however, continue to appear as obstacles to this achievement. These factors affect the nutrition security of many populations, as many are unable to make informed decisions about which nutrient-dense food ingredients to use in place of the inadequate amounts found in most staple crops (Muthayya *et al.*, 2013). Amaranth is one of the vegetables that have been found to be an effective element in meeting human nutrition requirements and addressing hidden hunger problems (Achigan-Dako *et al.*, 2014). Amaranth is regarded as a "pseudo-cereal," similar to the buckwheat crop, rather than a true cereal like wheat, sorghum, millet, maize, or barley (Achigan-Dako *et al.*, 2014).

Like other true cereals in the grass family, pseudo-cereals are a crop that are not grass plants. Thus, amaranth seeds may be crushed into flour and used to bake a wide range of

foods, particularly snacks. Even though amaranth is sometimes referred to as "pigweed," it is a distinct plant that grows on its own. They are so widely grown across the world for a variety of interesting uses, including as industrial, medicinal, decorative, feed, and nutritional. Since amaranth has demonstrated its importance in providing cereal grains and leafy vegetables with a high necessary nutritional value for animal and human nutrition, it is regarded as a versatile plant (Ruth *et al.*, 2021).

Amaranth contains vital minerals such as calcium, iron, protein, riboflavin ($B_2$), niacin ($B_3$), vitamin $B_6$, folate ($B_9$), and vitamins A, C, and K. The many and indisputable health advantages of amaranth are shown by several research. Consequently, micronutrient deficiencies in particular and malnutrition in general can be prevented with a consistent diet plan (Qumbisa *et al.*, 2020).

### 2.5 Nutraceutical and healing potentials of amaranth

Nutraceutical's properties are the non-specific biological agents that boost and promote well-being. It can regulate disease symptoms and act as a deterrent to cancerous processes (Manikandaselvi and Nithya, 2011). Several studies have reported that Amaranth seed or oil may benefit those with hypertension and cardiovascular disease; hence, regular consumption of this plant reduces blood pressure and cholesterol levels while improving the nutritional value of essential micro-nutrients, such as β-carotene, iron, calcium, vitamin C, and folic acid. Both the seeds and the leaves of the plant are highly nutritious for human consumption and promise to meet nutritional needs, so they can be explored as a food plant with an added advantage that can be explored for its preventive or curative purposes (Achigan-Dako *et al.*, 2014; Alemayehu *et al.*, 2015).

### 2.6 Problems associated with production and underutilization of Amaranth

A demand for peculiar vegetables causes many underused vegetables, like amaranth, to be neglected, which has an impact on amaranth production and usage (Mayekiso *et al.*, 2017). Additionally, there seems to be a shift in people's dietary habits toward fast food, which has an impact on the consumption of traditional vegetables since the younger generation seems to favor the fatty, sweet, and salty flavors found in many snacks and fast meals (Taleni and Goduka, 2013). Customers may also have issues with the preparation techniques and additional complimentary items employed in the cooking process. Therefore, a more inventive technique for making food items based on amaranth is recommended.

Amaranth cultivated in soils high in nitrogen may concentrate nitrate in the plant's leaves or any other tissue. Blue infants, stomach tumors, and other health issues may be caused by nitrates (Alegbejo, 2013). This is due to the fact that amaranth is a plant that readily accumulates nitrates, particularly in very fertile soil. Nitrates can only concentrate primarily in the plant tissues and not in the seeds, which is worse when nitrogen fertilizer is administered and if factors like herbicide, drought, or frost impair the processes of photosynthesis (Alegbejo, 2013). It is interesting to note that bacteria in the digestive tracts of humans and some animals cause nitrates to be converted to nitrite. As a result, by the time a human child is six months old, their stomach acid levels have increased higher; as a result, it eradicates these germs and reduces the likelihood of nitrate poisoning. On the other hand, a pregnant patient with low stomach acidity who is receiving cancer treatment has a higher risk (Alegbejo, 2013). Therefore, if this plant is cultivated naturally without the use of artificial fertilizers, it is advised to eat it.

## 2.7 Amaranth in the production of cereal-based products and other applications

While the overground portions of amaranth are utilized as green leafy vegetables that are eaten raw or processed, the seeds can be fried, roasted, burst, flaked, or extruded for human consumption. The primary goal of using amaranth in cereal products is to produce gluten-reduced and gluten-free goods; adding essential nutrients to these products is also an essential task. From this point of view, it is critical that amaranth be able to be produced as a high-protein flour that provides a nutritious supplement to wheat flour in several semitropical nations that are vulnerable to drought (Venskutonis and Kraujalis, 2013). The development of cereal-based foods with amaranth flour requires careful consideration of numerous processing parameters and the quality characteristics of the final product, as it can be challenging to produce high-quality bread from gluten-free flour due to the flour's extremely low gas binding and crumb structure forming capacity (Venskutonis and Kraujalis, 2013).

Amaranth does not completely solve the gluten issue when it is used for partial replacement of wheat or rye. Consequently, studies have been conducted to create bread and other meals entirely free of gluten, with amaranth serving as a key component in these tests. Using a 23-factorial screening experimental design, the effects of different factors on the structural, textural, and sensory qualities of a gluten-free bread containing amaranth flour were assessed. The most influential factor was the amount of water, while variations in the

amount of fat had no discernible effect. The combination of fat and albumen, on the other hand, produced the best ratings in terms of overall sensory acceptance (Schoenlechner *et al.*, 2010).

While amaranth is mostly used in baked goods made with grain, additional applications for amaranth flour and its ingredients have also been investigated. Among the four developed food supplements in Kenya, the "high-nutritional-value product" containing amaranth grain, sweet potato, pigeon pea, groundnuts, and brown sugar was found to be the most acceptable. Its nutritional value is 453.2 kcal energy, 12.7 g crude protein (21% total essential amino acid), 54.3 g soluble carbohydrates, 20.8 g crude fat, 10.1 g crude fiber, 93.0 mg Calcium (Ca), 172.4 mg Magnesium (Mendoza *et al.*), 2.7 mg Zinc (Zn), 5.7 mg Iron (Fe), 0.8 mg vitamin $B_1$, 0.2 mg vitamin $B_2$, 7.9 mg niacin, 100 µg folic acid, and 140 µg retinol per 110 g (Kunyanga *et al.*, 2012).

**Table 2.1** Amaranth-based food products

| Product | Amaranth (%) | Other components |
|---|---|---|
| Biscuit | 0-30 | Buckwheat and corn flours |
| Cookie | 0-100 | Whole wheat flour |
| Porridge | 90 | Sorghum flour |
| Extruded porridge flour | 0-40 | Bean, maize, groundnut |
| Protein concentrate | 100 | - |
| Protein rich flour | 100 | - |
| Multi-grain health mix | 20-100 | Buckwheat, flax-grain, ragi |
| Composite flour | 5-30 | Wheat flour |
| Extrusion cooked flour | 100 | - |

Source: Malik *et al.* (2023)

## 2.8 Nutritional composition of amaranth

The chemical composition of whole amaranth grain is shown in the Table 2.2, where moisture is expressed in wet basis whereas other parameters are expressed in dry basis.

**Table 2.2** Chemical composition of whole amaranth grain

| Parameter | Values |
|---|---|
| Moisture (%) | 6.5-11.1 |
| Ash (%) | 2.2-3.5 |
| Fat (%) | 1.7-10.3 |
| Carbohydrate (%) | 40.5-87.1 |
| Protein (%) | 12.7-19.8 |
| Crude fiber (%) | 2.4-5.8 |
| Energy (kcal/ 100g) | 250.8-441.2 |
| Starch (%) | 49.5-73 |
| Thiamine (mg/ kg) | 0.3-0.9 |
| Riboflavin (mg/ kg) | 0.1-0.7 |
| Calcium (mg/ kg) | 1463-2000 |
| Magnesium (mg/ kg) | 2466.2-3280 |
| Iron (mg/ kg) | 65.4-660 |
| Phosphorous (mg/ kg) | 4731.25-6630 |
| Phytate (mg/ 100g) | 237.7-1440 |
| Tannin (mg/ 100g) | 1.2-1.6 |

Source: Akin-Idowu *et al.* (2017)

### 2.8.1 Protein

Comparing amaranth grains to wheat (13.5–14.5%), maize (10.6–13.8%), barley (10–14.9%), and oats (12.4–12.9%), they have a balanced amino acid composition with 15.4–16% protein and total essential amino acids of around 47.6 g/100 g protein. Compared to main cereals like wheat, rice, and maize (which, according to the FAO, have 8–11% protein), as well as other pseudo-cereals like buckwheat and quinoa, amaranth has a greater protein content (approximately 16%) (De Bock *et al.*, 2021).

It has been recommended by FAO/WHO because of its balanced amino acid profile, and also has higher sulfur-containing amino acids which are limited in pulses (Aderibigbe *et al.*, 2022). In major cereal grains, the endosperm is the predominant part where proteins are found, however in amaranth grains, the perisperm and embryonic parts are mostly where proteins are found. With a 1.5–2.0 protein efficiency ratio and a 90% overall digestibility in cooked grains, amaranth protein offers high nutritional value. The protein found in amaranth is made up of albumins and globulins, which are lower in glutamic acid and proline than prolamins but higher in important amino acids including lysine, methionine, cysteine, and histidine (Motta *et al.*, 2019).

### 2.8.2 Lipid and oil composition

The lipid content of amaranth grains ranges from 6.98 to 7.22%, of which 71.58 to 72.44% are unsaturated fatty acids (Alemayehu *et al.*, 2015). About twice as much saturated fatty acids (C16:0 and C18:0) are found in amaranth as in quinoa. Compared to main grains and oilseeds, amaranth grains are found to be poor in oleic and linolenic acids but abundant in palmitic acid (Jahaniaval *et al.*, 2000). Their unsaturated-to-saturated ratio of 27:10 is mostly caused by oleic and linoleic acids (Tang *et al.*, 2016). About 70% of amaranth oil is made up of oleic and linoleic acids, 20% is stearic acid, and the remaining 1% is linolenic acid (El Gendy *et al.*, 2018). Moreover, this oil has a special amount of squalene.

There are several health benefits of amaranth oil. Because this oil has higher amounts of polyunsaturated fatty acids (PUFAs), particularly long-chain omega-3 fatty acids, and lower levels of total cholesterol, triglycerides, LDL, and VLDL, a daily intake of 18 ml may help cure coronary heart disease and hypertension. Furthermore, this oil's strong antioxidant content may protect cellular membranes from oxidation (Martirosyan *et al.*, 2007).

### 2.8.3 Carbohydrates

Amaranth grains have a starch concentration of 65–75%, dietary fiber content of 4–5%, a sucrose level that is 2–3 times greater than wheat grains, and non-starch polysaccharide components. The main sugar in amaranth grains is sucrose, which is followed in importance by raffinose. Small levels of inositol, stachyose, and maltose are present in the grains (Venskutonis and Kraujalis, 2013). Approximately 50% of raw grains, popped grains, and flakes are made up of starch, which is the main ingredient of *A. cruentus* grains (Sindhu *et al.*, 2021). With an average diameter of 1.38 μm, its starch granules are even smaller than those of buckwheat, maize, and rice (Alonso-Miravalles and O'mahony, 2018). The majority of starch, at 97.9%, is made up of amylopectin, which is closely packed in grain structure (Radosavljevic and Zemun Polje, 2006). Moreover, amylase takes less time to break down amaranth starch (3 hours) than it does to break down maize. Its low amylose concentration also plays a significant role in determining its thermal, textural, and pasting characteristics (Singla *et al.*, 2020).

### 2.8.4 Minerals, vitamins, and other bioactive compounds

There are a lot of macro- and microelements in amaranth grains. With the exception of magnesium, which is twice as abundant in amaranth as it is in wheat, macro-mineral components are typically lower or equivalent to those found in wheat grains (Berghofer and Baracskai, 2009). Amaranth grains are a suitable alternative to typical cereals and a possible source of health-promoting bioactive components since they have greater levels of phytochemical content and antioxidant activity than oat, barley, wheat, corn, millet, and rice (Akin-Idowu *et al.*, 2017). It has been found that amaranth grains contain a significant quantity of important minerals, such as Fe (65 μg/g), Phosphorous (P) (330 μg/g), Ca (519.3 μg/g), and Mg (848 μg/g) (Bhat *et al.*, 2015). Amaranth contains zinc and iron, which boost the immune system and treat anemia, respectively, while magnesium and manganese are necessary for healthy baby development. When it comes to vitamins, thiamine, riboflavin, and niacin are crucial for healthy nerve function, blood capillary dilatation, gastrointestinal tract functioning, blood circulation, and the proper metabolism of proteins and carbohydrates. Vitamin B1, B2, B3, and C contents in amaranth grains are estimated to be 0.12, 0.20, 0.92, and 4.20 mg/100 g, respectively (Schmidt *et al.*, 2023).

With a concentration of 0.08 g/kg, amaranth is a good source of rutin (quercetin-3-O-rutinoside). This rutin may be essential for people on a diet. There have been studies to show that consuming 100 g of amaranth grains might increase daily intake of flavonoids (rutin) by 5–10 mg. As a result, amaranth has an excellent prospect of being used as a functional food (Kalinova and Dadakova, 2009). Amaranth grain methanolic extracts have antihelmintic, antihyperlipidemic, and antidiabetic properties; their water extracts have antifungal, antidiarrheic, and antimalarial properties. Amaranth grains also contain certain polyphenols, such as rutin, nicotiflorin, and isoquercetin (Angel Huerta-Ocampo and Paulina Barba De La Rosa, 2011).

Furthermore, amaranth contains antioxidants as evidenced by its DPPH, FRAP, and ORAC properties. Amaranth lacks β-carotene but is rich in other carotenoids, particularly lutein and zeaxanthin (Peiretti *et al.*, 2017). Pseudocereals have a larger capacity to scavenge radicals than cereals. Higher than that of rice and wheat, but lower than that of quinoa, is the inhibitory activity of the angiotensin-converting enzyme (Ani and Abel). Because of this, amaranth can be a useful grain alternative (Asao and Watanabe, 2010). Comparing amaranth to other grains, studies show that it has more important vitamins, minerals, and antioxidants. Additionally beneficial effects on low-density lipoprotein cholesterol and total cholesterol are shown with amaranth grains (Chmelík *et al.*, 2013).

### 2.9 Anti-nutritional factors

Although plant-based diets are a great source of nutrients, they also include some substances known as "anti-nutritional factors" that are produced by the metabolism of secondary plants. These substances can hinder the digestion, absorption, or utilization of nutrients, lowering the nutritional value of a range of plant-based meals. If ingested in excess, these components may also have detrimental effects on health. Certain anti-nutrients, such as tannins, saponins, phytate, oxalates, nitrates, and protease inhibitors, have also been discovered to be present in amaranth (Aderibigbe *et al.*, 2022). Amaranth grains have varying levels of phytic acid content (2.9–7.9 g/kg) and saponins (0.9–4.91 mg/kg) (Thakur *et al.*, 2021b). When compared to other common cereals like wheat and maize, amaranth has fewer trace quantities of protease inhibitors (chymotrypsin and trypsin) and more concentrated nitrates in the leaves than in the grains, making it a safer food to ingest (Rastogi and Shukla, 2013). While phytic acid helps plants retain phosphorus, these anti-nutritional chemicals hinder humans' ability to absorb nutrients. Nevertheless, they have protective benefits on plants

(Aderibigbe *et al.*, 2022). Because it cannot be broken down by humans, phytate cannot be used as a source of phosphate or inositol. Instead, it forms complexes with proteins that decrease the availability of these nutrients. Studies have shown that oxalate and phytate can hinder starch digestion in addition to interfering with the absorption of minerals. According to (Cuadrado *et al.*, 2019), saponins have the ability to form complexes with minerals like iron and zinc, whereas oxalate can bind to calcium and reduce its absorption.

## 2.10 An overview of drying

Throughout history, drying has been a common practice that dates back to the dawn of civilization. It's interesting to note that knowledge about drying and storing crops developed sufficiently before crop cultivation was discovered, but scientific studies on crop production began before such studies on drying and storage (Bala, 2016).

The annual loss of grain from harvest to consumption is estimated to be between 10 and 25 percent; the amount varies depending on the country. Developing countries have higher losses due to favorable climates that cause stored grain to deteriorate and also to a lack of knowledge about drying (Bala, 2016). While great efforts are being made to increase crop productivity, little or no effort has been made to develop grain drying and storage, especially in developing countries, where food shortages are acute and the need is for food, not production statistics. Since post-harvest loss is proportionate to production and rises with increased production, a program to reduce drying and storage loss could likely result in a 10–20% increase in the amount of food available in some developing countries, which could also be used to feed the hungry in those countries (Bala, 2016).

### 2.10.1 Drying of grain kernel

Drying is the removal of moisture to the safe moisture content. In general, drying is the process of applying heat to remove moisture from grain in order to preserve its quality while preventing the growth of bacteria, fungus, insects, and mites. Heat is normally supplied to the grain by heated air naturally or artificially, and the vapor pressure or concentration gradient thus created causes the movement of moisture from inside of the kernel to the surface (Bala, 2016). The air removes the evaporated moisture. The drying capacity of air is dependent on temperature, grain moisture content, the relationship between grain moisture content and the relative humidity of the drying air, as well as the kind and maturity of the grain. Depending on the intended application of the grain, the drying air temperature must

be below a few specified values. The grain changes chemically and physically when the drying temperature is too high (Bala, 2016).

### 2.10.2 Importance of drying

- Grain may be stored for an extended period of time without losing quality by drying it out.
- Farmers that use drying techniques are able to produce higher-quality goods for both sale and consumption.
- By using drying, the product may be continuously supplied all year long and can benefit from increased prices following harvest.
- Drying allows farmers to use and sell higher-quality seeds while preserving the viability of the seeds (Bala, 2016).

### 2.10.3 Cabinet drying

Batch drying is the basis for how cabinet grain dryer work. These are the most often used drier types in the small-scale grain drying sector. In comparison to alternative drying techniques, they are reasonably priced and cover a broad variety of grains (Stephen and Emmanuel, 2009).

#### 2.10.3.1 Components of the cabinet grain dryer

The cabinet grain dryer is made up of three major components, namely:

- The energy supplier
- The burner
- The drying chamber

The energy supplier: This component consists of two gas bottles with hoses attached to them. The gas bottles are housed in a metallic box and each has a 75 L capacity. Gas is supplied by the hoses from the gas bottles to the burner, which produces heat.

The burner: The dryer generates heat using a five chambers burner arrangement. When gas is delivered from the gas bottle, switches in the burner have a sparking mechanism that ignites the gas.

The drying chamber: The section of the drier where the grains to be dried are fed and dried is called the drying chamber. Initially, the grains are put onto trays, which are subsequently put into the drying chamber. The heat supplied from the burner is transferred to the drying chamber by the principle of conduction (Stephen and Emmanuel, 2009).

#### 2.10.3.2 Principle of operation of the existing cabinet grain dryer

After the grains are placed onto the trays and fed into the drying chamber, the door is closed to seal the system and the grains are ready to be dried. The food particle size determines whether the trays' bottoms are solid or perforated. After that, the gas knob is turned to allow gas to enter the burner through the hoses. The burner features a switch that, when turned clockwise, activates a sparking mechanism. The drying chamber is heated by the spark that the switch's clockwise movement creates, which ignites the gas and creates a pale blue flame. Grain moisture evaporates through an outlet and into the surrounding air (Stephen and Emmanuel, 2009).

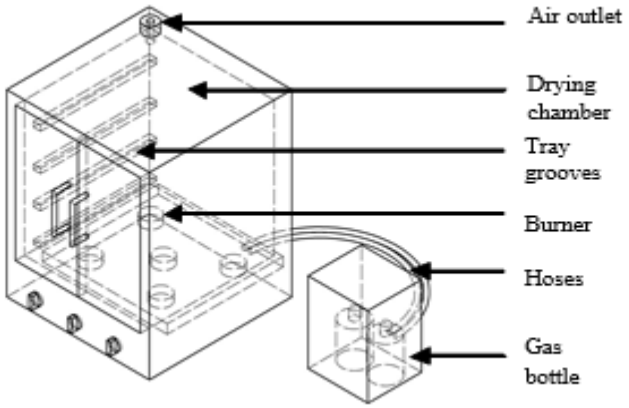


**Fig. 2.3** Diagram of the existing cabinet grain dryer

### 2.11 Drying modeling

Mathematical modeling is the process of constructing mathematical objects whose behaviors or properties correspond in some way to a particular real-world system. For designing the different types of dryers and selecting drying conditions, there is a need to develop

mathematical models to predict moisture content and drying rate. Generally, drying behavior could be seen as graphically. Numerous efforts have been made to develop empirical mathematical models. The moisture content curve could not explain drying behavior better than that of moisture ratio curve. The moisture ratio curve could be described as drying behavior with good results as compared to moisture content curve. Moisture ratio curve was used for describing drying behavior in many researchers relate to thin drying (Javeed Akhtar and Omre, 2017b).

For a good description of drying kinetics of food products, it is required to establish an appropriate mathematical model and find numerical values for the model parameters (Efremov, 2002). The most appropriate tool for characterizing the drying parameters of most food products is by use of the thin layer drying procedure (Akgun and Doymaz, 2005; E. K. Akpinar *et al.*, 2003b). Currently, the categories of thin layer drying models that are used for describing the drying characteristics of agricultural products include; empirical, theoretical and semi-theoretical models (Midilli *et al.*, 2002).

### 2.11.1 Theoretical models

The theoretical models consider both the external and internal resistance to moisture transfer. They involve the geometry of the material, its mass diffusivity, and the conductivity of the material. It is further subdivided into two groups, distributed model and lumped parameter models (Cihan and Ece, 2001).

### 2.11.2 Semi-theoretical or semi-empirical models

Semi-theoretical models, which are valid under experimental conditions, are often generated by simplifying general series solutions of Fick's second law or by modifying simplified models (Panchariya *et al.*, 2002). The drying temperature, drying air velocity, material thickness, initial moisture content, and relative humidity are some of the variables that may affect the application of these models (Erbay and Icier, 2010). Furthermore, under these conditions, it can be noted that the complexity of the models can be attributed to the number of constants, i.e., greater the number of constraints more complex will be the model, and hence it is difficult to understand the mechanism. Based on products nature, it is further subdivided into two groups;

#### 2.11.2.1 Models derived from Newton's law of cooling

**A. Lewis model**

According to Lewis (1921), the change in the material's moisture content in the falling rate period during the drying of porous hygroscopic materials is proportional to the instantaneous difference between the material's moisture content and the expected moisture content when it comes into equilibrium with drying air. So, this concept assumed that the material is thin enough, or the air velocity is high, and the drying air conditions such as the temperature and the relative humidity are kept constant.

$$\frac{dM}{dt} = -k\,(M - M_e)$$

Where, k is the drying constant ($s^{-1}$). The combination of drying transport characteristics such mass coefficients, moisture diffusivity, thermal conductivity, and interface heat results in the drying constant in the thin layer drying concept.

According to Newton's law of cooling, there is very little internal resistance to moisture transport and, consequently, moisture gradients inside the material. Only the surface resistance is taken into account (Madamba, 2003). Assuming a boundary condition as M = $M_o$ at t = 0, the solution of the above equation can also be rewritten as:

$$MR = \frac{M - M_e}{M_o - M_e} = \exp(-kt)$$

**B. Page model**

The Page model, also known as the Modified Lewis model, is an empirical version of the Newton model in which the dimensionless empirical constant (n) is added to significantly reduce the mistakes that arise when applying the Newton model. This parameter modifies the time, and in this instance, the model produces superior moisture loss forecast results (İ. Doymaz and İsmail, 2011).

$$MR = \frac{M - M_e}{M_o - M_e} = \exp(-kt^n)$$

**C. Modified Page model**

This is a variation of the Page model, as the name suggests. The Modified Page model was described in three different variations by Erbay and Icier (2010). According to Erbay and Icier (2010) the following modified Page model has been shown to be the best appropriate among them to describe how various fruits and vegetables behave after drying.

$$MR=\frac{M-M_e}{M_o-M_e}=\exp(-(kt)^n)$$

### 2.11.2.2 Models derived from Fick's Second law of diffusion

**A. Henderson and Pabis model**

The general solution of Fick's second law of diffusion begins with this model. Although it often seems to be less effective for the last stages of the process, this model accurately forecasts the drying rate at the start of the drying process (Dissa *et al.*, 2008).

$$MR=a\ \exp(-kt)$$

$$a=\frac{6}{\pi^2}$$

$$K=-\frac{\pi^2 D_{eff}}{r^2}$$

Where, r is the thin layer half-thickness (m), $D_{eff}$ is the moisture diffusivity ($m^2/s$) and, t is the time (h), respectively. The slope of this model, k is related to effective diffusivity when drying process takes place only in the falling rate period and liquid diffusion controls the process.

**B. Logarithmic model**

Another modified version of the Henderson and Pabis model, this one is sometimes referred to as an asymptotic model. It is the Henderson and Pabis model in logarithmic form with the addition of an empirical term. According to research, this model ranks fourth among thin-layer models for explaining the kinetics of drying different fruits and vegetables (Kaur and Singh, 2014).

$$MR=a\ \exp(-kt)+c$$

Where, c is a dimensionless empirical constant.

**C. Two-term model**

The two-term model is a second term general solution of Fick's second law of diffusion. Two dimensionless empirical constants and two model constants that may be obtained from experimental data are included in the model. The first term describes the last part of the drying process, while the second term describes the beginning of the drying process. This model can work effectively for most high-moisture fruits and vegetables since it assumes constant product temperature and diffusivity during the drying process (Sacilik, 2007).

$$MR=a \exp(-kt)+b \exp(-gt)$$

Where, a and b are dimensionless empirical constants, and k and g are the drying constants ($s^{-1}$).

**D. Two-term exponential model**

The two-term exponential model is a variant of the two-term model by modifying the indication of shape constant (b) of the second exponential term and by decreasing the number of constants. Erbay and Icier (2010) emphasized that constant b of the two-term model has to be (1-a) at t = 0 in order to obtain a moisture ratio of MR=1.

$$MR=a \exp(-kt)+(1-a)\exp(-kat)$$

### 2.11.3 Empirical models

Empirical models give a direct relationship between the average moisture content and drying time. Semi-theoretical models and empirical models have many similar traits. They provide just a limited amount of information regarding the product's drying characteristics and are heavily dependent on the experimental setup (Erbay and Icier, 2010). Dimensional analysis and experimental data serve as the foundation for the empirical approach. Since they rely on experimental data, they can be simply applied to drying simulation. Only the exterior resistance to moisture transfer between the product and air is taken into account in empirical models (Onwude *et al.*, 2016).

## 2.12 Effective moisture diffusivity

In the modeling of the drying process of fruits and vegetables, the effective moisture diffusivity—a function of temperature and moisture content of material— is an important

transport property. Effective moisture diffusivity is determined experimentally using Fick's second rule of diffusion. The simplified form of Fick's second law of diffusivity is given as:

$$\ln(MR) = \ln\left(\frac{M-M_e}{M_o-M_e}\right) = \ln\left(\frac{6}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{r_s^2}\right)t$$

by comparing the above equation to y = mx + c,

$$y = \ln(MR)$$

$$m = \frac{\pi^2 D_{eff}}{r_s^2}$$

Where, r is the thin layer half-thickness (m), $D_{eff}$ is the moisture diffusivity ($m^2/s$) and, t is the time (h), respectively. Experimental evidence shows that the diffusion coefficient increases with the temperature of the drying air. The temperature dependence can be expressed by an Arrhenius type equation (E. K. Akpinar *et al.*, 2003b).

$$D_{eff} = D_o \exp\left(-\frac{E_a}{RT_a}\right)$$

Where, $E_a$: the energy of activation (kJ/mol),

R: Universal gas constant (8.3143 J $mol^{-1}$ $K^{-1}$),

$T_a$: Absolute air temperature (K), and

$D_o$: The pre-exponential factor of the Arrhenius equation ($m^2/s$).

Moisture diffusivity of different food stuff has been summarized by Zogzas *et al.* (1996). According to Shi *et al.* (2008), the effective moisture diffusivity is dependent upon the temperature of the drying due to the increased activity of water molecules.

### 2.13 Procedure for finding best fit model

The following steps should be taken into account in order to choose the best model explaining the behavior and circumstances of thin layer drying for every given application (E. K. Akpinar *et al.*, 2003b).

i. Compute the correlation coefficient, coefficient of determination, adjusted $R^2$, reduced chi-square, and root mean square error values.

ii. Determine and select the highest values of the correlation coefficient and the coefficient of determination.

iii. Determine and select the lowest values of the chi-square, the root mean square error.

iv. Choose the drying curve model whose values for the criterion in Step ii and Step iii have the greatest and lowest values, respectively. This model can be assumed to be the best model describing the thin-layer drying curve.

# Part III

# Materials and methods

## 3.1 Materials

### 3.1.1 Chemicals and apparatus

All the chemicals, laboratory glassware and equipment used for the study were obtained from the laboratory of Central Campus of Technology. The apparatus and chemicals required are listed in Appendix E.

### 3.1.2 Sample collection

Amaranth seed of mixed (white and red) variety was purchased from Kathmandu organics, a grocery store in Kathmandu, Nepal.

## 3.2 Methods

### 3.2.1 Drying

The experiment was carried out under ambient condition in a cabinet dryer (PCD-E3000 Serials, volts- 220V) containing an air fan. In a study by Calzetta Resio *et al.* (2005), temperature range of 40 °C to 70 °C were used to dry the amaranth grain. Previous studies showed that drying at temperatures between 60 and 115 °C induced a two- to three-fold increase in breakage susceptibility (Hawkins *et al.*, 2005). Drying temperatures above 60 °C led to a significant reduction in germination and an increase in the number of stress cracks of hybrid maize grains. Drying at 100 °C increases internal compaction between the starch granules and the protein, in addition to causing deformation in the starch granules and reduced starch extraction. Among the dried samples, the increase in drying temperature reduced digestibility, but the lower starch digestibility was achieved on the oven-drying of popcorn grains at 30 °C (Ziegler *et al.*, 2020).

Taking all these factors into consideration, lowest temperature of 40 °C and highest temperature of 60 °C was taken in this study. Therefore, the drying experiments was done at temperatures of 40 °C, 50 °C, and 60 °C. The drying process was carried out until constant weight was obtained for three consecutive readings and the readings were taken at 30 min intervals. Once the process was completed, the samples of dried amaranth seeds were stored

in moisture proof LDPE zipper bags for physical analysis. The dried grain samples were grinded to powdered form and stored in LDPE zipper bags for further analyses.

#### 3.2.1.1 Drying kinetics

Drying kinetics is the transport of mass and heat during drying, which is influenced by temperature, drier type, and sample characteristics (Pandiselvam *et al.*, 2024). Several studies by Agarry (2016); (Torres-Ossandón *et al.*, 2018) suggested that drying models can help determine the optimal temperature and duration for achieving desired moisture content in various food items. So, to understand the suitable model for the drying characteristics of the samples, the experimental data were fitted in six models described in Table 3.1.

**Table 3.1** Mathematical drying models

| Models | Equation | References |
|---|---|---|
| Henderson and Pabis | MR=a exp(-kt) | (Aregbesola *et al.*, 2015) |
| Newton | MR=exp(-kt) | (Kingsly *et al.*, 2007) |
| (Midilli *et al.*, 2002) | MR=a exp(-kt$^n$)+bt | (Midilli *et al.*, 2002) |
| Two term exponential | MR=a exp(-kt)+(1-a) exp (-kat) | (Saeed *et al.*, 2008) |
| Logarithmic | MR=a exp(-kt)+c | (Toğrul and Pehlivan, 2003) |
| Page | MR=a exp (-ktn) | (Ismail and Ibn Idriss, 2013) |

These models show relationship between moisture ratio and drying time. Moisture ratio during the thin layer drying was calculated using equation 1 (Javeed Akhtar and Omre, 2017a).

$$MR=\frac{M-M_e}{M_o-M_e} \qquad (1)$$

Where, M is the moisture content at time 't' of the drying process and $M_o$ is the initial moisture content and $M_e$ is the equilibrium moisture content.

Drying rate (DR) is the quantity of moisture evaporated with respect to time (Demiray *et al.*, 2023). Equation 2 was used to calculate the drying rate throughout the drying process:

$$DR=\frac{M_t-M_{(t+dt)}}{dt} \qquad (2)$$

Where, $M_t$ is the moisture content (g water/g dry matter) at any time t, $M_{(t+dt)}$ is the moisture content (g water/g dry matter) at time (t+dt), and dt is the drying time (min).

### 3.2.1.2 Estimation of the drying models constants

The drying model constants was estimated using a non-linear regression analysis. The reliability of the models was verified using statistical criteria such as coefficient of determination ($R^2$), reduced chi-square ($\chi^2$), and root mean square error (RMSE). A good fit is said to occur between experimental and predicted values of a model when $R^2$ is high, and $\chi^2$, and RMSE are lower (Ajala and Ajala, 2014; Demir *et al.*, 2004). The statistical criteria to test the reliability of the models are as follows:

$$\chi^2=\frac{\sum_{i=1}^{N}(MR_{(exp,\ i)}-MR_{(pred,i)})^2}{N-n} \qquad (3)$$

Where, N is the total number of experiments and n is the number of constants in the drying model.

$$RMSE=[\frac{1}{N}\sum_{i=1}^{N}(MR_{(pred,i)}-MR_{(exp,i)})^2]^{1/2} \qquad (4)$$

$$R^2=\frac{\sum_{i=1}^{N}(MR_{exp,i}-MR_{exp})(MR_{pre,i}-MR_{pre})}{\sqrt{[\sum_{i=1}^{N}(MR_{exp,i}-MR_{exp})^2\sum_{i=1}^{N}(MR_{pre,i}-MR_{pre})^2]}} \qquad (5)$$

### 3.2.1.3 Determination of moisture diffusivity

The equation (6) was used for diffusivity which was compared as y= mx+c from the ln (MR) vs time plot (Sousa *et al.*, 2024).

$$\ln\left(\frac{X}{X_0}\right)=\ln\left(\frac{8}{\pi^2}\right)-\frac{\pi^2}{4L^2}D_{eff}\times t \qquad (6)$$

The equation can further be written as:

$$m = -\frac{\pi^2}{4L^2} D_{eff} \times t \qquad (7)$$

where, m is the slope, $D_{eff}$ is the effective diffusivity ($m^2/s$), and L is the half thickness of slab (m).

#### 3.2.1.4 Determination of activation energy

The effective moisture diffusivity is related to temperature by Arrhenius equation (E. Akpinar *et al.*, 2003a);

$$D_{eff} = D_0 \exp\left[-\frac{E_a}{R(T+273.15)}\right] \qquad (8)$$

Where, $D_0$ is the constant of Arrhenius equation in ($m^2/s$), $E_a$ is the energy of activation in (kJ/mol), R is the universal gas constant (8.314 J $mol^{-1}$ $K^{-1}$) and T is the temperature in (°C). The rearranged form of the equation (8):

$$\ln(D_{eff}) = \ln(D_0) - \frac{E_a}{R(T+273.15)} \qquad (9)$$

The activation energy was calculated using the curve between ln ($D_{eff}$) versus 1/(T+273.15).

### 3.2.2 Analytical procedures

#### 3.2.2.1 Physical properties of amaranth

Amaranth was analyzed for the following physical characteristics:

##### 3.2.2.1.1 Bulk density

A five-gram sample of amaranth was precisely weighed and then placed in graduated measuring cylinders. 5 ml was deducted from the total volume to record the sample volume. The bulk density was calculated as weight per unit volume (g/ml) (Grundy *et al.*, 2020). It was calculated by using the following equation:

Bulk Density (g/ml) = (Mass of sample and graduated cylinder) – (Mass of graduated cylinder)/ Volume of sample)

#### 3.2.2.1.2 True density

A 100 ml graduated measuring cylinder was filled with 50 ml of water, and a known weight of sample was immersed in the water. The volume of water that was displaced was measured and recorded (Karababa and Coşkuner, 2013).

Pt = weight of sample/ volume of displaced water

Where, Pt = true density

#### 3.2.2.1.3 Porosity

The method of Varnamkhasti *et al.* (2008) was used to compute porosity, based on the true density and bulk density.

$\varepsilon = (Pt- Pb)/Pt \times 100$

where, ε = porosity, Pt = true density and Pb = bulk density.

#### 3.2.2.1.4 Thousand kernel weight

The weight of a thousand grain was calculated by taking 100 grains at random from the entire sample, weighing them using a digital electronic balance with an accuracy of 0.001 g, obtaining the mass of 1000 grains by multiplying by 10 (Altuntaş *et al.*, 2005).

#### 3.2.2.1.5 Angle of repose

The angle with the horizontal at which the material will stand when stacked up is known as the angle of repose. A topless and bottomless cylinder with known dimensions was used to calculate the angle of repose. The cylinder was placed at the center of a raised circular plate, which was then filled with amaranth grains. The cylinder was gradually lifted until the grains on the circular plate with a known diameter formed a cone. After that, the cone's height and radius was measured to determine the angle of repose (Kaleemullah and Gunasekar, 2002) using the following relationship:

$\theta = \tan^{-1} 2(H/D)$

Where, θ= Angle of repose, degrees,

H= Height of cone formed, mm, and

D= Diameter of cone, mm

#### 3.2.2.2 Determination of functional properties

##### 3.2.2.2.1 Determination of swelling capacity

Swelling capacity was calculated using the techniques described by Lagnika *et al.* (2019). 0.3 g of sample in 10 ml of distilled water was allowed to stand in a water bath at 60 ℃ for 30 min, then the mixture was allowed to cool and then centrifuged for 20 min at 3000 rpm. After discarding the supernatant, the residue was weighed. The following formula was used to calculate swelling capacity:

$$\text{Swelling capacity} = \frac{\text{weight of residue}}{\text{weight of flour}}$$

##### 3.2.2.2.2 Determination of dispersibility

Dispersibility was measured by following the process mentioned by Oluwole *et al.* (2016). 10g sample was dispersed in distilled water in a 100 ml measuring cylinder, and distilled water was added up to the 50 ml mark. The mixture was rapidly agitated and allowed to settle for 3h. The volume of settling particles was measured, and the % dispersibility was computed as follows:

$$\%\ \text{Dispersibility} = \frac{(50 - \text{volume of settled particles})}{50} \times 100$$

##### 3.2.2.2.3 Water absorption capacity (WAC)and oil absorption capacity (OAC)

WAC and OAC was measured by following the process as described in Modipuram (2013). To measure the water absorption capacity, 1 g of sample and 10 ml of distilled water were combined, then mixed in vortex shaker for 30 s and allowed to remain at room temperature for 30 min. In a centrifuge, the mixture was spun for 10 min at 2000 rpm. Supernatants were thrown away. Using refined soybean oil, a similar process was followed to calculate oil absorption capacity. Water and oil absorption capacity was expressed as percent water bound per gram of the sample. before

$$\text{WAC} = \frac{(\text{weight of sample after centrifugation-weight of sample before centrifugation})}{\text{weight of sample}} \times 100$$

$$\text{OAC} = \frac{(\text{weight of sample after centrifugation-weight of sample before centrifugation})}{\text{weight of sample}} \times 100$$

#### 3.2.2.2.4 Bulk density

Bulk density was determined by measuring 10 ml capacity graduated cylinder, weighed and recorded. The cylinder was filled with the flour sample and tapped gently from the bottom for 30 times until there was no further dimension of the sample level and calculated using method of Mandge *et al.* (2014).

$$\text{Bulk density (g/ ml)} = \frac{\text{weight of flour}}{\text{Volume of flour after tapping}}$$

### 3.2.2.3 Proximate analysis of amaranth

Parameters like digestible crude protein (DCP), total organic matter, total carbohydrates, and nitrogen-free extract were estimated on a dry matter basis using the methods outlined by Mondal *et al.* (2020) for wheat and Sood *et al.* (2023) for millet.

1. DCP = (0.916 × CP) -3.09

2. NFE (%) = 100 - (CP (%) + CF (%) + EE (%) + ash (%))

3. TOM = NFE + CF (crude fiber) + EE (crude fat) + CP (crude protein)

4. TC= NFE + CF

#### 3.2.2.3.1 Moisture content

The hot air oven technique was used to determine the moisture content. A 5 g sample was weighed and heated in an insulated oven at 110 °C to a constant weight. The amount of water that would evaporate was represented by the weight differential (AOAC, 2023).

#### 3.2.2.3.2 Protein content

The nitrogen content was determined by using Kjeldahl method, and it was multiplied by a factor of 6.25 to determine the crude protein (AOAC, 2023).

#### 3.2.2.3.3 Fat content

The fat content of the samples was determined by using the Soxhlet apparatus as described in AOAC (2023).

#### 3.2.2.3.4 Ash content

The ash content was determined by incinerating the amaranth (5 g) in a muffle furnace at 525 ºC for 4-6 h (AOAC, 2023).

#### 3.2.2.3.5 Crude fiber content

A chemical procedure was used to determine crude fiber; the sample was first treated with boiling dilute sulphuric acid, then with boiling sodium hydroxide, and finally with alcohol as the standard method of AOAC (2023).

#### 3.2.2.3.6 Energy

The energy was calculated by using the formula as per AOAC (2023). The energy was calculated as kcal per 100 g.

Gross energy (kcal/100 g) = Fat × 9 + T.C × 4 + Protein × 4

#### 3.2.2.3.7 Free fatty acid (FFA)

The FFA content of the stored samples was determined as per the AOAC (2023) method. Fat from the powdered sample was extracted using petroleum ether. To the known amount of fat, an equal volume of warm neutral alcohol and petroleum ether were added along with few drops of phenolphthalein indicator and titrated against 0.1 N NaOH. The results were expressed in terms of oleic acid equivalents.

$$\text{Free fatty acid (\% as oleic acid)} = \frac{\text{ml of alkali} \times \text{N of alkali} \times 28.2}{\text{weight of fat (g)}}$$

Where, N= Normality

#### 3.2.2.3.8 Determination of acid value (AV)

The acid value was determined based on the method described by Rose *et al.* (2008). The acid value (AV) was expressed as mg potassium hydroxide (KOH) required to neutralize the free fatty acids in 1 g of oil.

### 3.2.2.4 Anti-nutritional factors determination of amaranth

#### 3.2.2.4.1 Determination of oxalate

The 0.1 g sample was mixed with 30 ml of 1 M HCL. After that, each mixture was shaken for 30 min at 100 °C in a water bath. To precipitate out the calcium oxalate, 0.5 ml of 5% $CaCl_2$ was added to each mixture and stirred thoroughly. The supernatant was separated from the mixture after it was centrifuged for 15 min at 3000 rpm. The pellet was then washed twice with 2 ml of 0.35 M $NH_4OH$, then dissolved in 10 ml 0.5 M $H_2SO_4$. The solution was then titrated, using a standard solution of 0.1 M $KMnO_4$ at 60 °C to a faint violet color that persisted for at least 15 s (Patel and Dutta, 2018).

#### 3.2.2.4.2 Determination of phytate

A 250 ml conical flask was filled with the 0.2 g sample. The material was soaked for 3 h in 100 ml of 20% concentrated HCl, and the sample was then filtered. 100 ml of distilled water was added to 50 ml of the filtrate that had been transferred to a 250 ml beaker. Then, 10 ml of 0.3% ammonium thiocyanate solution was added as an indicator and titrated with a standard iron (III) chloride solution (Emmanuel and Deborah, 2018).

#### 3.2.2.4.3 Determination of tannin

The detection of the blue color produced by tannin-like substances reducing Folin-Ciocalteu reagent in alkaline condition is the basis for colorimetric estimation of tannins. Test tubes was filled with 0.1 ml of prepared sample extract, and each was then added with 7.5 ml of water. The volume was then increased to 10 ml by adding 1 ml of $Na_2CO_3$ solution and 0.5 ml of Folin-Ciocalteu reagent. After then, color was measured after 30 min at 760 nm (AOAC, 2023).

#### 3.2.2.4.4 Determination of saponin

The saponin analysis was conducted by following the process as described in Ayo *et al.* (2016). A 250 ml beaker was filled with 1 g of the finely powdered material and 100 ml of isobutyl alcohol. For two hours, the mixture was shaken to ensure even mixing. After that, the mixture was increased to 250 ml in a 250 ml standard flask by filtering it through Whatman No. 1 filter paper into a 100 ml beaker and adding 20 ml of a 40% saturated solution of magnesium carbonate. To get a clear, colorless solution, the mixture made with saturated $MgCO_3$ was once again filtered using Whatmann No. 1 filter paper. After pipetting 1 ml of the colorless solution into a 50 ml volumetric flask, 2 ml of 5% $FeCl_3$ solution was added, and the volume was adjusted with distilled water. It was let to stand for 30 min in order for the blood red color to appear. From the saponin stock solution, 0–10 ppm standard saponin was prepared. 2 ml of 5% $FeCl_3$ were added to the standard solutions respectively. Following color development, the absorbance of the sample and the standard saponin solution were measured using a spectrophotometer set at 380 nm. Saponin content was measured as saponin equivalent.

### 3.2.2.5 Determination of phytochemicals

#### 3.2.2.5.1 Determination of total phenolic content (TPC)

TPC determination was carried out by following the process as described in Mahdavi *et al.* (2010). 1 g of fresh ground sample was extracted using 25 ml of methanol, and the resulting extracts was shaken for 3 h at room temperature in a rotary shaker. After passing the extract through Whatmann No. 1 filter paper, the filtrate was kept at 4±2 ºC until use. Next, 2.5 ml of Folin- Ciocalteu reagent was added to 0.5 ml of the concentrated solution, and 5 min later, 2.5 ml of $Na_2CO_3$ (7.5% w/v) was added. The mixed sample was incubated in an incubator at 45 ºC for 45 min. The absorbance was measured at 765 nm against a reagent blank. Using a known concentration of gallic acid, a standard calibration plot was generated. The concentrations of phenolic content in the test samples were calculated from the calibration plot and expressed as mg of gallic acid equivalent (GAE)/ g of dry weight.

#### 3.2.2.5.2 DPPH radical scavenging activity

Spectrophotometric method was used to determine the DPPH free radical scavenging activity of amaranth extract (Casagrande *et al.*, 2007). In short, 2 ml of 0.1 mM DPPH

solution (4 mg DPPH of 100 ml methanol) was mixed with 1 ml of the extract. After the mixture was sealed, it was then left in the dark for 30 min. The absorbance was then measured with a UV Vis spectrophotometer at a wavelength of 517 nm. Finally, the following equation was used to calculate the percentage scavenging activity:

$$\% \text{ scavenging activity} = \frac{(Ac - As)}{Ac} \times 100$$

where Ac and As refer to absorbance of control and test samples, respectively.

#### 3.2.2.5.3 Total flavonoid content (TFC)

TFC of amaranth was determined using a modified aluminum chloride assay method as described in Rebaya *et al.* (2015). 4 ml of distilled water, 0.3 ml of 5% sodium nitrate, and 1 ml of amaranth extract was mixed together. After a 5 min duration, 0.6 ml of 10% aluminum chloride was added to the mixture, and it was once more let to stand for 5 min. Lastly, 2 ml of 1 M sodium hydroxide was added, and then distilled water was added to make up the volume to 10 ml. The liquid was well mixed after 15 min time, and the absorbance was determined at 510 nm using a UV Vis spectrophotometer. Likewise, absorbance values was determined for standard quercetin solutions (20, 40, 60, 80, and 100 µg/ml) and calibration curve was drawn.

#### 3.2.2.5.4 Total alkaloid content

5 g of the samples were mixed with 200 ml of 10% acetic acid in ethanol, covered, and left to stand for 4 h. Whatman No. 1 filter paper was used to filter the mixture, and a water bath set at 100 °C was used to concentrate the filtrate to a fourth of its initial volume. Next, drops of concentrated ammonium hydroxide was added and precipitates were formed. These precipitates were filtered, washed with dilute ammonium hydroxide, dried in an oven, and weighed. Alkaloid concentration was given as milligrams per kilogram dry weight of the sample (Bukuni *et al.*, 2022).

$$\text{Alkaloid content (mg/kg)} = \frac{\text{weight of alkaloids}}{\text{weight of sample}} \times 100$$

#### 3.2.2.5.5 L-ascorbic acid (Vitamin C)

Vitamin C content was determined by standardization of 2,4-dichloroindophenol dye followed by the titration of extract solution against the standardized dye as mentioned in AOAC (2023).

$$\text{mg\% ascorbic acid} = \frac{\text{Titer} \times \text{dye factor} \times \text{volume made up}}{\text{ml of aliquot} \times \text{ml or g of sample taken}} \times 100$$

### 3.2.2.6 Determination of mineral content

#### 3.2.2.6.1 Acid-insoluble ash

Ash content was cooked with 25 ml of HCL for AIA determination as mentioned in AOAC (2023).

$$\text{Acid-insoluble ash (\%, db)} = \frac{\text{Acid-insoluble ash (g)} \times 100 \times 100}{\text{Sample (g)} \times \text{Dry matter(\%)}}$$

#### 3.2.2.6.2 Calcium content

Calcium content was determined by the titration process with $KMnO_4$ as mentioned in AOAC (2023).

#### 3.2.2.6.3 Phosphorous content

Phosphorous content was determined by titration process with NaOH as mentioned in AOAC (2023).

## 3.3 Statistical methods

All the analyses were performed in triplicate. Statistical tests were performed using statistical software SPSS. Microsoft Excel 2019 was used for graphical representation of the obtained results and preparation of drying curves. Statistical significance of differences among the means was determined using one-way analysis of variance ANOVA with Tukey's post-hoc test at a significance level of $p<0.05$. For mathematical modeling, the different semi theoretical equations were tested to select the best model for describing the drying process. The model parameters estimation was carried out by a nonlinear regression using the Solver tool in Microsoft Excel 2019 (Ghimire *et al.*, 2021). The goodness of fit of the tested mathematical models on the experimental data were evaluated using coefficient of

determination ($R^2$) and chi square test ($\chi^2$), root mean square error (RMSE). Higher $R^2$ value and lower $\chi^2$ and RMSE values indicates a better fit. XLSTAT 2024 data analysis add-on in Microsoft excel 2019 was used for preparation of bi-plot and clusters.

# Part IV

## Results and discussion

The present study was conducted to help optimize the drying process by understanding the drying kinetics, to achieve maximum efficiency and quality. The variation in drying temperature can significantly impact various properties of amaranth seeds, which are important to understand for consumer acceptance and shelf-life stability. Study of anti-nutritional factors was carried out to ensure that the drying process reduces or eliminates these compounds, which can interfere with nutrient absorption and health outcomes. The raw amaranth seeds and the three samples dried at 40°C, 50°C and 60°C were analyzed for physical, functional, nutritional and anti-nutritional properties. The drying kinetics of the amaranth seeds were evaluated at the temperatures of 40°C, 50°C and 60°C. Results and discussion of the overall study are described in the following headings.

### 4.1 Effect of different drying temperatures on moisture ratio

Fig. 4.1 shows the variation of moisture ratio with drying time at different temperatures of 40, 50 and 60 ºC.

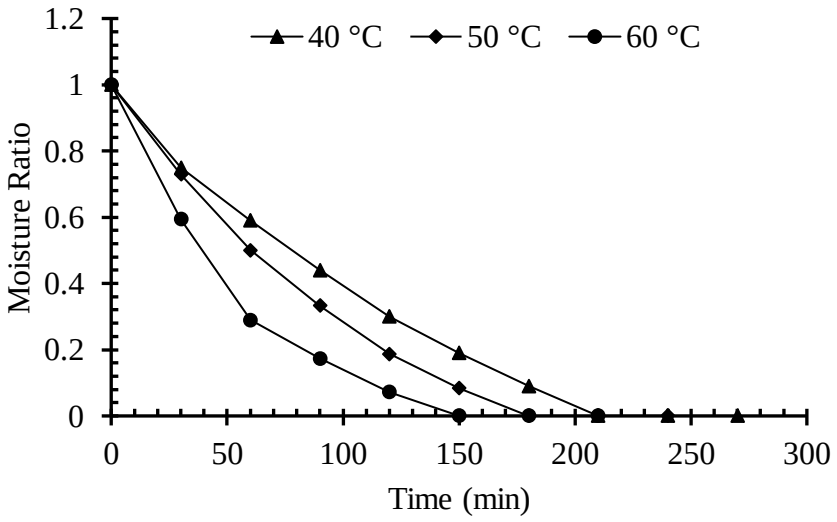


**Fig. 4.1** Moisture ratio of amaranth seed at different temperatures

Dimensionless moisture ratio was calculated from the data obtained from drying and then plotted against time. It was observed that the moisture ratio decreased with the increase in drying time. The attainment of equilibrium moisture content was denoted by the value of MR being zero.

### 4.2 Effect of different drying temperatures on rate of drying

The drying temperature had a substantial effect on the drying rate of amaranth seed. The drying rate increases at high temperatures due to the excitation of molecules in the samples (Jamali *et al.*, 2006). The rate of drying may depend not only on temperature but also on the relative humidity, initial moisture content of the product, air velocity, and the nature of the product (Zhao *et al.*, 2019). As the temperature rises, the water molecules in the sample move faster, increasing the distance between them and indirectly decreasing their attractive forces. Thus, raising the drying temperature increases the quantity of moisture removed from the samples (Poudel, 2018). The drying curve of drying rate versus moisture is shown below in the Fig. 4.2.

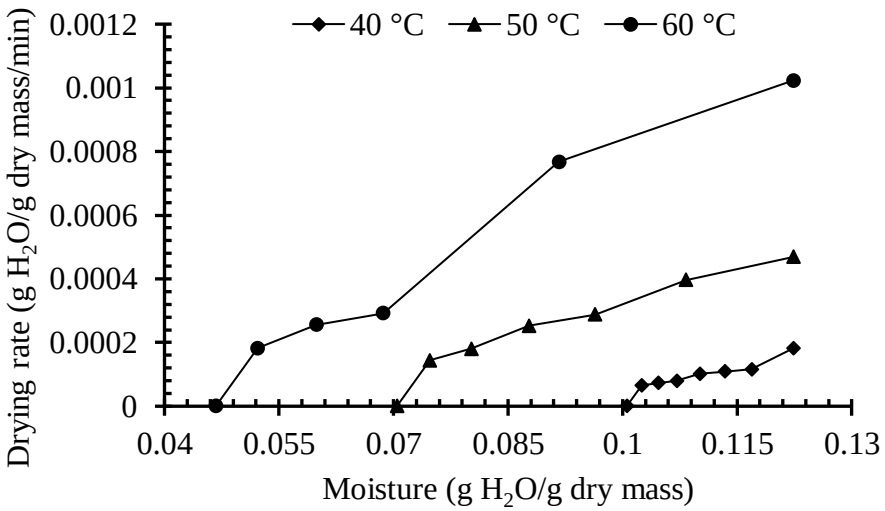


**Fig. 4.2** Drying rate versus moisture of amaranth seed at different temperatures

Most of the agricultural products often exhibit falling rate period as reported by Ajala (2020). From the graph, it was observed that the dried samples exhibited a falling rate pattern. During the falling rate period, drying occurs which is mainly controlled by internal factor of diffusion mechanism in the grain as reported by Ramaswamy and Marcotte (2005).

The initial drying rate at 40 ºC was found to be 0.000181 g $H_2O$/g dry matter/min, 0.000468 g $H_2O$/g dry matter/min at 50 ºC, and 0.001022 g $H_2O$/g dry matter/min at 60 ºC. Within the temperature range utilized, the time to attain equilibrium moisture in amaranth seed decreased as temperature increased. The greater the drying rate, defined as the amount of water removed per time, the shorter the time required to dry the product (İ. Doymaz, 2005). In all cases, the drying rate was higher at the start of the process, but it gradually declined with decreasing moisture content as the drying time passed. There was no distinct constant rate phase at the selected temperatures.

Compared to other temperatures, 40 ºC had a lower initial drying rate. At this low temperature, heat transmission was slower than at the other two temperatures examined. This maybe because higher drying temperature and longer drying period improves the material's ability to expel water from its surface, leading to a lower water content and faster drying rate (Asgar *et al.*, 2022). However, the drying rate at all three temperatures were not so high. This may be because, the conventional cabinet dryers rely entirely on hot air for drying, resulting in slower drying rates. This approach may take longer as it warms the surface, slowing moisture movement from the inside to the surface for evaporation (Pandiselvam *et al.*, 2024). Similarly, the drying curve of drying rate versus time is shown in the Fig. 4.3.

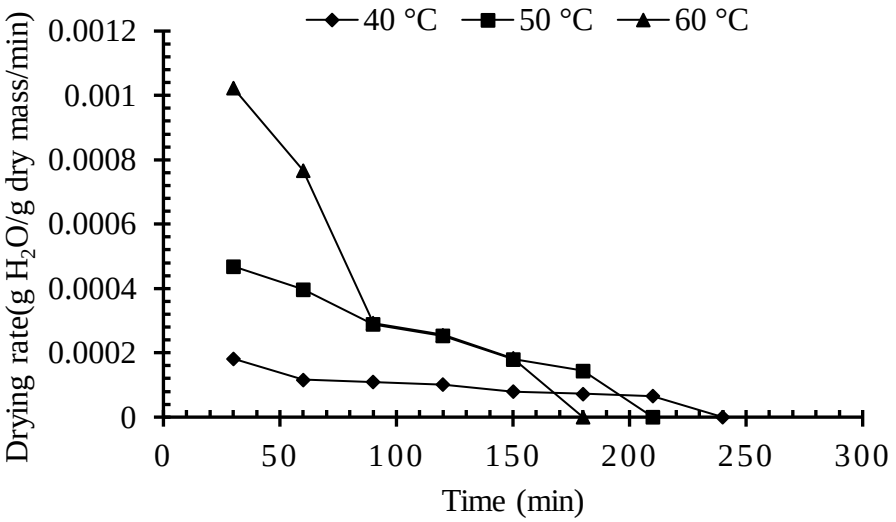


**Fig. 4.3** Drying rate versus time of amaranth seed dried at different temperatures

From Fig. 4.3, it was observed that, the drying rate for 40 ºC was found to be zero at 240 min which indicates that no change in weight was recorded between the interval of 210 and 240 min. Therefore, we can conclude that equilibrium moisture content was reached at 210 min. Similarly, as shown in Fig 4.3, the drying rate for 50 ºC was found to be zero at 210 and for 60 ºC at 180 min, suggesting that no change in weight was recorded between the interval of 180 and 210 min for 50 ºC, and between the interval of 150 and 180 min for 60 ºC. Therefore, we can conclude that the equilibrium moisture content was reached at 210 min for 40 ºC, 180 min for 50 ºC, and 150 min for 60 ºC.

## 4.3 Mathematical modeling of drying

Modeling is an excellent method for explaining the kinetics, moisture, and temperature of food materials (Pandiselvam *et al.*, 2024). Table 4.1 displays the computed results of model constants for the thin layer drying model that was used. In comparison with other models, the Midilli *et* al. model was best fit at all drying temperatures, with the lowest RMSE and $\chi^2$ and the highest $R^2$ values (Table 4.2).

**Table 4.1** Mathematical drying model constants

| Temperature (°C) | Model name | Model constants |
|---|---|---|
| | Henderson and Pabis | a= 1.0216, k= 0.0103 |
| | Newton | k=0.0105 |
| 40 | Midilli *et* al. | a= 0.9762, k= 0.0021, b= 0, n= 1.3336 |
| | Two term exponential | a= 0.9996, k= 0.0105 |
| | Logarithmic | a= 1.0331, k= 0.0108, c= 0 |
| | Page | a= 1.0331, k= 0.0094, n= 1.1521 |
| | Henderson and Pabis | a= 1.0370, k= 0.0136 |
| | Newton | k= 0.0131 |
| 50 | Midilli *et* al. | a= 0.9895, k= 0.0028, b= 0, n= 1.3384 |
| | Two term exponential | a= 0.9999, k= 0.0131 |
| | Logarithmic | a=1.0370, k= 0.0136, c= 0 |
| | Page | a= 1.0370, k= 0.0115, n= 1.1835 |
| | Henderson and Pabis | a= 1.0153, k= 0.0201 |
| | Newton | k= 0.0199 |
| 60 | Midilli *et* al. | a= 0.9999, k= 0.0095, b= 0, n= 1.1771 |
| | Two term exponential | a= 1.7068, k= 0.0263 |
| | Logarithmic | a= 1.0153, k= 0.0201, c= 0 |
| | Page | a= 1.0153, k= 0.0177, n= 1.1351 |

**Table 4.2** Statistical results for thin layer mathematical modeling with different temperatures

| **Temperature (°C)** | **Model name** | **$R^2$** | **$\chi^2$** | **RMSE** |
|---|---|---|---|---|
| 40 | Henderson and Pabis | 0.972717 | 0.15675 | 0.05311 |
| | Newton | 0.972464 | 0.15041 | 0.05335 |
| | Midilli *et* al. | 0.988403 | 0.07962 | 0.03462 |
| | Two term exponential | 0.972464 | 0.15041 | 0.05335 |
| | Logarithmic | 0.974311 | 0.14212 | 0.05153 |
| | Page | 0.974311 | 0.14212 | 0.05153 |
| 50 | Henderson and Pabis | 0.979212 | 0.11980 | 0.04837 |
| | Newton | 0.977004 | 0.12877 | 0.05088 |
| | Midilli *et* al. | 0.994380 | 0.05624 | 0.02515 |
| | Two term exponential | 0.977004 | 0.12877 | 0.05088 |
| | Logarithmic | 0.979212 | 0.11980 | 0.04837 |
| | Page | 0.979212 | 0.11980 | 0.04837 |
| 60 | Henderson and Pabis | 0.993291 | 0.05687 | 0.02829 |
| | Newton | 0.992926 | 0.05891 | 0.02905 |
| | Midilli *et* al. | 0.997377 | 0.03620 | 0.01769 |
| | Two term exponential | 0.997266 | 0.03771 | 0.01806 |
| | Logarithmic | 0.993291 | 0.05687 | 0.02829 |
| | Page | 0.993291 | 0.05687 | 0.02829 |

$R^2$ values for all models were greater than the acceptable threshold of 0.90, indicating a good fit (Madamba *et al.*, 1996). Goodness of fit was determined by a greater $R^2$ and lower RMSE and $\chi^2$ values. Table 4.2 shows coefficients of determination ranging from 0.9884 to 0.9724, 0.9943 to 0.9770, and 0.9973 to 0.9929 at temperatures of 40, 50, and 60 °C, respectively. The lowest $\chi^2$ values ranged from 0.0796 to 0.1567, 0.0562 to 0.1287, and 0.0362 to 0.0589 at temperatures of 40, 50, and 60 °C, respectively. RMSE values ranged between 0.0346 to 0.0533, 0.0251 to 0.0508, and 0.0176 to 0.0290 at the temperatures of 40, 50, and 60 °C, respectively.

At 60 °C, the value of $R^2$ obtained for the Midilli *et* al. model was highest (0.997377) than those obtained from other models. Also, the values of $\chi^2$ and RMSE obtained for Midilli *et* al. model were lower than rest of the models. At 50 °C, the value of $R^2$ obtained for the Midilli *et* al. model was higher i.e., 0.994380 and also the values of $\chi^2$ and RMSE obtained for Midilli *et* al. model were lower than the rest of the models. Similarly, at 40 °C, the value of $R^2$ obtained for the Midilli *et* al. was higher i.e., 0.988403 and also the values of $\chi^2$ and RMSE obtained for Midilli *et* al. model were lower than the rest of the models. The Midilli *et* al. model had higher $R^2$ values, as well as lower $\chi^2$ and RMSE. As a result, the Midilli *et* al. model fits the curve far more accurately than other models. Midilli *et* al. provided the most accurate model for simulating amaranth drying characteristics during cabinet drying at temperatures ranging from 40 to 60 °C.

According to Onwude *et al.* (2016), this model is cited as the most appropriate model in almost 24% of the literature sources analyzed. Thus, statistical results revealed that Midilli *et* al. was the best appropriate drying model for describing the drying kinetics of amaranth seeds during hot air convective drying at temperatures of 40, 50 and 60 °C.

### 4.3.1 Relationship between predicted MR and experimental MR

The graphical representation of predicted MR against experimental MR is shown below in Fig. 4.4, Fig. 4.5 and Fig. 4.6 for 40, 50 and 60 ºC, respectively.

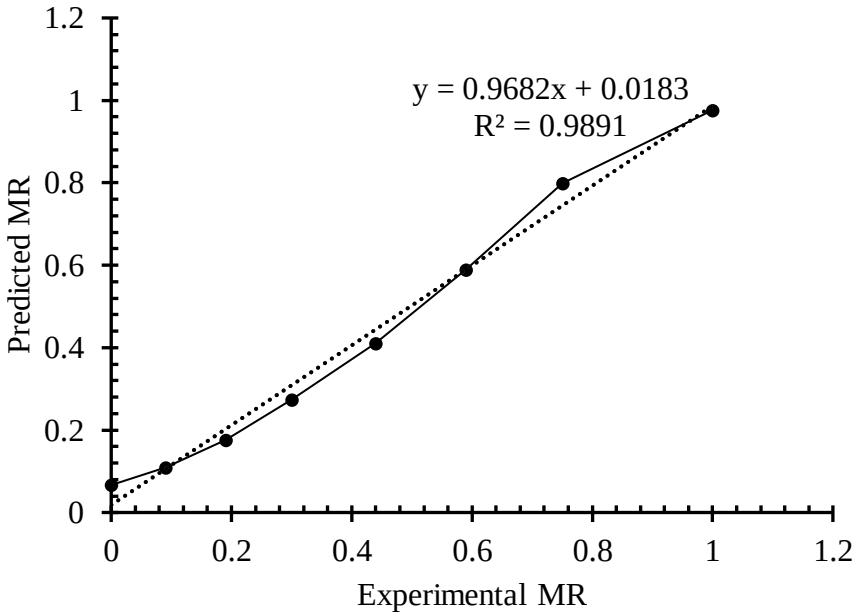


**Fig. 4.4** Calculated MR vs. actual MR for the Midilli *et. al* model at 40 ºC

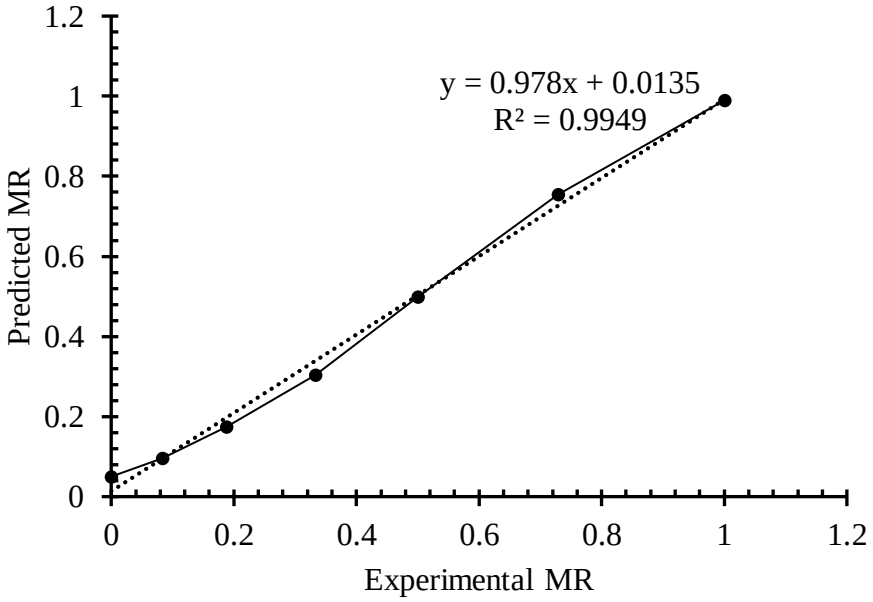


**Fig. 4.5** Calculated MR vs. actual MR for the Midilli *et. al* model at 50 ºC

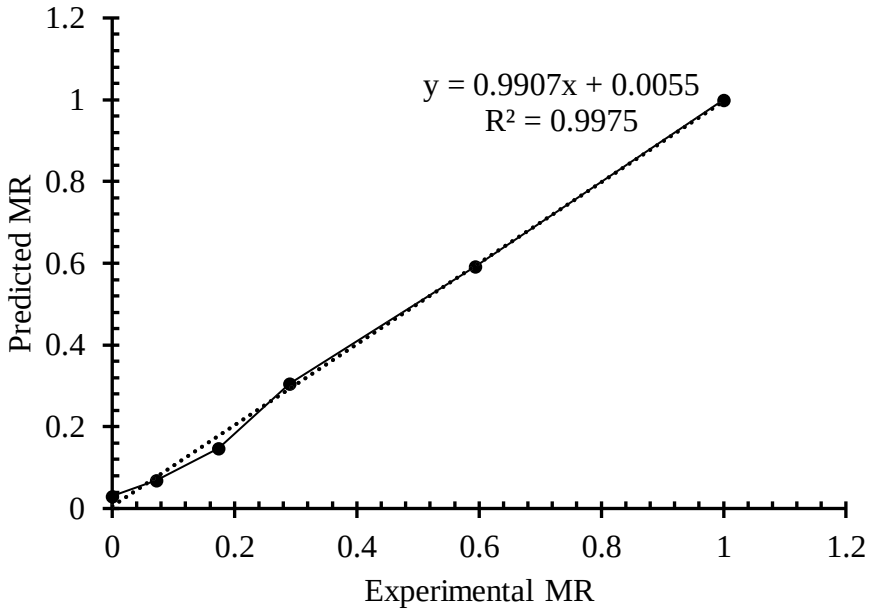


**Fig. 4.6** Calculated MR vs. actual MR for the Midilli *et. al* model at 60 ºC

The relationship between predicted and experimental MR can be shown graphically. The correlation coefficient ($R^2$) indicates how well the predicted and experimental moisture ratios correlates. A very strong correlation requires a value greater than 0.90 (Schober *et al.*, 2018). Across all drying temperatures, the correlation coefficient was close to 1. This suggests they have a high correlation. Experimental data were often grouped around a straight-line indicating data found computation. This showed that the mathematical model was suitable for describing the drying behavior of amaranth seed.

### 4.4 Determination of Effective diffusivity

The samples utilized in this research were examined in slab geometry form. The results revealed that internal mass transfer resistance impacted the drying time because of the presence of a falling rate drying phase. As a result, it was crucial to calculate the values of the effective moisture diffusivities for a given condition.

### 4.4.1 Moisture diffusivity at 40 °C

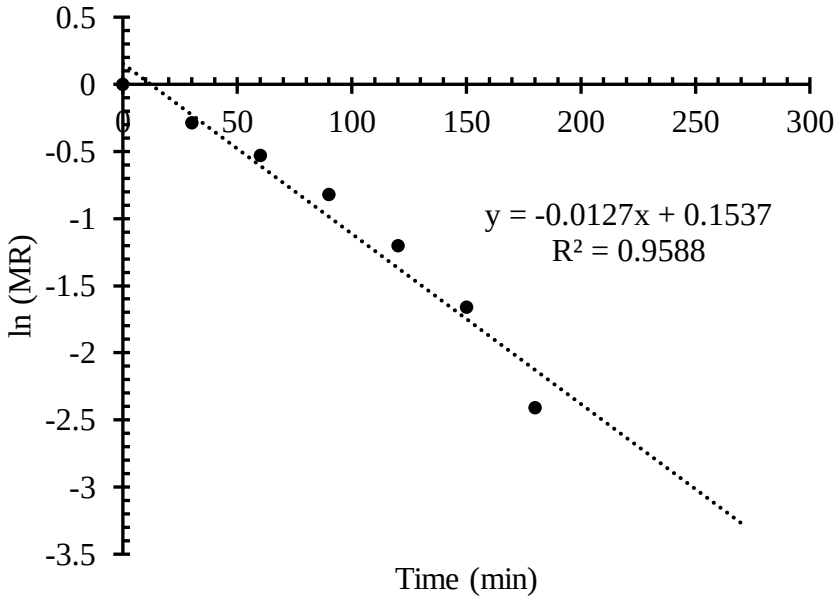


**Fig. 4.7** Graphical representation of ln (MR) vs. time at 40 °C

Average half thickness of slab (amaranth)= $1.5\times10^{-3}$ m

Slope of curve = -0.0127

Diffusivity = $1.1592 \times 10^{-8}$ $m^2/s$.

The effective moisture diffusivity of amaranth seed during cabinet drying at 40 °C was found to be $1.1592 \times 10^{-8}$ $m^2/s$.

### 4.4.2 Moisture diffusivity at 50 °C

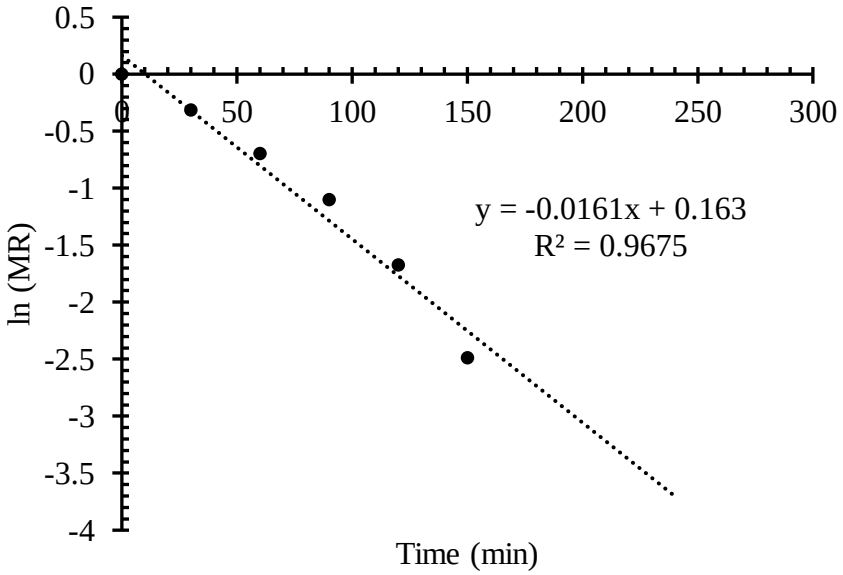


**Fig. 4.8** Graphical representation of ln (MR) vs. time at 50 °C

Average half thickness of slab (amaranth)= $1.5\times10^{-3}$ m

Slope of curve = -0.0161

Diffusivity = $1.4696 \times 10^{-8}$ $m^2/s$.

The effective moisture diffusivity of amaranth seed during cabinet drying at 50 °C was found to be $1.4696 \times 10^{-8}$ $m^2/s$.

### 4.4.3 Moisture diffusivity at 60 °C

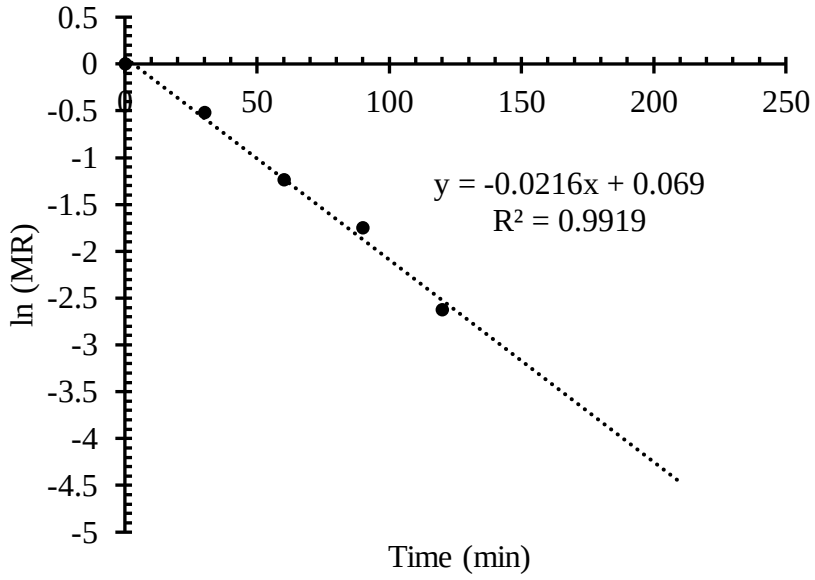


**Fig. 4.9** Graphical representation of ln (MR) vs. time at 60 °C

Average half thickness of slab (amaranth)= $1.5\times10^{-3}$ m

Slope of curve = -0.0216

Diffusivity = $1.9716 \times 10^{-8}$ $m^2/s$.

The effective moisture diffusivity of amaranth seed during cabinet drying at 60 °C was found to be $1.9716 \times 10^{-8}$ $m^2/s$. The results showed that the effective moisture diffusivity for amaranth seed was found to be $1.1592 \times 10^{-8}$ $m^2/s$ for 40 °C, $1.4696 \times 10^{-8}$ $m^2/s$ for 50 °C, and $1.9716 \times 10^{-8}$ $m^2/s$ for 60 °C. With increase in drying temperature, the value of effective moisture diffusivity also increased.

**Table 4.3** Effective diffusivities of dried amaranth at different temperatures

| Temperature (ºC) | Effective diffusivity, $D_{eff}$ ($m^2/s$) |
|---|---|
| 40 | $1.1592 \times 10^{-8}$ |
| 50 | $1.4696 \times 10^{-8}$ |
| 60 | $1.9716 \times 10^{-8}$ |

The above results demonstrated that effective moisture diffusivity increases with drying temperature and vice versa. A similar finding been was reported by Soares *et al.* (2016) in drying barley grains. Diffusivity decreases with increase in drying time due to the fact that, the water activity is reduced as the water content reduces during drying and the remaining water to be removed is increasingly bound water (Erbay and Icier, 2010).

## 4.5 Determination of Activation Energy

Activation energy is crucial in drying processes, particularly in understanding how temperature affects moisture removal rate. The activation energy is a measure of the amount of energy necessary to start a chemical reaction or physical process, such as moisture diffusion when drying (Adus and Wisdom, 2024). It is one of the most crucial terms used in drying. Hii *et al.* (2009) suggested that raising the temperature and drying rate can overcome the energy barrier. The Arrhenius equation was used to explain the relationship between effective diffusivity and drying temperature.

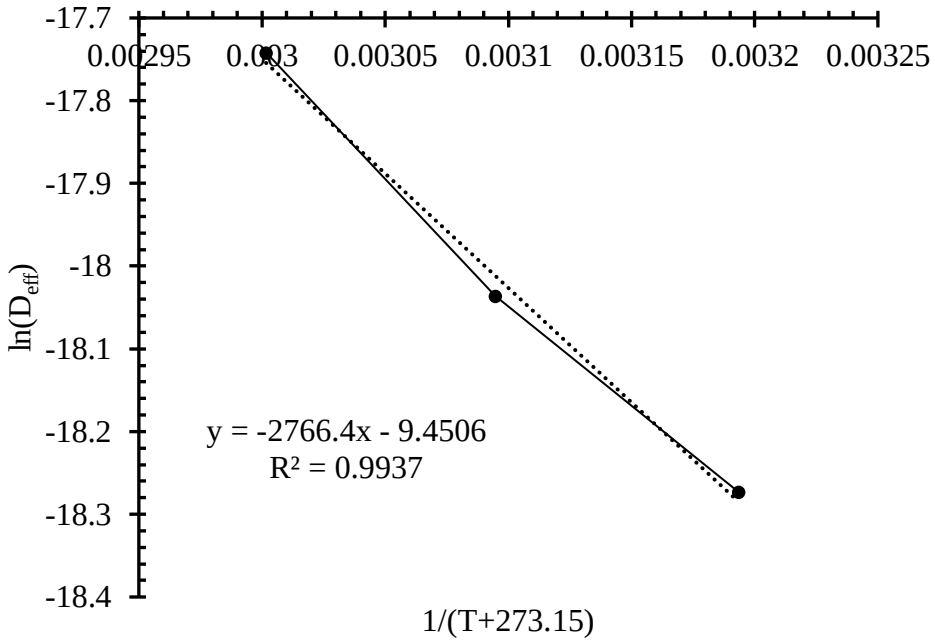


**Fig. 4.10** Arrhenius-type relationship between effective moisture diffusivity and the reciprocal of absolute temperature

From the graph,

Slope = -2766.4

$E_a$ = 22.999 kJ/mol

$D_0 = 7.86 \times 10^{-5}$ $m^2/s$

The estimated diffusivity constant, Do, and activation energy, $E_a$, were $7.86 \times 10^{-5}$ $m^2/s$ and 22.99 kJ/mol, respectively. Thus, the calculated $E_a$ values for amaranth was within the 10-50 kJ/mol range described in the literature for crop products (Marinos-Kouris and Maroulis, 2014). Furthermore, the activation energy of amaranth was higher than that reported for sorghum (14.32 kJ/mol) (Perazzini *et al.*, 2021) and lower than that reported for soyabean (27 kJ/mol) (Gely and Giner, 2007), green peas (26.86 kJ/mol) (İ. Doymaz and Kocayigit, 2011) and corn (29.56 kJ/mol) (İ. Doymaz and Pala, 2003). The values of drying rate constant and activation energy were determined by a variety of parameters, including drying temperature, air supply flow, humidity ratio, and specimen thickness. Higher activation energy may be attributable to the thicker and harder properties of the utilized sample. Higher activation energy may result in an increase in the time, it takes for water to

diffuse from inside to outside, requiring longer time for the water content to evaporate entirely (Kosasih *et al.*, 2020).

### 4.6 Effect of different drying temperatures on physical and functional properties

The physical and functional properties of fresh and dried amaranth seed is given in Table 4.4.

**Table 4.4** Physical and functional properties of fresh and dried amaranth seed

| | Sample | | | |
|---|---|---|---|---|
| Parameters | Fresh | 40 °C | 50 °C | 60 °C |
| Physical properties | | | | |
| Bulk density (g/ml) | $0.867^{a}\pm$ 0.011 | $0.863^{ab}\pm$ 0.0086 | $0.871^{a}\pm$ 0.0055 | $0.894^{b}\pm$ 0.006 |
| True density (g/ml) | $1.25^{a}\pm$ 0 | $1.261^{b}\pm$ 0 | $1.268^{c}\pm$ 0 | $1.273^{d}\pm$ 0.002 |
| Porosity (%) | $30.63^{ab}\pm$ 0.91 | $31.55^{b}\pm$ 0.688 | $30.76^{ab}\pm$ 0.435 | $29.77^{a}\pm$ 0.482 |
| Thousand kernel weight (g) | $0.933^{b}\pm$ 0.208 | $0.566^{a}\pm$ 0.057 | $0.5^{a}\pm$ 0 | $0.433^{a}\pm$ 0.057 |
| Angle of repose | $25.006^{b}\pm$ 1.74 | $22.76^{ab}\pm$ 1.293 | $22.05^{ab}\pm$ 0.655 | $21.64^{a}\pm$ 1.140 |
| Functional properties | | | | |
| Swelling capacity (g/g) | $7.826^{c}\pm$ 0.057 | $4.623^{a}\pm$ 0.058 | $4.589^{a}\pm$ 0.009 | $5.523^{b}\pm$ 0.007 |
| Bulk density (g/ml) | $0.663^{b}\pm$ 0.005 | $0.613^{a}\pm$ 0.0087 | $0.644^{b}\pm$ 0.0089 | $0.713^{c}\pm$ 0.013 |
| Dispersibility (%) | $55.66^{a}\pm$ 0.577 | $58^{b}\pm$ 1 | $57.33^{ab}\pm$ 0.577 | $57.66^{ab}\pm$ 1.154 |
| Water absorption capacity (%) | $144.59^{c}\pm$ 4.698 | $132.54^{b}\pm$ 1.969 | $122.45^{a}\pm$ 2.636 | $116.08^{a}\pm$ 1.168 |
| Oil absorption capacity (%) | $111.55^{b}\pm$ 6.178 | $103.93^{ab}\pm$ 1.673 | $102.10^{a}\pm$ 0.601 | $100.03^{a}\pm$ 0.85 |

* Values are represented as mean ± standard deviation of triplicate determinations.

Drying at different temperatures showed significant differences in physical properties ($p<0.05$) except for porosity ($p>0.05$). The grains of amaranth are lenticular or spherical in form and have a hue that ranges from cream to golden brown to brownish yellow. The grains of amaranth are smaller than those of main cereals; around 1500 grains weigh between 0.4 to 1 g (Kahlon and Chiu, 2015; Sangeeta, 2018). While true density, bulk density, and angle of repose vary inversely with moisture content, thousand-grain weight, specific volume, and porosity vary linearly with moisture value (Kudos and Solanki, 2018). The bulk density and swelling index of amaranth grains were reported as 0.66 g/ml, and 0.63, respectively (Sangeeta, 2018).

The bulk density as a physical property of fresh amaranth seed was found to be 0.867 g/ml; which was similar to the reported value of 0.82 g/ml by Dharshini and Meera (2023); and higher than the reported value of 0.7 g/ml by Mburu *et al.* (2011). Mendoza *et al.* (2003) reported a bulk density value of 860 kg/m$^3$ for the variety *Amaranthus hipocondriacus*, without specifying the moisture range taken into account. In the moisture content range of 7-8% db, amaranth bulk density was 15% greater than that of quinoa seed, a pseudo cereal of similar characteristics as reported by Vilche *et al.* (2003). The bulk density of amaranth seeds was slightly influenced by the temperature treatment. The drying temperature of 40 °C did not significantly reduce the bulk density, dropping it down to 0.863 g/ml from 0.867 g/ml. The temperature of 50 °C and 60 °C showed increase in bulk density to 0.871 g/ml and 0.894 g/ml respectively. The results differed from those of Sindhu *et al.* (2019), whose study found that the bulk density of amaranth decreased from 0.82 g/ml to 0.48 g/ml and 0.14 g/ml after cooking and roasting.

The true density of fresh amaranth seed was found to be 1.25 g/ml; which was lower than the reported value of 1.38-1.53 g/ml as per the moisture content of amaranth seed by Kudos and Solanki (2018). Mendoza *et al.* (2003) reported true density to be 1370 kg/m$^3$ for *Amaranthus hipocondriacus*. The drying temperatures of 40 °C, 50 °C and 60 °C led to slight rise in true density than that of raw amaranth seeds with the value of 1.261 g/ml, 1.268 g/ml and 1.273 g/ml respectively. The porosity of fresh amaranth seed was found to be 30.63%; which was much lower than the reported value of 40-47% as per the moisture content of the amaranth seed by Kudos and Solanki (2018). The porosity of amaranth seeds was also not significantly influenced by drying. It was observed that the porosity of amaranth seeds raised

with the heat treatment from 30.63% to 31.55% at 40 °C; similarly, it raised to 30.76% at 50 °C; while the porosity reduced with the heat treatment at 60 °C from 30.63% to 29.77%.

The thousand kernel weight of fresh amaranth seed was found to be 0.933 g; similar to the reported value of 0.9 g by Thakur *et al.* (2021a). The temperature treatment reduced the moisture content of the seeds and its influence was observed in the thousand kernel weight of amaranth seeds; reducing the thousand kernel weight from 0.933 g (fresh seeds) to 0.566 g, 0.5 g and 0.433 g after the treatment at 40 °C, 50 °C and 60 °C respectively.

The experimental results of angle of repose with respect to moisture content showed a significant increase of angle from 24.60° to 26.43° with the decrease in moisture content ranging from 21 to 7% w.b (Kudos and Solanki, 2018). The trend may have resulted from a lack of surface tension caused by moisture in the grain's surface layer (Pradhan *et al.*, 2008). When designing hopper apertures, side walls, and storage structures for the majority of grains per ramp, the angle of repose is crucial (Solomon and Zewdu, 2009). The angle of repose of fresh amaranth seed was found to be 25.006° ;the value determined was lower than the reported value of 32.05° for amaranth seed by Dharshini and Meera (2023). The angle of repose of amaranth seeds was significantly reduced by drying temperature. It was observed that the angle of repose of amaranth seeds reduced from 25.006° to 22.76°, 22.05° and 21.64° at 40 °C, 50 °C and 60 °C respectively.

Drying at different temperatures showed significant difference in functional properties ($p<0.05$). The bulk density of fresh grounded amaranth seed as a functional property was found to be 0.663 g/ml, the value obtained was higher than 0.61 g/ml and 0.57 g/ml in the study conducted by Chauhan *et al.* (2015) and Tanimola *et al.* (2016), respectively. The bulk density of amaranth flour was also influenced by the treatment at different drying temperatures. It was found that the bulk density of amaranth flour was 0.613 g/ml, 0.644 g/ml and 0.713 g/ml at 40 °C, 50 °C and 60 °C respectively. The swelling capacity of fresh amaranth was found to be 7.826 g/g; similar to the reported value of 7.76 g/g by Tanimola *et al.* (2016). The swelling capacity of amaranth seeds was also significantly influenced by different drying temperatures. It was observed that the swelling capacity of amaranth seeds reduced from 7.826 g/g to 4.623 g/g, 4.589 g/g and 5.523 g/g at 40 °C, 50 °C and 60 °C respectively. The dispersibility of fresh amaranth flour was found to be 55.66%. The

dispersibility of amaranth was not much influenced by the temperature treatment. Dispersibility at 40, 50 and 60 °C was found to be 58%, 57.33% and 57.66%, respectively.

The water absorption capacity of fresh amaranth flour was found to be 144.59%; which was higher than the reported value of 134.02% by Tripathi *et al.* (2019) and lower than the reported value of 160% by Tanimola *et al.* (2016). The water absorption capacity of amaranth flour was found to be reduced by approximately 15% after the temperature treatment. The WAC of amaranth samples at 40,50 and 60 °C was found to be 132.54%, 122.45% and 116.08% respectively. Higher WAC of flour are ideal for bakery applications, allowing bakers to use more water to improve dough management and bread freshness (Shevkani *et al.*, 2014). Similarly, the oil absorption capacity of fresh amaranth flour was found to be 111.55%; which was much lower than the reported value of 143.62% in the study conducted by Tripathi *et al.* (2019). The oil absorption capacity of amaranth flour was also reduced by approximately 10% after been exposed to different drying temperatures bearing the value of 103.93%, 102.10% and 100.03% at 40, 50 and 60 °C respectively. The OAC of flours impacts the mouthfeel and taste retention of goods (Shevkani *et al.*, 2014).

### 4.7 Effect of different drying temperatures on proximate composition

Table 4.5 shows the mean values and standard deviations of the proximate compositions of fresh and dried amaranth seeds samples.

**Table 4.5** Proximate composition of fresh and dried amaranth seed

| Parameters | Sample | | | |
|---|---|---|---|---|
| | Fresh | 40 °C | 50 °C | 60 °C |
| Moisture (%) | $10.90^{d}$± 0.015 | $9.37^{c}$±0.01 | $6.99^{b}$±0 | $4.58^{a}$±0.005 |
| Crude protein (%, db) | $14.87^{c}$± 0.270 | $13.53^{a}$±0.02 | $13.98^{b}$±0.11 | $14.07^{b}$±0.07 |
| Crude fat (%, db) | $6.779^{b}$± 0.06 | $6.48^{a}$±0.11 | $6.80^{b}$±0.12 | $6.88^{b}$±0.03 |
| Total ash (%, db) | $3.284^{c}$± 0.028 | $3.28^{c}$±0.02 | $3.21^{b}$±0.006 | $3.14^{a}$±0.005 |
| Crude fiber (%, db) | $3.806^{a}$± 0.004 | $3.878^{b}$± 0.006 | $3.928^{b}$± 0.007 | $4.043^{c}$± 0.04 |
| Total carbohydrate (%, db) | $75.05^{a}$± 0.218 | $76.70^{c}$± 0.126 | $75.99^{b}$± 0.128 | $75.89^{b}$± 0.071 |
| NFE (%, db) | $71.25^{a}$± 0.216 | $72.82^{c}$± 0.123 | $72.06^{b}$± 0.122 | $71.85^{b}$± 0.082 |
| TOM (%, db) | $96.71^{a}$± 0.028 | $96.71^{a}$± 0.022 | $96.78^{b}$± 0.006 | $96.85^{c}$± 0.005 |

* Values are represented as mean ± standard deviation of triplicate determinations.

The varied drying temperatures were found to have significant effect on the proximate composition of the amaranth seeds ($p<0.05$).The primary components of grains and flour were carbohydrates, which were followed by protein, water, and fat (Malik *et al.*, 2023).

When analyzing Table 4.5, the fresh amaranth seed moisture content was 10.90 %; which was exact with the reported value of 10.90% of *A. hypochondriacus* by Grundy *et al.* (2020) and greater than the reported values of 11.38% by Chemeda and Bussa (2018) and 11.3% by Caselato-Sousa and Amaya-Farfán (2012). Moisture content was significantly influenced by drying. The moisture content of amaranth seeds reduced consecutively with the rise in the drying temperature; resulting the moisture of 9.37%, 6.99% and 4.58% at 40 °C, 50 °C and 60 °C respectively. In a study by Miranda *et al.* (2010), the moisture of quinoa seeds was

reduced from 13.42% to the range of 10.67-5.74% with the increase in drying temperature from 40 to 70 °C, respectively.

The crude protein content of fresh amaranth seed was 14.87%. The result was close to the one reported by Grundy *et al.* (2020) as 14.6% and was greater than the previous report presented as 13.07% by Chemeda and Bussa (2018). Njoki *et al.* (2014) also reported the crude protein content of 14.44% in amaranth seed in wb. Some of the earlier works also found that amaranth grain are good sources of high quality proteins compared to the protein contents found in grains of common cereal crops (8 to 12%) (Koehler and Wieser, 2012). When comparing the fresh with the corresponding dehydrated amaranth samples, it was observed that the drying operation leads to reductions of approximately 8.5% in proteins. Drying temperature of 40 °C reduced the crude protein content from 14.87% to 13.53%; similarly, the drying temperature of 50 °C and 60 °C reduced the crude protein content to 13.8% and 14.07% respectively. Similar result was found for quinoa seeds by Miranda *et al.* (2010) where protein content of quinoa seeds reduced from 12.46% to 11.17%, 11.82% and 12.59% after drying at 40 °C, 50 °C and 60 °C respectively. Denaturation or changes in solubility during drying may be the cause of the protein loss. Additionally, the release of amino acids from proteins after denaturation may also be a contributing factor in this reduction. These amino acids may mix with other chemicals or substances, such as sugars, to form melanoidins through the Maillard reaction (Borompichaichartkul *et al.*, 2009; Miranda *et al.*, 2009).

The crude fat content of fresh amaranth seed was 6.77 %; which was similar to the reported value of 6.68% by Chauhan *et al.* (2015) and less than reported values of 7.33% and 7.49% by Chemeda and Bussa (2018) and Emire and Arega (2012), respectively. Others depending on species, fat content in amaranths grains were reported to range from 2 to 10% (Caselato-Sousa and Amaya-Farfán, 2012). Thus, the amaranth grain studied is regarded among the variety characterized to be high in fat content. The fat content of amaranth seed dried at 40 °C reduced to 6.48%; which may be due to oxidation of fat during heat treatment; similar result of decrease in fat content after the heat treatment at 40 °C was observed in quinoa seed by Miranda *et al.* (2010). The fat content in amaranth seed dried at 50 °C and 60 °C was found to be 6.80% and 6.88% respectively. Similar report was made by Ma *et al.* (2020) on roasted buckwheat. In this study, roasting also led to increase in fat content of buckwheat from 1.18% to 2.53%. The FFA content in fresh amaranth seed sample was

observed to be 1.337%; slightly higher than the reported value of 1.26% by Mekonnen *et al.* (2018). The FFA content of amaranth seed was shown to increase after being subjected to various drying temperatures. Amaranth's FFA concentration was determined to be 3.796% at 40 °C, 3.57% at 50 °C, and 3.412% at 60 °C. Similarly, the acid value of fresh amaranth seed was found to be 2.661%. The acid value of amaranth seed increased after heat treatment, with values of 7.555%, 7.104%, and 6.79% at 40, 50, and 60 °C, respectively. The fatty acid composition of lipid is dominated by palmitic, oleic, and linoleic acids, with over 70% unsaturated fatty acids (Nasirpour-Tabrizi *et al.*, 2020).

The crude fiber content of fresh amaranth seed was 3.806%; similar to the reported value of 3.8% by Mburu *et al.* (2011) and was lower than the reported value of 4.8% by Chauhan *et al.* (2015). Njoki *et al.* (2014) reported the crude fiber content of 4.27% in amaranth seed in wb. When comparing the fresh with the corresponding dehydrated amaranth samples, it was observed that the drying operation leads to rise in fiber content by approximately 5%. The crude fiber content of amaranth seeds at 40, 50, and 60 °C was found to be 3.878%, 3.928%, and 4.043%, respectively; a similar increase in crude fiber content on temperature treatment of okra was reported before by Famurewa and Olumofin (2015). In this study, the crude fiber content of okra increased from 11% to 15.17%, 12.86%, and 11.72% at 40 °C, 50 °C, and 60 °C, respectively. The total carbohydrate content of the fresh amaranth seed was 75.05%. The total carbohydrate content of 66.28% in wb was also reported by Njoki *et al.* (2014). Amaranth grains are reported to contain about 60% starches (Temesgen and Bultosa, 2017; Zhu, 2017). It was observed that the carbohydrate content of amaranth slightly raised after the temperature treatment. Drying temperature of 40 °C raised the carbohydrate content from 75.05% to 76.70%; similarly, the drying temperature of 50 °C and 60 °C raised the carbohydrate content to 75.99% and 75.89%, respectively. Miranda *et al.* (2010) presented a similar study for quinoa seeds, in which the carbohydrate content increased in proportion to the temperature. The carbohydrate content of quinoa seeds had increased from 60.01% to 66.40%, 65.50%, and 71.43% following treatment at 40, 50, and 60 °C, respectively.

The NFE content in fresh amaranth seed was found to be 71.25%. The NFE content in amaranth sample thus found was higher than the reported range of 58.6-68.9% by Mburu *et al.* (2011). The NFE concentration of amaranth was observed to marginally increase from 71.25% to 72.82% at 40 °C, while drying temperatures of 50 °C and 60 °C increased the

NFE content to 72.06% and 71.85%, respectively. The DCP content of fresh amaranth seed was found to be 10.53%. Similarly, the TOM content in fresh amaranth seed was found to be 96.71%. The DCP and TOM content was found to be 9.304%, 9.717%, 9.806% and 96.71%, 96.78%, 96.85% at 40, 50, and 60 °C, respectively.

### 4.8 Effect of different drying temperatures on physicochemical composition

Table 4.6 shows the mean values and standard deviations of the physicochemical compositions of fresh and dried amaranth seeds samples.

**Table 4.6** Physicochemical composition of fresh and dried amaranth seed

| | Sample | | | |
|---|---|---|---|---|
| Parameters | Fresh | 40 °C | 50 °C | 60 °C |
| Acid value (%) | $2.661^{a}$± 0.021 | $7.555^{d}$± 0.129 | $7.104^{c}$± 0.121 | $6.79^{b}$± 0.019 |
| FFA (%) | $1.337^{a}$± 0.01 | $3.796^{d}$± 0.065 | $3.57^{c}$± 0.06 | $3.412^{b}$± 0.009 |
| DCP (%, db) | $10.53^{c}$± 0.248 | $9.304^{a}$± 0.019 | $9.717^{b}$± 0.109 | $9.806^{b}$± 0.065 |
| Energy (kcal/100 g, db) | $420.75^{b}$±0.329 | $419.29^{a}$± 0.528 | $421.20^{b}$±0.633 | $421.86^{b}$±0.165 |
| Calcium (mg/100 g, db) | $471.17^{a}$± 1.03 | $509.57^{b}$± 0.618 | $515.56^{c}$±0.961 | $522.61^{d}$±0.58 |
| Phosphorous (mg/100g, db) | $671.17^{a}$±1.023 | $680.52^{b}$± 0.418 | $688.15^{c}$±0.576 | $698.93^{d}$±0.736 |
| Acid insoluble ash (%) | ND | ND | ND | ND |

* Values are represented as mean ± standard deviation of triplicate determinations.

Where, ND= not detected

Physicochemical properties showed significant differences between the raw sample and the samples dried at different temperatures ($p<0.05$). The energy value of fresh amaranth seed was 420.75 kcal/100 g; similar to the reported value of 417.28 kcal/100 g by Tanimola *et al.* (2016). Energy content for the amaranth seed was found to be 251 kcal/100 g by Emire and Arega (2012), and 371 kcal/100 g by Caselato-Sousa and Amaya-Farfán (2012). The energy content of amaranth seed was slightly influenced by the drying process. The energy content was therefore determined to be 419.29, 421.20, and 421.86 kcal/100g at 40, 50, and 60 °C, respectively.

It was observed that amaranth seeds had no acid insoluble ash. The AIA content of amaranth fresh as well as after treatment at all three temperatures were non-detectable. The ash content of fresh amaranth seed was 3.28%; which was greater than the reported values of 2.92% and 2.9% by Chemeda and Bussa (2018) and Caselato-Sousa and Amaya-Farfán (2012), respectively. The ash content of 3.18% in wb was also reported by Njoki *et al.* (2014). It was observed that the drying process resulted in ash content reduction of about 2.0% when comparing the fresh with corresponding dehydrated amaranth samples. The total ash content of amaranth seed heated at 40 °C, 50 °C and 60 °C was found to be 3.28%, 3.21% and 3.14% respectively; similar report had been given earlier on temperature treatment of quinoa seeds by Miranda *et al.* (2010) . In this study, the ash content of quinoa seeds reduced from 3.71% to 2.63%, 2.43% and 2.60% at 40 °C, 50 °C and 60 °C, respectively. When compared to other conventional food items like buckwheat, millet, or brown rice, amaranth-based products were shown to be good providers of minerals (Gliszczyńska-Świgło *et al.*, 2018).

Phosphorous was found to be 330 μg/g and calcium was found to be 519.3 μg/g in amaranth grains (Bhat *et al.*, 2015). The ratio of calcium and phosphorus was reported to be in the range of 1: 1.9-2.7 by Pastor and Acanski (2018). The phosphorous content in fresh amaranth seed was found to be 671.17 mg/100 g; which was higher than the range of reported value of 325-612 mg/100 g for whole, fine and coarse amaranth by Ramesh and Prakash (2020). The drying process led to slight increment in the phosphorous content of amaranth. The phosphorous content of amaranth dried at 40, 50 and 60 °C was observed to be 680.52, 688.15 and 698.93 mg/100 g, respectively. The calcium content of fresh amaranth seed was found to be 471.17 mg/100 g. Njoki *et al.* (2014) reported the calcium content of amaranth to be 578.28 mg calcium/100 g in wb. It was observed that the temperature treatment of

amaranth seeds led to increase in calcium content by approximately 10% than that of the fresh seeds. The temperature of 60 ℃ showed the maximum rise in calcium content to 522.61 mg/100 g, followed by the treatment at 50 ℃ to 515.56 mg/100 g, while 40 ℃ showed minimal rise as compared to two other temperatures investigated with the value of 509.57 mg/100 g.

Amaranth grains varied noticeably in composition due to different cultivars, varieties, or growth environments (Malik *et al.*, 2023).

### 4.9 Effect of different drying temperatures on phytochemical and anti-nutritional properties

The phytochemical composition and anti-nutritional factors of fresh and dried amaranth seed is given in Table 4.7.

**Table 4.7** Phytochemical and anti-nutritional constituents of fresh and dried amaranth

| Parameters | Sample | | | |
|---|---|---|---|---|
| | Fresh | 40 °C | 50 °C | 60 °C |
| Phytochemical composition | | | | |
| Total phenolic content (mg GAE/ g dry extract) | $0.374^{c}$± 0.002 | $0.291^{a}$± 0.001 | $0.294^{a}$± 0.002 | $0.319^{b}$± 0.003 |
| Total flavonoid content (mg QE/ g dry extract) | $1.984^{d}$± 0.003 | $1.111^{c}$± 0.006 | $1.415^{b}$± 0.006 | $1.558^{a}$± 0.033 |
| Total alkaloid content (%) | $3.957^{d}$± 0.049 | $3.579^{b}$± 0.011 | $3.451^{a}$± 0.017 | $3.775^{c}$± 0.013 |
| L-ascorbic acid content (mg/100 g) | $5.393^{d}$± 0.09 | $3.983^{c}$± 0.015 | $3.396^{b}$± 0.065 | $3.116^{a}$± 0.015 |
| DPPH radical scavenging activity (%) | $94.64^{d}$± 0.196 | $33.62^{c}$± 0.246 | $35.48^{b}$± 0.156 | $38.03^{a}$± 0.254 |
| Antinutritional factors | | | | |
| Phytate content (g/100 g) | $1.61^{d}$± 0.036 | $1.441^{c}$± 0.006 | $1.317^{b}$± 0.005 | $1.202^{a}$± 0.012 |
| Tannin content (mg TAE/ g dry extract) | $0.727^{d}$± 0.008 | $0.625^{c}$± 0.011 | $0.552^{b}$± 0.005 | $0.484^{a}$± 0.008 |
| Oxalate content (%) | $0.406^{d}$± 0.005 | $0.369^{c}$± 0 | $0.328^{b}$± 0 | $0.282^{a}$± 0.002 |
| Saponin content (mg SE/ g dry extract) | $0.845^{d}$± 0.025 | $0.731^{c}$± 0.022 | $0.63^{b}$± 0.01 | $0.543^{a}$± 0.01 |

* Values are represented as mean ± standard deviation of triplicate determinations.

Phytochemicals and anti-nutritional properties showed significant differences between the raw sample and the samples dried at different temperatures ($p<0.05$). The TPC of fresh

amaranth seed was found to be 0.374 mg GAE/ g dry extract; which was higher than the reported value of 0.3079 and 0.3003 mg GAE/ g dry extract for *Amaranthus hybridus* and *Amaranthus hypochondriacus* by Akin-Idowu *et al.* (2017). The TPC of amaranth thus obtained was also higher than the reported value of 0.218 mg GAE/ g dry extract by Lopez-Martinez and Ahmad (2024). Akin-Idowu *et al.* (2017) found total polyphenol of amaranth seed to be in the range of 0.255-0.307 mg GAE/g as per its variety. Following the drying process, the TPC content was found to be lower than in fresh seeds. TPC was retained the best at 60 °C when compared to the other two temperatures investigated. The TPC content at 40, 50 and 60 °C was found to be 0.291, 0.294 and 0.319 mg GAE/ g dry extract, respectively. Earlier studies have reported conflicting results with respect to the effect of heat on total phenolics. Heat has been reported to cause reduction in TPC of autoclaved grain amaranth (Olawoye and Gbadamosi, 2017). Increased phenolic content has been reported for tomatoes treated at 88°C for 30 min (Choi *et al.*, 2006). The increased phenolic content of thermally processed foods can be attributed to the heat-induced release of more bound phenolics (Jannat *et al.*, 2010). The TFC of fresh amaranth seed was found to be 1.984 mg QE/ g dry extract; higher than the reported value of 0.075 mg QE/ g dry extract for *Amaranthus hypochondriacus* by Stănilă *et al.* (2019). The flavonoid content was observed to be greater than the reported range of 0.029-0.075 mg QE/ g dry extract by Stănilă *et al.* (2019). The drying process had an impact on TFC. The TFC was found to be 1.111, 1.415 and 1.558 mg QE/ g dry extract at 40, 50 and 60 °C, respectively. The TFC content was observed to be reduced as compared to fresh seeds, but there was consecutive rise in TFC with rise in temperature from 40 to 60 °C. This may be attributed to enhanced extractability of bound flavonoid compounds resulting from heat-induced disruption of the plant cell wall. Heat-induced increase in flavonoid content has also been associated with deactivation of endogenous oxidative enzymes, thereby preventing enzymatic oxidation which causes loss of the antioxidant compounds in the raw plant materials (Jannat *et al.*, 2010).

The alkaloid content of fresh amaranth seed was found to be 3.957%; the value so obtained was lower than the reported value of 5.572% by Bhat *et al.* (2015). The alkaloid content of amaranth seeds was observed be to be slightly reduced after the temperature treatment. The alkaloid content of amaranth was found to be 3.579%, 3.451% and 3.775% at 40, 50 and 60 °C, respectively. The vitamin C content in fresh amaranth seed was found to be 5.393 mg/100 g; which was higher than the reported value of 4.20 mg/ 100 g by

Schmidt *et al.* (2023). The vitamin C content was observed to be consecutively reduced with increase in drying temperature. The vitamin C was maximum retained at the temperature of 40 °C with the value of 3.983 mg/100 g, followed by at 50 °C and 60 °C with the value of 3.396 mg/100 g and 3.116 mg/100 g, respectively. The DPPH radical scavenging activity of fresh amaranth seed was found to be 94.64%; similar to the reported value of 93.35% in *Amaranthus hybridus* by Akin-Idowu *et al.* (2017) and much higher than the reported value of 75.91% by Iqbal *et al.* (2012). The anti-oxidant activity of amaranth significantly reduced after the drying operation, with maximum reduction showed by 40 °C with the value of 33.62%, followed by 50 °C and 60 °C comprising anti-oxidant activity of 35.48% and 38.03%, respectively. Much of the antioxidant activity of plant materials is attributable to flavonoids and other phenolics (Kähkönen *et al.*, 1999; Nicoli *et al.*, 1999). Therefore, the sequential increase in DPPH radical scavenging activity from 40 to 60 °C maybe due to the observed increase in total flavonoids in the similar pattern. Significant diversity in the phytochemical content and antioxidant activity of cereals (amaranth) is to be expected, since several factors, such as agrotechnical procedures, environmental circumstances, and genetics, influence phenolic compound concentration (Akin-Idowu *et al.*, 2017). Amaranth seeds have a high concentration of phenolic acids and have a remarkable antioxidant activity, making them suitable for food biofortification (Akin-Idowu *et al.*, 2017).

Small amounts of tannin may be present in amaranth flour (Emire and Arega, 2012). The phytate content of fresh amaranth seed was found to be 1.61 g/100 g; similar to the reported value of 1.58 g/100 g in *Amaranthus hybridus* by Akin-Idowu *et al.* (2017). The phytate concentration obtained in this study was higher than 0.2377 g/100g that was reported by Emire and Arega (2012). The tannin content of fresh amaranth seed was found to be 0.727 mg TAE/ g dry extract. Tannin content was lower than the reported range of 0.10-0.14 g/100 g as per the variety of amaranth seed by Akin-Idowu *et al.* (2017). In the study conducted by Olawoye and Gbadamosi (2017), the tannin content in whole amaranth flour has been reported to be 3.459 mg/100 g. Heat has been reported to cause reduction in phytate and tannin content of roasted and soak-oven dried grain amaranth (Chemeda and Bussa, 2018). Similarly, in this study, heat has been observed to cause significant reduction in phytate and tannin content, consecutively with the rise in drying temperature. The drying temperatures of 40, 50 and 60 °C reduced the phytate content from 1.61 g/100 g to 1.441, 1.317 and 1.202 g/100 g, respectively. The phytate content of amaranth has been reported to be reduced from

250.32 mg/100 g to 242.25 mg/100 g and 220.65 mg/100 g after roasting and soak-oven drying, respectively (Chemeda and Bussa, 2018). The tannin content was observed to be reduced from 0.727 mg TAE/g dry extract to 0.625, 0.552 and 0.484 mg TAE/ g dry extract at 40, 50 and 60 °C, respectively. Similarly, the tannin content reduced from 6.63 mg/100 g to 5.25 mg/100 g and 3.34 mg/100 g after roasting and oven-drying , respectively (Chemeda and Bussa, 2018).

The oxalate content in fresh amaranth seed was found to be 0.406%; higher than the reported value of 0.278% by Gelinas and Seguin (2007). Heat led to reduction in oxalate content. The oxalate content was observed to be reduced from 0.406% to 0.369, 0.328 and 0.282% at 40, 50 and 60 °C, respectively. The saponin content in fresh amaranth was found to be 0.845 mg SE/ g dry extract. The saponin content of raw amaranth seed has been reported to be in the range of 0.9-4.9 mg/ kg by Thakur *et al.* (2021b). Sindhu *et al.* (2019) has reported the saponin content of fresh amaranth as 2.66 g/100 g. The tannin, oxalate and saponin content of amaranth has been reported to decrease after various heat processing process. Similarly, in this study, heat treatment resulted in reduction of saponin content. The saponin content at 40, 50 and 60 °C was found to be 0.731, 0.63 and 0.543 mg SE/ g dry extract, respectively.

### 4.10 Chemometrics

Chemometrics is a chemical science that combines mathematical and statistical approaches to extract as much chemical information as possible from chemical data (Andre and Soukoulis, 2020). Chemometric approaches are used to distinguish relevant information from noise, discover hidden connections, and give a visual approach to multivariate data analysis (Granato *et al.*, 2018). Chemometric ideas may be used to data from chemical analyses, which are commonly utilized in the fundamental research of foods (Varmuza and Filzmoser, 2016).

Chemometrics may be separated into supervised and unsupervised approaches. The first class includes a wide range of methodologies and algorithms, including qualitative and quantitative approaches (Oliveri and Simonetti, 2016). Unsupervised techniques, also known as clustering or display methods, are used to investigate data structure, identify similarities between multiple items, and detect outliers in the data set (Liu *et al.*, 2018).

### 4.10.1 Pearson's correlation

Correlation, in its widest definition, is a measure of the relationship between variables. Correlation coefficients are scaled from -1 to +1, with 0 indicating no linear or monotonic link and the relationship becoming stronger and eventually approaching a straight line as the coefficient approaches an absolute value of one (Schober *et al.*, 2018). The values approaching +1 shows positive correlation while approaching -1 shows negative correlation. Positive correlation indicate that as one property increases, the other tends to increase, while negative correlation shows inverse relationship.

**Table 4.8** Pearson's correlation for moisture, physical, and functional properties

| S.N | Variables | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Bulk density (P) | 1 | 0.712 | -0.907 | -0.625 | -0.519 | 0.200 | -0.155 | -0.724 | -0.397 | 0.769 | -0.815 |
| 2 | True density | 0.712 | 1 | -0.351 | -0.855 | -0.789 | 0.637 | -0.711 | -0.970 | -0.825 | 0.412 | -0.961 |
| 3 | Porosity | -0.907 | -0.351 | 1 | 0.324 | 0.221 | 0.115 | -0.217 | 0.384 | 0.034 | -0.777 | 0.512 |
| 4 | 1000 kernel weight | -0.625 | -0.855 | 0.324 | 1 | 0.749 | -0.551 | 0.788 | 0.861 | 0.669 | -0.120 | 0.777 |
| 5 | Angle of repose | -0.519 | -0.789 | 0.221 | 0.749 | 1 | -0.548 | 0.658 | 0.679 | 0.394 | -0.201 | 0.696 |
| 6 | Dispersibility | 0.200 | 0.637 | 0.115 | -0.551 | -0.548 | 1 | -0.732 | -0.557 | -0.616 | -0.067 | -0.465 |
| 7 | Swelling capacity | -0.155 | -0.711 | -0.217 | 0.788 | 0.658 | -0.732 | 1 | 0.666 | 0.706 | 0.330 | 0.508 |
| 8 | WAC | -0.724 | -0.970 | 0.384 | 0.861 | 0.679 | -0.557 | 0.666 | 1 | 0.856 | -0.427 | 0.952 |
| 9 | OAC | -0.397 | -0.825 | 0.034 | 0.669 | 0.394 | -0.616 | 0.706 | 0.856 | 1 | -0.183 | 0.764 |
| 10 | Bulk density (F) | 0.769 | 0.412 | -0.777 | -0.120 | -0.201 | -0.067 | 0.330 | -0.427 | -0.183 | 1 | -0.617 |
| 11 | Moisture | -0.815 | -0.961 | 0.512 | 0.777 | 0.696 | -0.465 | 0.508 | 0.952 | 0.764 | -0.617 | 1 |

From Table 4.8, we can see that moisture content showed strong positive correlation with water absorption capacity (WAC) i.e., 0.952, and strong negative correlation with true density (-0.961) and bulk density (-0.815). Porosity, thousand kernel weight, angle of repose, swelling capacity, and oil absorption capacity (OAC) showed moderate positive correlation with moisture, while dispersibility and bulk density as functional property showed moderate negative correlation with moisture content. Bulk density as physical property showed strong

negative correlation with porosity (-0.907) and showed moderate positive correlation with true density (0.712) and bulk density as functional property (0.769).

**Table 4.9** Pearson's correlation for anti-nutrients, phytochemicals, and anti-oxidants

| S.N | Variables | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Phytate | 1 | 0.994 | 0.980 | 0.976 | 0.617 | 0.428 | 0.470 | 0.967 | 0.790 |
| 2 | Tannin | 0.994 | 1 | 0.985 | 0.979 | 0.623 | 0.432 | 0.466 | 0.969 | 0.795 |
| 3 | Oxalate | 0.980 | 0.985 | 1 | 0.988 | 0.511 | 0.312 | 0.347 | 0.926 | 0.708 |
| 4 | Saponin | 0.976 | 0.979 | 0.988 | 1 | 0.587 | 0.389 | 0.431 | 0.948 | 0.762 |
| 5 | TPC | 0.617 | 0.623 | 0.511 | 0.587 | 1 | 0.944 | 0.919 | 0.790 | 0.962 |
| 6 | TFC | 0.428 | 0.432 | 0.312 | 0.389 | 0.944 | 1 | 0.812 | 0.618 | 0.886 |
| 7 | TAC | 0.470 | 0.466 | 0.347 | 0.431 | 0.919 | 0.812 | 1 | 0.650 | 0.817 |
| 8 | Vitamin C | 0.967 | 0.969 | 0.926 | 0.948 | 0.790 | 0.618 | 0.650 | 1 | 0.910 |
| 9 | DPPH | 0.790 | 0.795 | 0.708 | 0.762 | 0.962 | 0.886 | 0.817 | 0.910 | 1 |

From Table 4.9, we can see that DPPH showed strong positive correlation with total phenolic content (TPC) i.e., 0.962, vitamin C i.e., 0.910, and total flavonoid content (TFC) i.e., 0.886. TPC and TFC showed strong positive correlation with each other i.e., 0.944. Pearson's correlation coefficient is a simple statistic to generate and test for correlation, however it is not an unbiased estimate of correlation (Moltchanova *et al.*, 2017). Therefore, some parameters showing the association may don't have the expected relationship between each other rather than the association could be shown because of the rise or decrease in the quantity of one parameter with respect to other.

### 4.10.2 Multivariate analysis

Principal Components Analysis (PCA) and Hierarchical Cluster Analysis (HCA) are popular "unsupervised classification" approaches for assessing relationships in food chemistry

research (Brereton, 2015). Among the common type of multivariate tests, PCA and Hierarchical cluster analysis were performed in this study.

For figures of multivariate analysis, 'A' represents a sample dried at 40°C, whereas 'B' and 'C' represent samples dried at 50°C and 60°C, respectively. PCA was performed to show how the drying temperature affected the physical, functional, physicochemical, anti-nutritional and phytochemicals and how these quality parameters were correlated.

**Table 4.10** Component scores of the parameters obtained from PCA for the factors

| | | F1 | F2 | F3 |
|---|---|---|---|---|
| | Bulk density (P) | 0.576 | 0.710 | -0.313 |
| | True density | 0.968 | 0.225 | 0.004 |
| | Porosity | -0.188 | -0.812 | 0.422 |
| Physical properties | Thousand kernel weight | -0.906 | -0.018 | 0.240 |
| | Angle of repose | -0.779 | -0.024 | 0.409 |
| | Dispersibility | 0.707 | -0.317 | 0.099 |
| | Swelling capacity | -0.848 | 0.492 | -0.007 |
| | WAC | -0.938 | -0.287 | -0.088 |
| Functional properties | OAC | -0.857 | 0.000 | -0.411 |
| | Bulk density (F) | 0.200 | 0.913 | -0.055 |
| | Moisture | -0.881 | -0.464 | -0.025 |
| | Crude protein | -0.728 | 0.654 | -0.091 |
| Physicochemical properties | Crude fat | 0.114 | 0.860 | 0.408 |
| | Total ash | -0.738 | -0.632 | 0.008 |
| | Crude fiber | 0.868 | 0.411 | -0.028 |
| | Carbohydrate | 0.654 | -0.730 | -0.041 |
| | Energy | 0.273 | 0.873 | 0.340 |
| | Calcium | 0.997 | -0.062 | -0.004 |
| | Phosphorus | 0.916 | 0.376 | 0.038 |
| | FFA | 0.908 | -0.412 | -0.042 |
| | AV | 0.908 | -0.412 | -0.042 |
| | DCP | -0.728 | 0.654 | -0.091 |
| | NFE | 0.546 | -0.820 | -0.038 |

| | | | | |
|---|---|---|---|---|
| | TOM | 0.738 | 0.632 | -0.008 |
| | Phytate | -0.951 | -0.292 | -0.068 |
| Anti-nutrients | Tannin | -0.954 | -0.291 | -0.015 |
| | Oxalate | -0.906 | -0.406 | -0.013 |
| | Saponin | -0.932 | -0.320 | 0.001 |
| | TPC | -0.820 | 0.535 | 0.018 |
| Phytochemicals | TFC | -0.677 | 0.721 | 0.082 |
| | TAC | -0.657 | 0.553 | -0.173 |
| | Vitamin C | -0.993 | -0.073 | -0.014 |
| Anti-oxidant | DPPH radical | -0.939 | 0.340 | 0.018 |
| | Eigenvalue | 20.510 | 9.374 | 1.042 |
| | Variability (%) | 62.151 | 28.406 | 3.158 |
| | Cumulative % | 62.151 | 90.557 | 93.715 |

In Table 4.10, the negative values in each column shows the negative influence of those parameters to the respective factor/principal component. Three principal components were initially obtained by analyzing all the parameters because of their eigenvalue being greater than 1. Whereas, the first and the second PCs explained 90.55% of total variance. The most dominant principal components were then subjected to Varimax rotation and bi-plot was created for two dimensions D1 and D2 (Fig. 4.11).

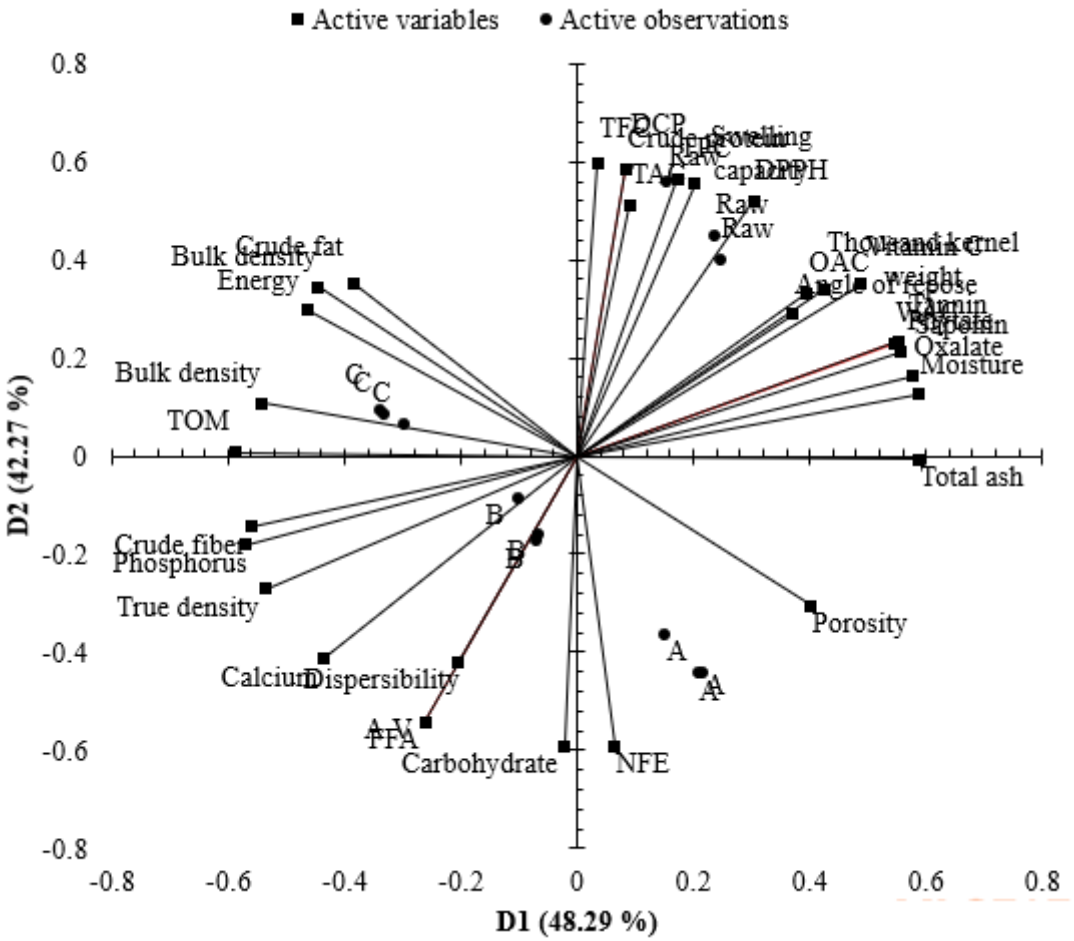


**Fig. 4.11** Bi-plot for principal component analysis (PCA) with varimax rotation in two dimensions D1 and D2

Varimax rotation is a popular orthogonal rotation approach that seeks to maximize the variation of factor loadings within each column, resulting in clearer and simpler factor structures (Weide and Beauducel, 2019). Varimax rotation reduces the factor structure while improving the findings' interpretability (Mooi *et al.*, 2018). Dimension 1 (D1) accounted for 48.29% of the total variance, while dimension 2 (D2) explained 42.71% of the variance. Together, these dimensions explained approximately 90.56% of the total variation. The clear separation of the samples into distinct clusters (raw, A, B, and C) highlighted that the different treatments had distinct effects on the physical, chemical, and functional properties of the samples. Raw sample clustered near the variables like TPC, TAC, and crude protein, showing that these properties were strongly associated with the raw samples and same followed for all the groups. Observations near variables suggest that the observation had

high values for those variables. Variables close to each other indicates a positive correlation. Variables in opposite direction indicates a negative correlation (Cañeque *et al.*, 2004).

Variables that are grouped close to each other in the bi-plot are highly correlated (Cañeque *et al.*, 2004). Similarly, length of the vectors indicates the contribution and correlation of each variable to the principal components and the angle between two vectors reflects the correlation between the variables (smaller angles indicate a strong positive correlation). D1 showed strong positive associations with variables like total ash, moisture, porosity, crude protein, oxalate, total phenolic content (TPC), and total alkaloid content (TAC), as these variables aligned closely along the positive side of D1. D2 showed strong association with bulk density, crude fat, energy, true density, and phosphorus, as these variables aligned highly in the positive direction on D2.

Chemometrics can be used in food science and technology research to measure similarities/differences between several samples or to project things into a two/three-dimensional factor plane depending on various features. As a result, clustering may be detected and the causes for the grouping can be pinpointed (Erasmus *et al.*, 2018; Lund *et al.*, 2017).

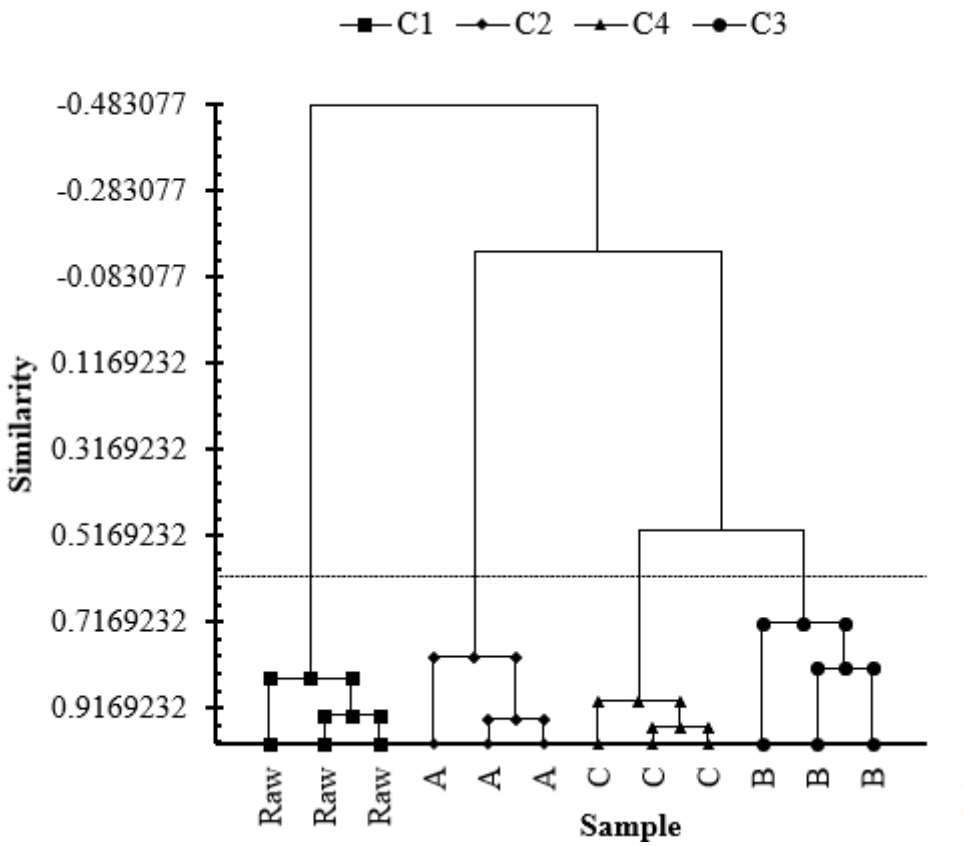


**Fig. 4.12** Dendrogram from Ward's method of Agglomerative Hierarchical cluster analysis

A dendrogram (Fig. 4.12) was prepared from Ward's method of Agglomerative Hierarchical cluster analysis showing the clusters based on the similarities of the observation groups. As shown in figure, four cluster groups were formed. The y-axis represents similarity values ranging from negative to positive, where lower values (closer to the negative side) represent lower similarity, and higher values (closer to 1) indicate greater similarity. Higher the cluster bar more will be the dissimilarity, and lower the cluster bar more be the similarity.

The distinction between the different clusters could be tied to physical, functional, or chemical changes due to drying. The dendrogram highlighted that raw samples are the most distinct, as they are separated at the highest dissimilarity (largest negative similarity values). The high dissimilarity of the raw samples from the processed groups (A, B, C) indicated that processing methods or treatments significantly altered their properties. The raw samples are grouped separately, meaning they share less similarity with the dried samples. The dried samples clustered at higher similarity levels, indicating that they share more common traits among themselves compared to the raw samples.

Samples B and C were shown to cluster closely together at a higher similarity level. This indicated that samples from these two groups have similar characteristics or properties, reflecting a stronger association between them compared to the other groups. Sample A formed a moderate cluster with B and C. This indicates that while A shares some similarities with both B and C, it is not as closely related to them as B is to C.

# PART V

## Conclusions and Recommendations

### 5.1 Conclusions

Based on the result and discussion following conclusions can be drawn.

1. Drying at different temperatures showed significant differences in physical properties ($p<0.05$) and functional properties ($p<0.05$) except for porosity ($p>0.05$).
2. The varied drying temperatures were found to have significant effect on the physicochemical properties of the amaranth seeds ($p<0.05$).
3. Phytochemicals and anti-nutritional properties showed significant differences between the raw sample and the samples dried at different temperatures ($p<0.05$).
4. The drying rate at 60 °C was higher as compared to that of 40 °C and 50 °C.
5. The Midilli *et* al. model obtained the highest $R^2$ and least $\chi^2$ and RMSE at all temperatures and better reflected the drying mechanism of amaranth seed than other five models and was determined to be the best fit.
6. Effective moisture diffusivity recorded 40 to 60 °C increased with the increase in drying temperature.
7. The activation energy and $D_0$ for cabinet drying of amaranth seed at temperature from 40 to 60 °C were found to be 22.99 kJ/mol and $7.86 \times 10^{-5}$ $m^2/s$, respectively.

### 5.2 Recommendations

The following suggestions for future research might be made based on the current study's findings.

1. A specific variety of amaranth seeds can be taken for study.
2. The effect of drying temperatures on the color parameters and microbial properties can be studied.
3. Drying could be performed in controlled condition with respect to air velocity and humidity.

# PART VI

## Summary

Amaranth is a superfood grain and known for its protein, fiber, vitamin and mineral richness— ideal for human as well as animal use. Regular consumption of amaranth grains can be linked to a number of health advantages. For humans, it can be utilized for the preparation of functional food while for animals, it serves as a nutrient-dense feed.

In this study, Amaranth seed was purchased from Kathmandu organics, a grocery store in Kathmandu, Nepal. The study was done to examine the drying kinetics as well as to investigate effect of different drying temperatures on various properties of amaranth seeds and to observe the drying temperature that would retain maximum nutritional value for the use of amaranth in the development of functional foods.

The raw samples were observed for the physicochemical, physical, functional and anti-nutritional properties. The samples were then dried; the range of drying temperatures were 40 °C, 50 °C, and 60 °C; in a cabinet dryer (PCD-E3000 Serials, volts- 220V). The drying kinetics of samples were also observed. The dried samples were further examined for physicochemical, physical, functional and anti-nutritional properties to determine the effect of drying temperature on those parameters. The mathematic modeling of drying kinetics of all three temperatures were carried out in six different models. The Midilli *et* al. model obtained the highest $R^2$, least RMSE and least $\chi^2$ at all three temperatures and better reflected the drying mechanism of amaranth seed than other five models. The effective diffusivity values varied from $1.1592 \times 10^{-8}$ $m^2/s$ at 40 °C to $1.9716 \times 10^{-8}$ $m^2/s$ at 60 °C. Effective moisture diffusivity range of 40 to 60 °C increased with increase in drying temperature. Similarly, the activation energy and $D_0$ for cabinet drying of amaranth seed at temperature from 40 to 60 °C were found to be 22.999 kJ/mol and $7.86 \times 10^{-5}$ $m^2/s$, respectively. Amaranth seeds dried at 60 °C recorded the highest scores for maximum retention of proximate constituents at the end of drying. The drying of seed caused reduction in protein content but increment by approx. 1.25% in fat content at 50 °C and 60 °C and by approx. 5% in crude fiber in all three dried samples content as compared to raw seeds. Amaranth seeds dried at 60 °C showed maximum retention of the phytochemical constituents and maximum reduction of anti-nutritional factors.

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# Appendices

## Appendix A

### A.1 Standard curve

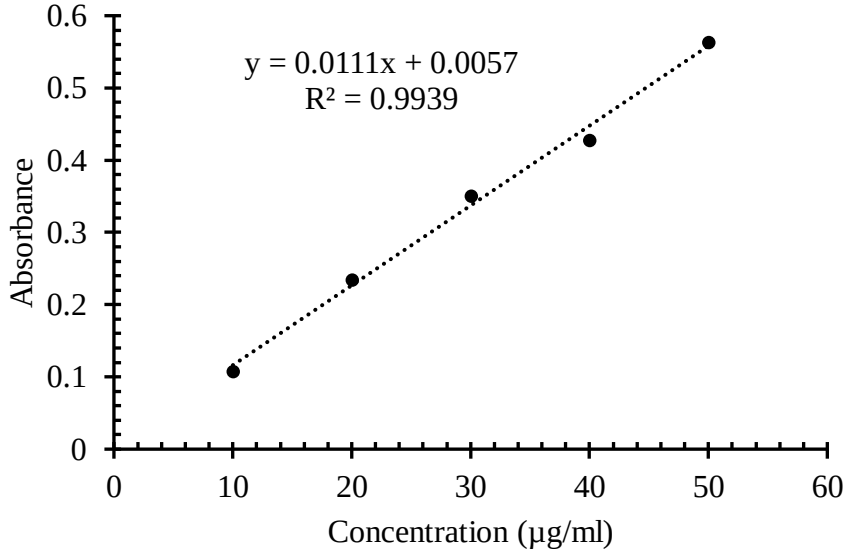



**Fig. A.1** Standard curve for TPC

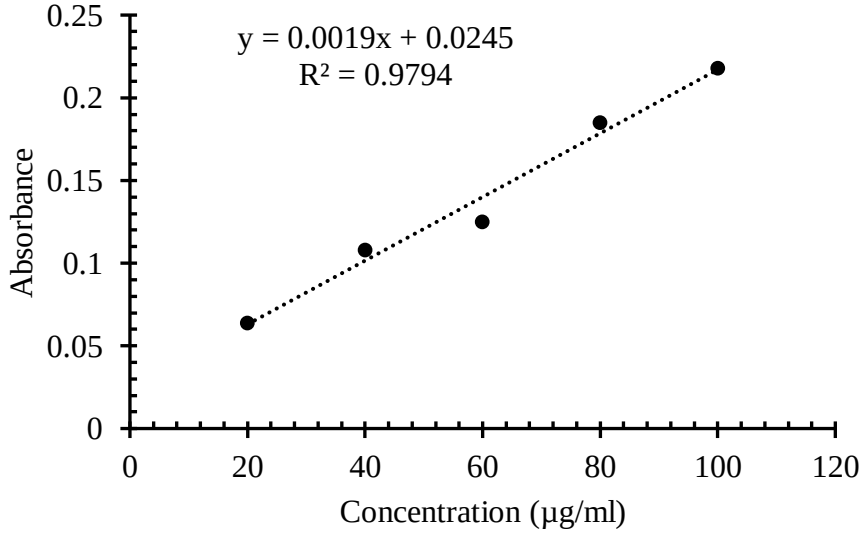



**Fig. A.2** Standard curve for TFC

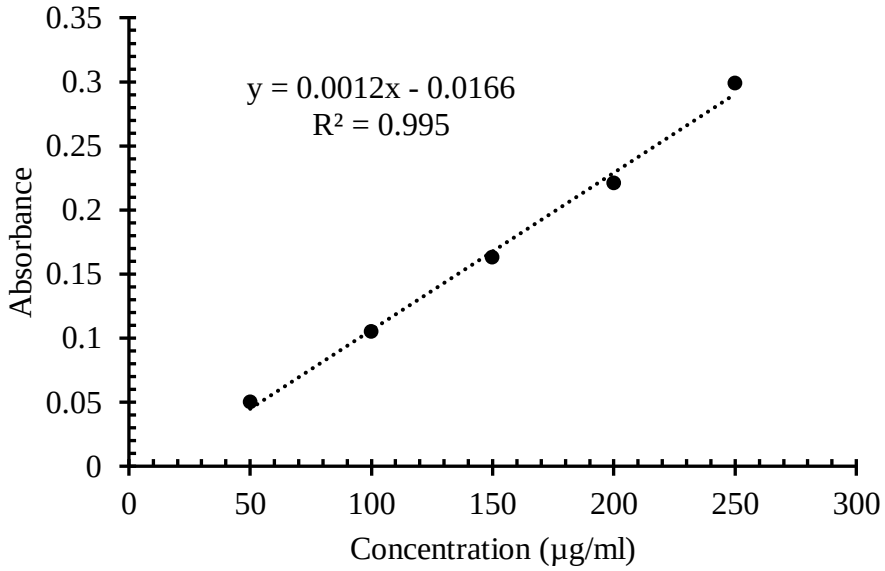



**Fig. A.3** Standard curve for tannin

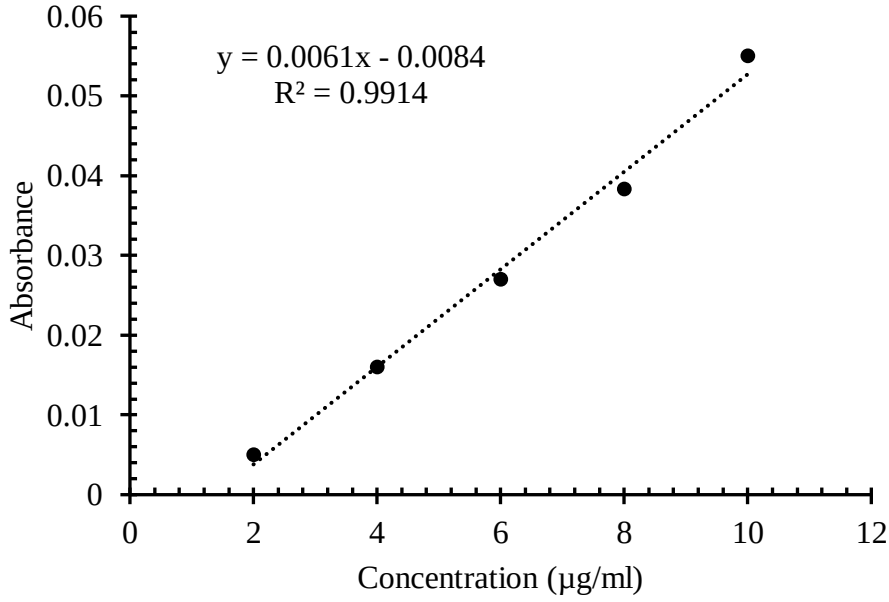



**Fig. A.4** Standard curve for saponin

## Appendix B

### B.1 Analysis of Variance

**Table B.1 One-way ANOVA for physical properties**

| | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| Bulk density | Between Groups | .002 | 3 | .001 | 8.391 | .007 |
| | Within Groups | .001 | 8 | .000 | | |
| | Total | .002 | 11 | | | |
| True density | Between Groups | .001 | 3 | .000 | 262.007 | .000 |
| | Within Groups | .000 | 8 | .000 | | |
| | Total | .001 | 11 | | | |
| Porosity | Between Groups | 4.768 | 3 | 1.589 | 3.685 | .062 |
| | Within Groups | 3.450 | 8 | .431 | | |
| | Total | 8.218 | 11 | | | |
| Thousand kernel weight | Between Groups | .449 | 3 | .150 | 11.978 | .003 |
| | Within Groups | .100 | 8 | .013 | | |
| | Total | .549 | 11 | | | |
| Angle of repose | Between Groups | 20.240 | 3 | 6.747 | 4.179 | .047 |
| | Within Groups | 12.914 | 8 | 1.614 | | |
| | Total | 33.153 | 11 | | | |

**Table B.2 One-way ANOVA for functional properties**

| | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| Dispersibility | Between Groups | 9.667 | 3 | 3.222 | 4.296 | .044 |
| | Within Groups | 6.000 | 8 | .750 | | |
| | Total | 15.667 | 11 | | | |
| Swelling capacity | Between Groups | 20.796 | 3 | 6.932 | 3988.204 | .000 |
| | Within Groups | .014 | 8 | .002 | | |
| | Total | 20.810 | 11 | | | |
| WAC | Between Groups | 1395.626 | 3 | 465.209 | 54.295 | .000 |
| | Within Groups | 68.545 | 8 | 8.568 | | |
| | Total | 1464.171 | 11 | | | |
| OAC | Between Groups | 227.048 | 3 | 75.683 | 7.198 | .012 |
| | Within Groups | 84.116 | 8 | 10.514 | | |
| | Total | 311.164 | 11 | | | |
| Bulk density | Between Groups | .016 | 3 | .005 | 47.381 | .000 |
| | Within Groups | .001 | 8 | .000 | | |
| | Total | .017 | 11 | | | |

**Table B.3 One-way ANOVA for physicochemical composition**

| | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| | Between Groups | 68.915 | 3 | 22.972 | 250598.879 | .000 |
| Moisture | Within Groups | .001 | 8 | .000 | | |
| | Total | 68.915 | 11 | | | |
| | Between Groups | 2.825 | 3 | .942 | 40.467 | .000 |
| Crude protein | Within Groups | .186 | 8 | .023 | | |
| | Total | 3.012 | 11 | | | |
| | Between Groups | .279 | 3 | .093 | 11.222 | .003 |
| Crude fat | Within Groups | .066 | 8 | .008 | | |
| | Total | .345 | 11 | | | |
| | Between Groups | .042 | 3 | .014 | 39.971 | .000 |
| Total ash | Within Groups | .003 | 8 | .000 | | |
| | Total | .044 | 11 | | | |
| | Between Groups | .089 | 3 | .030 | 68.053 | .000 |
| Crude fiber | Within Groups | .004 | 8 | .000 | | |
| | Total | .093 | 11 | | | |
| | Between Groups | 4.092 | 3 | 1.364 | 64.105 | .000 |
| Carbohydrate | Within Groups | .170 | 8 | .021 | | |
| | Total | 4.262 | 11 | | | |
| Energy | Between Groups | 10.662 | 3 | 3.554 | 17.407 | .001 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Within Groups | 1.633 | 8 | .204 | | |
| | Total | 12.295 | 11 | | | |
| | Between Groups | 4759.734 | 3 | 1586.578 | 2344.537 | .000 |
| Calcium | Within Groups | 5.414 | 8 | .677 | | |
| | Total | 4765.147 | 11 | | | |
| | Between Groups | 1244.811 | 3 | 414.937 | 791.182 | .000 |
| Phosphorous | Within Groups | 4.196 | 8 | .524 | | |
| | Total | 1249.007 | 11 | | | |
| | Between Groups | 11.669 | 3 | 3.890 | 1909.917 | .000 |
| FFA | Within Groups | .016 | 8 | .002 | | |
| | Total | 11.685 | 11 | | | |
| | Between Groups | 46.209 | 3 | 15.403 | 1909.917 | .000 |
| AV | Within Groups | .065 | 8 | .008 | | |
| | Total | 46.273 | 11 | | | |
| | Between Groups | 2.371 | 3 | .790 | 40.467 | .000 |
| DCP | Within Groups | .156 | 8 | .020 | | |
| | Total | 2.527 | 11 | | | |
| | Between Groups | 3.803 | 3 | 1.268 | 63.896 | .000 |
| NFE | Within Groups | .159 | 8 | .020 | | |
| | Total | 3.962 | 11 | | | |
| | Between Groups | .042 | 3 | .014 | 39.971 | .000 |
| TOM | Within Groups | .003 | 8 | .000 | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Total | .044 | 11 | | | |

**Table B.4 One-way ANOVA for anti-nutritional factors**

| | | **Sum of Squares** | **df** | **Mean Square** | **F** | **Sig.** |
|---|---|---|---|---|---|---|
| Phytate | Between Groups | .274 | 3 | .091 | 241.292 | .000 |
| | Within Groups | .003 | 8 | .000 | | |
| | Total | .277 | 11 | | | |
| Tannin | Between Groups | .098 | 3 | .033 | 417.628 | .000 |
| | Within Groups | .001 | 8 | .000 | | |
| | Total | .098 | 11 | | | |
| Oxalate | Between Groups | .026 | 3 | .009 | 1024.692 | .000 |
| | Within Groups | .000 | 8 | .000 | | |
| | Total | .026 | 11 | | | |
| Saponin | Between Groups | .153 | 3 | .051 | 151.345 | .000 |
| | Within Groups | .003 | 8 | .000 | | |

**Table B.5 One-way ANOVA for phytochemical composition**

| | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| TPC | Between Groups | .013 | 3 | .004 | 2564.911 | .000 |
| | Within Groups | .000 | 8 | .000 | | |
| | Total | .013 | 11 | | | |
| TFC | Between Groups | 1.185 | 3 | .395 | 1322.687 | .000 |
| | Within Groups | .002 | 8 | .000 | | |
| | Total | 1.188 | 11 | | | |
| TAC | Between Groups | .444 | 3 | .148 | 189.445 | .000 |
| | Within Groups | .006 | 8 | .001 | | |
| | Total | .450 | 11 | | | |
| L-ascorbic acid | Between Groups | 9.249 | 3 | 3.083 | 960.910 | .000 |
| | Within Groups | .026 | 8 | .003 | | |
| | Total | 9.274 | 11 | | | |
| DPPH radical scavenging activity | Between Groups | 7843.888 | 3 | 2614.629 | 55436.814 | .000 |
| | Within Groups | .377 | 8 | .047 | | |
| | Total | 7844.266 | 11 | | | |

## Appendix C

### C.1 Calculation of drying rate

**Table C.1** Calculation of drying rate of amaranth seed dried at 40 ℃

| **Input data** | | **Calculated data** | | |
|---|---|---|---|---|
| Time<br>t<br>(min) | Weight | Moisture wet basis<br>Y<br>g water / g product | Moisture dry basis<br>X<br>g water / g d.s | Drying rate<br>R<br>g water/g d.s / min $m^2$ |
| 0 | 10.3 | 1.1227 | 0.122334456 | |
| 30 | 10.25 | 1.0727 | 0.11688623 | 0.000181608 |
| 60 | 10.218 | 1.0407 | 0.113399366 | 0.000116229 |
| 90 | 10.188 | 1.0107 | 0.110130431 | 0.000108965 |
| 120 | 10.16 | 0.9827 | 0.107079424 | 0.0001017 |
| 150 | 10.138 | 0.9607 | 0.104682205 | 7.99073E-05 |
| 180 | 10.118 | 0.9407 | 0.102502915 | 7.2643E-05 |
| 210 | 10.1 | 0.9227 | 0.100541554 | 6.53787E-05 |
| 240 | 10.1 | 0.9227 | 0.100541554 | 0 |
| 270 | 10.1 | 0.9227 | 0.100541554 | 0 |
| Initial moisture= | 10.9% | | | |
| Tray surface area= | 0.127575 $m^2$ | Dry solid (d.s) content= 9.1773 | | |

**Table C.2** Calculation of drying rate of amaranth seed dried at 50 °C

| **Input data** | | **Calculated data** | | |
|---|---|---|---|---|
| Time<br>t<br>(min) | Weight | Moisture wet basis<br>Y<br>g water / g product | Moisture dry basis<br>X<br>g water / g d.s | Drying rate<br>R<br>g water/g d.s / min $m^2$ |
| 0 | 10.38 | 1.13142 | 0.122334456 | |
| 30 | 10.25 | 1.00142 | 0.108278244 | 0.00046854 |
| 60 | 10.14 | 0.89142 | 0.096384526 | 0.000396457 |
| 90 | 10.06 | 0.81142 | 0.08773455 | 0.000288333 |
| 120 | 9.99 | 0.74142 | 0.08016582 | 0.000252291 |
| 150 | 9.94 | 0.69142 | 0.074759585 | 0.000180208 |
| 180 | 9.9 | 0.65142 | 0.070434596 | 0.000144166 |
| 210 | 9.9 | 0.65142 | 0.070434596 | 0 |
| 240 | 9.9 | 0.65142 | 0.070434596 | 0 |
| Initial moisture= | 10.9% | | | |
| Tray surface area= | 0.127575 $m^2$ | Dry solid content= 9.24858 | | |

**Table C.3** Calculation of drying rate of amaranth seed dried at 60 °C

| **Input data** | | **Calculated data** | | |
|---|---|---|---|---|
| Time<br>t<br>(min) | Weight | Moisture wet basis<br>Y<br>g water<br>g product | Moisture dry basis<br>X<br>g water<br>g d.s | Drying rate<br>R<br>g water/g d.s<br>min $m^2$ |
| 0 | 10.24 | 0.122334456 | 0.122334456 | |
| 30 | 9.96 | 0.091645623 | 0.091645623 | 0.001022961 |
| 60 | 9.75 | 0.068628998 | 0.068628998 | 0.000767221 |
| 90 | 9.67 | 0.05986076 | 0.05986076 | 0.000292275 |
| 120 | 9.6 | 0.052188552 | 0.052188552 | 0.00025574 |
| 150 | 9.55 | 0.046708403 | 0.046708403 | 0.000182672 |
| 180 | 9.55 | 0.046708403 | 0.046708403 | 0 |
| 210 | 9.55 | 0.046708403 | 0.046708403 | 0 |
| Initial moisture= | 10.9% | | | |
| Tray surface area= | 0.127575 $m^2$ | Dry solid content= 9.12384 | | |

# Appendix D

## D.1 Principal Component Analysis (PCA)

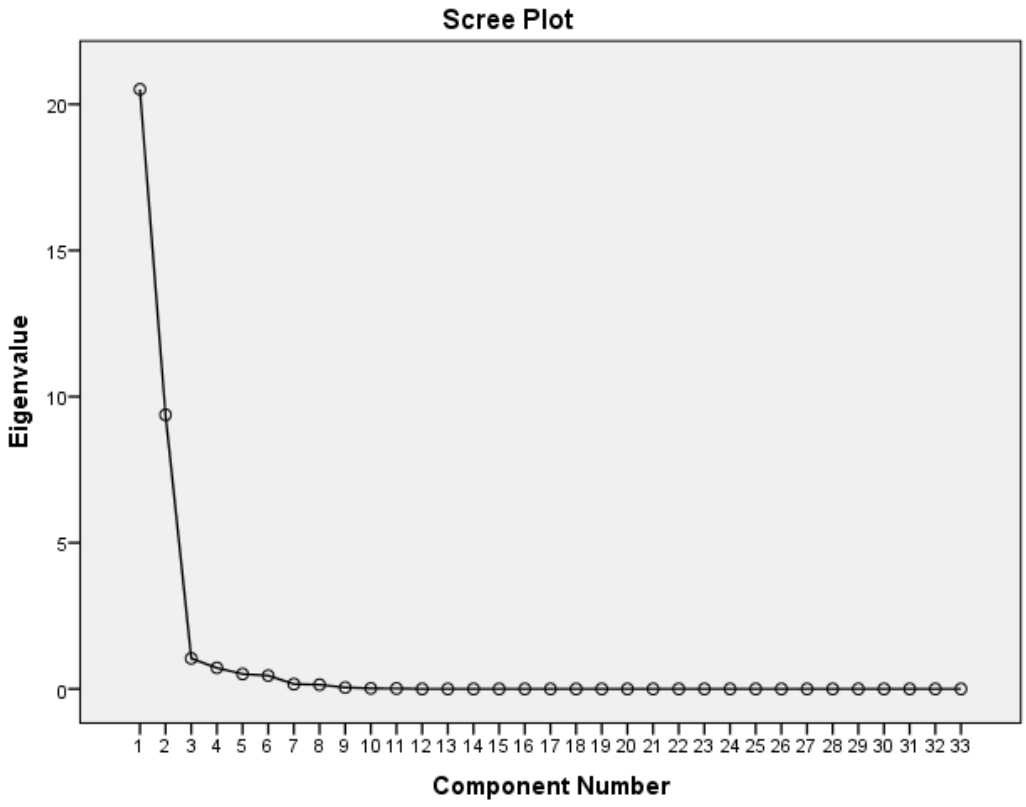



**Fig. D.1** Scree plot showing Eigen value for all the components

## D.2 Hierarchical Cluster analysis (HCA)

**Table D.1** Results by cluster

| **Cluster** | **1** | **2** | **3** | **4** |
|---|---|---|---|---|
| Number of objects by cluster | 3 | 3 | 3 | 3 |
| Sum of weights | 3 | 3 | 3 | 3 |
| Within-cluster variance | 6.975 | 3.569 | 2.002 | 2.591 |
| Minimum distance to centroid | 1.530 | 1.261 | 0.890 | 1.072 |
| Average distance to centroid | 2.111 | 1.510 | 1.141 | 1.293 |
| Maximum distance to centroid | 2.586 | 1.952 | 1.283 | 1.616 |
| | Raw | A | B | C |
| | Raw | A | B | C |
| | Raw | A | B | C |

## Appendix E

**Table E.1** Chemicals used

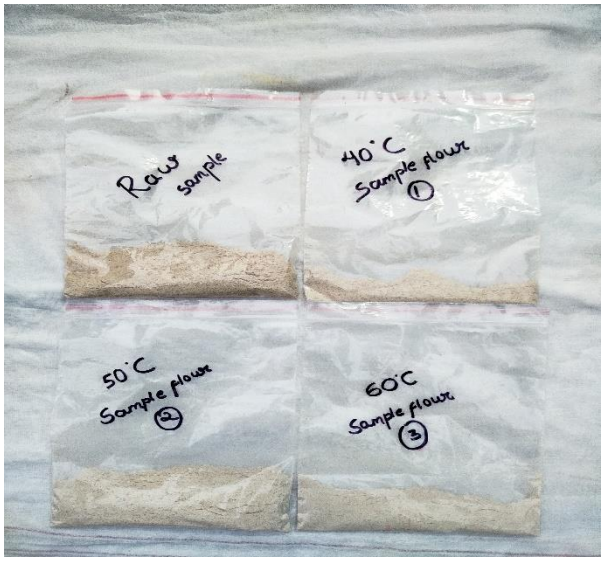
| **Chemicals** | **Manufacturer** | **Assay** |
|---|---|---|
| Ethanol | Sisco | 99.9% |
| Methanol | Sisco | 99.9% |
| Sodium carbonate ($Na_2CO_{3)}$ | Qualigens | 99% |
| Sodium hydroxide (NaOH) | Qualigens fine chemicals | 97% |
| Sulphuric acid ($H_2SO_4$) | Thermofisher scientific India Pvt. Ltd | 97% |
| Hydrochloric acid (HCl) | Thermofisher scientific India Pvt. Ltd | 35-37% |
| Ferric chloride ($FeCl_3$) | Thermo Fischer scientific India, Pvt. Ltd | 96%, |
| Gallic acid | Lobachemie, India | 99.5%), |
| Quercetin | Himedia laboratories India Pvt. Ltd | 98% |

**Table E.2** Apparatus used

| **Equipments** | **Manufacturer** |
|---|---|
| Electric weighing balance | Petra Mechatronics |
| Hot air oven | VITCO |
| Glasswares | Qualigens |
| Rotary shaker | COSLAB |
| Kjeldahl digestion set | Y.P. scientific |
| Muffle furnace | Accumax India |
| Cabinet dryer | Y.P. scientific |
| Whatman filter paper | Whatman International L.t.d |
| Buchner's filter assembly | Labtronics, India |
| Spectrophotometer | Labtronics, India |

## Color plates

**P1** Grain drying in cabinet dryer


**P2** Dried samples for analysis