THE EFFECTS OF DIFFERENT STORAGE ENVIRONMENTS ON THE QUALITY OF STORED *AMADUMBE* (*COLOCASIA ESCULENTA L. SCHOTT)* CORMS, FLOURS, AND THEIR STARCHES

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SUPERVISOR'S APPROVAL

As the candidate's supervisors, I have approved this review and proposal for submission

Supervisor…[redacted] Date…19/01/2022

Professor TS Workneh

DECLARATION

I, Demian Vusimusi Mukansi, declare that:

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RESEARCH OUTPUT

International conference

- Chapter 3 Abstract was accepted for the Vth International Conference on Postharvest and Quality Management of Horticultural Products of Interest for Tropical Regions. The conference was held in Toluca, Mexico (06 – 09 October 2021). This conference could not be attended due to challenges submitting the article.

- Chapter 3 abstract has been submitted to the International Symposium on Postharvest Technologies to Reduce Food Losses. The symposium will be held in Angers, France (14 – 20 August 2021).
  - Link (https://www.actahort.org/members/symposiaa?action=abstractforcoauthor&abstractforcoauthorlink=SeKMmzKXSeKMm-24723-DrikX)

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  - The research was awarded the best engineering industry impact.
  - The researcher was awarded the second-best presenter for the Engineering category.

Manuscript ready for publication

- Mukansi, DV and Workneh, TS. 2022. The Effect of different storage methods on the quality attributes of *amadumbe* (*Colocasia esculenta l. Schott*) corms and their starches: a review:
- Mukansi, DV and Workneh, TS. 2022. The Effect of different storage methods on the physiological and mechanical properties of *amadumbe* (*Colocasia esculenta l. Schott*) corms.

Demian Mukansi (Student) conducted the write-up in all the above manuscripts while the supervisors corrected and proofread the manuscripts.

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ABSTRACT

Amadumbe, the Zulu name for Taro (*Colocasia esculenta L. Schott*), is an edible aroid. *Amadumbe* remains an underutilised crop in South Africa, and very little research is available on the post-harvest storage of the tuber. The tuber has gained interest due to nutritional benefits that protect against certain cancers, sugar diabetes, and cardiovascular diseases. The tuber is susceptible to microbial spoilage because it has a high moisture content. Therefore, there is a need to store *amadumbe* or process it into flour or starch. However, there is limited research done to evaluate the effect of different storage conditions on the quality attributes of *amadumbe* grown in South Africa. This study aimed to determine the optimum storage conditions that result in reduced post-harvest quality loss of *amadumbe*. Three different experimental designs were used in this study. The first two experimental designs had two treatments: storage conditions and storage period. The corms were stored in the following storage conditions:(1) Low-cold storage (LC), (2) High-cold storage (HC), (3) CoolBot® and evaporative cooler storage (CBEC), (4) Underground storage (U), and (5) Ambient storage (A) as a control). The storage period and sampling for experimental design 1 were days 0, 14, 28, 42, 56, and 70, while experimental design 2 was days 0 and 70. The third experimental design had three treatments: storage conditions (Similar to experimental designs 1 and 2), storage period (0 day, 14 day, 28 day, 42 day, 56 day, and 70 days), and temperature (50°C, 60°C, 70°C,80°C, and 90°C). The corms were all stored in three replications using a completely Randomised Block Design. The results showed that High-cold storage conditions (9.26 – 11.54°C, 97.57 – 100.00 %) followed by CoolBot® and evaporative cooler storage conditions (12.32 – 15.72°C, 64.75 – 92.76 %) are best storage methods and resulted in a minimal loss in the quality attributes of *amadumbe* corms, flours, and starches. While Ambient storage conditions (17.30 – 23.59°C, 75.02 – 75.15 %) resulted in a short shelf life and massive loss in quality attributes. High cold storage had the lowest reduction in physiological weight loss, shear force, cutting energy, protein content, starch yield, granular size, swelling power, solubility, and L* of starch. It had the lowest increase in dry matter content, hardness, toughness, specific gravity, flour yield, ash content, crude fibre, and a* of flour. High-cold storage also resulted in the highest increase in water and oil holding capacities, fat content, and b* of starch. Since CoolBot® and evaporative is the second-best storage method, it is recommended that the micro-environment inside a CoolBot® and evaporative cooler be improved by lowering the temperature to 10°C and increasing the ventilation.

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1. INTRODUCTION

Amadumbe (*Colocasia esculenta L. Schott*), also known as Taro, is an edible corm grown in tropical and subtropical regions (Mawoyo *et al.*, 2017). The world production of *amadumbe* stands at approximately 10.2 million tons, and 73 % of that is produced in Africa. The exact quantity of *amadumbe* produced in South Africa is unknown (DAFF, 2011; Muinat *et al.*, 2017). The crop is currently underutilised and produced by small-scale farmers in KwaZulu-Natal, Mpumalanga, Eastern Cape, and Limpopo (Mare, 2009; Mabhaudhi and Modi, 2015). *Amadumbe* has attracted research interest recently, which has resulted in the commodity gaining entry into South Africa's major retail outlets (Mabhaudhi *et al.*, 2017). This development means that the shelf life of the tuber needs to be improved to ensure that it's available for extended periods in the market. The tuber also needs to be processed into other products to ensure that it is available year-round. The tuber has gained recognition due to the health-related benefits it confers to consumers (Falade and Okafor, 2015). This tuber has high resistance starch, which resists the absorption of glucose in the small intestine and helps in reducing health issues like diabetes and obesity (Liu *et al.*, 2006). *Amadumbe* has a high carotene content, which helps protect consumers from certain chronic diseases (Kaushal *et al.*, 2015)

The utilisation of tubers is moving from direct consumption to processed products such as fries, spices, mash, and canned products (Bekele and Haile, 2019). According to Carputo *et al.* (2004) and Kirkman (2007), about 60 % of all potatoes produced in developed countries are consumed as processed products. Kirkman (2007) reported that this trend is due to the consumer's change in lifestyle, which generally prefers convenience over direct consumption that usually requires more time and effort before use. However, for processing to occur, processers need the tubers to be of high quality. According to Hollyer *et al.* (2000), the processing of *amadumbe* chips is similar to the processing of potato chips; thus, the quality attributes for both tubers should be of comparable standards. Naziri *et al.* (2014) and Pérez *et al.* (2005) showed that cassava and *amadumbe* have high moisture content and proposed that the commodity must be consumed or processed immediately after harvesting. However, processing does not always happen immediately. Therefore, there is a need to design storage facilities that will improve the shelf life of tubers. Besides designing storage facilities, processing of *amadumbe* is essential because

it makes the tuber palatable, extends its shelf life, and reduces post-harvest losses (Kaushal *et al.*, 2015).
One of the techniques used for maintaining the quality and shelf life of *amadumbe* is low-temperature storage. Even though low-temperature storage is effective at sprout suppression and extending the shelf life of tubers, it comes with other quality deterioration challenges. Storage of potatoes and *amadumbe* tubers at low temperature enhances the conversion of starch to reducing sugars, resulting in potatoes that are not suitable for the processing industry (Baidoo *et al.*, 2014; Kiaitsi *et al.*, 2020). Tubers with high reducing sugars are not ideal because of the dark fry colour, which is undesirable to consumers (Foukaraki *et al.*, 2016). High-temperature storage is also not desirable because it increases the respiration rate of *amadumbe* (Agbor-Egbe and Rickard, 1991; Sajeev *et al.*, 2004). The majority of *amadumbe* producers are small-scale farmers that don't have access to environmentally controlled storage units (Paul *et al.*, 2016). The farmers use on-farm storage methods, which can reduce the temperature of the storage chamber below ambient conditions (Mehta *et al.*, 2010). Evaporative coolers are affordable alternative storage systems that small-scale farmers can use. They can lower the temperature and increase the relative humidity to conditions that are more conducive for the storage of fruits and vegetables (Tolesa and Workneh, 2017).

The quality of *amadumbe* is determined using biochemical, physiological, and mechanical properties. These properties are important because they give the commodity value. The external properties influence the consumer's acceptability of the product (Mare, 2009). At the same time, the processors use intrinsic properties to determine the suitability of the tuber for processing (Kader and Rolle, 2004). The qualities of *amadumbe* corms, flours, and starches are influenced by storage conditions. Therefore, the current study was undertaken to evaluate the quality attributes of *amadumbe* corms, flours, and starches subjected to different storage conditions.

1.1 Problem Statement

The problem statement of this research is as follows:

The current long-term storage method of tubers uses controlled storage facilities such as refrigerators. These methods require high capital and operating costs which is not sustainable for small-scale farmers. CoolBot® and evaporative cooler and underground storage pits are affordable and readily available methods that can be used to store tubers. However, there hasn't been much work done to evaluate the impact of these methods on the physiological, mechanical, and biochemical properties of corms, flours, and starches of South African *amadumbe* cultivars. The present study assesses the effect of different storage methods on the quality attributes of the commonly cultivated amadumbe variety (*Dumbe-dumbe*) in South Africa.

1.2 Aims

The aim of this research is:

To determine the storage conditions that result in reduced post-harvest quality loss of *amadumbe* corms, flours, and starches.

1.3 Objectives

The objectives of this research are:

1.3.1 General objectives

The objectives of this research are:

a) To evaluate and analyse the effect of the following storage methods: Ambient (A), Underground pit (U), CoolBot® and evaporative cooler (CBEC), High-Cold (HC), and Low-cold (LC) on the quality attributes of *amadumbe* corms, flours, and their starches.

b) To determine whether a controlled environment such as mechanical refrigeration is required for short-term storage of *amadumbe* by analysing and evaluating the quality properties of *amadumbe* corms, flours, and their starches.

1.3.2 Specific objectives

The specific objectives of this chapter are as follows:

a) To determine and analyse the effect of different storage conditions on the physiological, and mechanical properties of *amadumbe* corms.
b) To determine and analyse the effect of different storage conditions on the physicochemical properties of Amadumbe flour.
c) To determine and analyse the effect of different storage conditions on the physicochemical properties of Amadumbe starch.

1.4 Research Questions

To achieve the research objectives, the following research questions will be answered:

a) What is the effect of storage conditions on the mechanical and physiological properties of *amadumbe* corms?
b) What is the effect of *amadumbe* storage conditions on the physicochemical properties of *amadumbe* flour?
c) What is the effect of *amadumbe* storage conditions on the physicochemical properties of *amadumbe* starch?

1.5 Research Hypothesis

The hypothesis of this study is as follows:

a) High-cold storage will significantly impact maintaining the mechanical and physiological properties of *amadumbe* corms.
b) High-cold storage will significantly impact maintaining the physicochemical properties of *amadumbe* flour.
c) High-cold storage will significantly impact maintaining the physicochemical properties of *amadumbe* starch.

1.6 Outline of Dissertation Structure

This dissertation comprises of six chapters:

a) Chapter 1: Introduction.
b) Chapter 2: A review of post-harvest losses and the effect of different storage environments on *amadumbe*.
c) Chapter 3: The physiological and mechanical properties of *amadumbe* corms subjected to different storage methods.

d) Chapter 4: Physicochemical properties of *amadumbe* flour subjected to different storage methods.
e) Chapter 5: Physicochemical properties of *amadumbe* starch subjected to different storage methods.
f) Chapter 10: Conclusion, recommendation, and future research opportunities.

1.7 References

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2. A REVIEW OF POST-HARVEST LOSSES AND THE EFFECT OF DIFFERENT STORAGE ENVIRONMENTS ON *AMADUMBE*

The storage temperature and relative humidity of the storage environment of fruits and vegetables can significantly impact post-harvest losses. These extrinsic factors influence the quality attributes of fruit and vegetable. This review will assess the impact of storage environments on the post-harvest loss of *amadumbe*.

2.1 *Amadumbe*

Amadumbe, the Zulu name for Taro (*Colocasia esculenta L. Schott*), is an edible aroid in the Araceae family (Shange, 2004; Muinat *et al.*, 2017). It is also known as Dasheen, Kolokasie, Eddoe, and old cocoyam (Kaushal *et al.*, 2015). *Amadumbe* is one of the most important species of aroids used as a staple food in tropical and subtropical regions (Agbor-Egbe and Rickard, 1991; Modi, 2007; Gerrano *et al.*, 2019). It has more fibre and ash content than sweet potatoes and cassava (Gerrano *et al.*, 2019). This high fibre content helps regulate blood sugar levels (Kaushal *et al.*, 2015). The nutritional content of *amadumbe* differs due to different factors such as geographical location, cultivar, and environmental factors (Tattiyakul *et al.*, 2006; Naidoo *et al.*, 2015; Mawoyo *et al.*, 2017). The different varieties of *amadumbe* include *Alocasia macrorrhiza* (Giant taro), *Colocasia esculenta* (*amadumbe), Cyrtosperma merkusii* (Giant swamp taro), and *Xanthosoma sagittifolium* (cocoyam) (Kaushal *et al.*, 2015). According to Gerrano *et al.* (2019), *amadumbe* remains an underutilised crop in South Africa, and there is limited information on the agronomic productivity of the crop. In South Africa, the common varieties are Dasheen (*var. esculenta*) and the Eddoe (*var. antiquorum*) (Sibiya, 2015). From Figure 2.1, the Dasheen type produces a large corm and few side cormels, while the Eddoe type produces a small corm with many side cormels. The most cultivated *amadumbe* cultivar in South Africa is *Dumbe-dumbe* (Modi and Bornman, 2004). This cultivar can be characterised as having a red petiole at the upper 3 – 5 cm. The tuber is cultivated between September and October and is harvested around April to July (Mare, 2009). So, storage and proper techniques are needed to guarantee year-round availability.

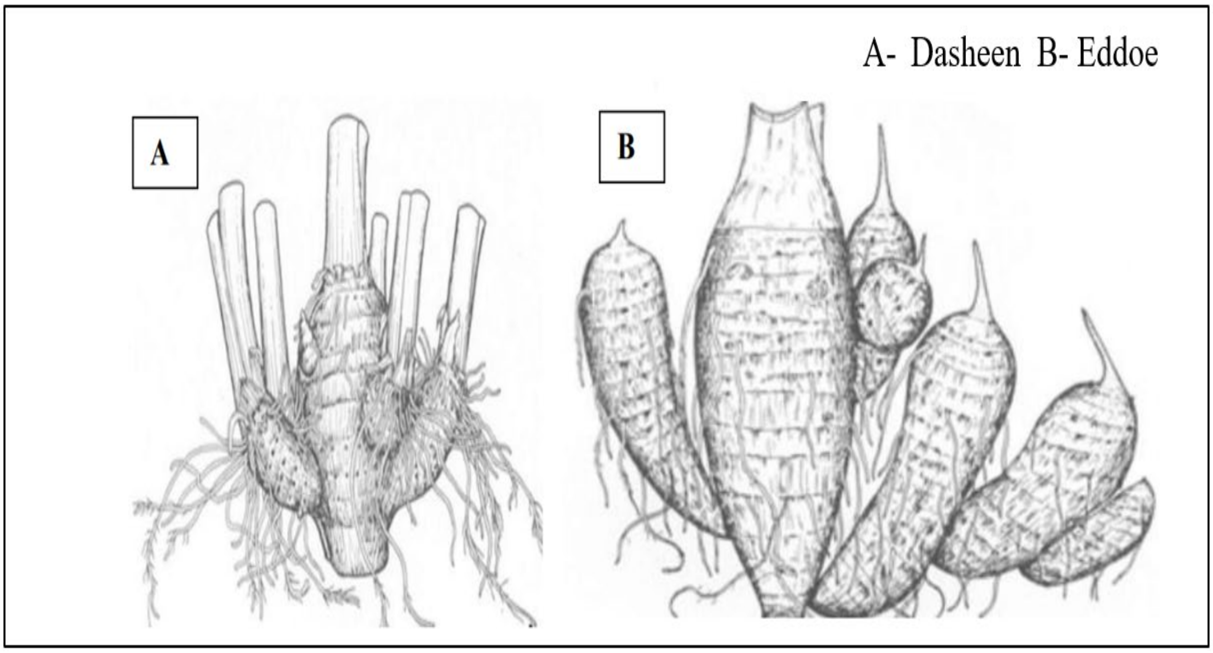

Figure 2.1 Illustration of the structure of two common *amadumbe* varieties (Sibiya, 2015)

2.1.1 *Amadumbe* production and consumption

Table 2.1 shows the global production of *amadumbe*, potatoes, sweet potatoes, and cassava. The world production of *amadumbe* is approximately 10.2 million tons.yr$^{-1,}$ of which 73 % is produced in Africa (FAOSTAT, 2017). Western Africa is the largest producer of *amadumbe* globally. Most production occurs in Cameroon, Nigeria, Ghana, and Burkina Faso (Chaïr *et al.*, 2016). There is limited information on the production of *amadumbe* in Southern Africa (FAOSTAT, 2017). DAFF (2011) also reported that there is currently no record of the production of *amadumbe* in South Africa. However, *amadumbe* is widely grown in the subtropical parts of South Africa, including Mpumalanga, Limpopo, Eastern Cape, and KwaZulu-Natal (Mare, 2009; McEwan *et al.*, 2014). It is not extensively commercialised at present as it is grown mainly by small-scale farmers in rural areas (Mngadi *et al.*, 2015). *Amadumbe* is a source of dietary starches and can be processed by baking, boiling, and roasting, and its leaves are cooked like spinach or as a salad (McEwan *et al.*, 2014). Africa produces more cassava and *amadumbe* than any other continent because the tubers are consumed as a staple food due to their high starch content (Chisenga *et al.*, 2019a; Singla *et al.*, 2020).

Table 2.1 The production of starchy underground, or root, crops in different regions in Africa as a percentage of the global production (FAOSTAT, 2017)

Crop	Global Commodity produced (tons)	Commodity produced by region %					
		Africa	Western Africa	Eastern Africa	Northern Africa	Southern Africa	Middle Africa
Cassava	279304523	60.27	32.75	10.61	–	–	16.91
Sweet potatoes	91219184	29.10	6.37	19.31	0.67	0.09	2.66
Potatoes	373774234	6.82	0.70	1.92	3.36	0.50	0.34
Taro	10529092	73.68	47.00	4.90	1.04	–	20.73

(–) implies that the parameter was not studied.

The presences of calcium oxalate crystals limit the consumption of *amadumbe* due to its association with acridity factors which cause irritation and burning upon consumption (Kaushal *et al.*, 2015). The acridity can be reduced by cooking the tubers before consumption (Sajeev *et al.*, 2004). *Amadumbe* starch has health benefits due to resistant starch and carotene (Naidoo *et al.*, 2015).

The resistant starch content of *amadumbe* was reported to be about 51.50 % of the total dry matter content (Liu *et al.*, 2006; Kaushal *et al.*, 2015). The resistance starch in *amadumbe* was found to be more than maize (1.30 %), rice (6.50 %), potatoes (22.50 %), and wheat (1.00 %) (Van Hung *et al.*, 2016; Van Hung *et al.*, 2017; Liang *et al.*, 2019). *Amadumbe* and yellow sweet potatoes were reported to have high carotene content. (Englberger *et al.*, 2003; Huang *et al.*, 2007). Foods with high carotene content help protect against certain cancers, eye diseases, and cardiovascular diseases (Kaushal *et al.*, 2015).

2.1.2 Nutritional composition of *amadumbe*

The chemical composition of *amadumbe* corms grown in different countries is presented in Table 2.2. The chemical composition varied among the different countries.

Table 2.2 Proximate composition of *amadumbe* corms.

Country	Moisture (%)	Ash (%)	Protein (%)	Lipids (%)	Fibre (%)	Carbohydrates (%)	References
Nigeria	63.00 – 85.00	0.60 – 1.28	1.36 – 3.00	0.18 – 0.39	–	13.00 – 29.00	Onwueme and Charles (1994)
United States of America	65.80 – 72.40	1.00 – 1.80	1.10 – 1.90	0.20	3.60 – 3.80	–	Huang *et al.* (2000)
India	–	0.80	1.50	0.20	4.10	26.40	(Rashmi *et al.*, 2018)
China	63.60 –72.40	0.90 – 1.40	1.80 – 2.60	0.09 – 0.15	–	–	Huang *et al.* (2007)
Tanzania	68.36	1.82	3.89	0.37	1.16	24.43	(Ndabikunze *et al.*, 2011)
South Africa	89.00	3.30 – 4.40	4.50 – 5.04	0.28 – 0.80	–	–	(McEwan *et al.*, 2014)
Uganda	69.05	3.56	3.70	0.51	1.53	21.65	(Ndabikunze *et al.*, 2011)
China	82.88	0.76	2.18	0.09	1.37	–	(Yu *et al.*, 2016)
Papua New Guinea	55.80 – 74.40	0.80 – 1.20	0.50 – 2.10	0.40 – 0.50	3.30 – 5.10	–	(Wills *et al.*, 1983)

(–) Implies that the parameter was not studied.

These chemical and nutritional composition differences can be ascribed to differences in cultivar, geographical location, maturity stage, planting period, and planting conditions (Naidoo *et al.*, 2015; Mawoyo *et al.*, 2017; Rashmi *et al.*, 2018). Huang *et al.* (2007) reported that upland cultivated *amadumbe* retained more moisture and could resist water shortage than *amadumbe* cultivated in flooded conditions. The moisture content ranged from (55.80 – 89.00 %). This high moisture content makes *amadumbe* susceptible to microbial spoilage (Kaushal *et al.*, 2015). Therefore, *amadumbe* is processed into flour to increase its availability in the market (Njintang and Mbofung, 2003). *Amadumbe* has a high fibre content (5.10 %) than potatoes (2.30 %), sweet potatoes (2.30 %), and cassava (0.90 %) (Ukom *et al.*, 2009; Somendrika *et al.*, 2016; Rashmi *et al.*, 2018; Lin *et al.*, 2019). This high fibre content regulates blood sugar levels and aid with the digestion of consumers (Adepoju and Adejumo, 2015). The ash content of *amadumbe* (4.40 %) was found to be less than potatoes (5.80 %) (Huang *et al.*, 2000; Liang *et al.*, 2019). Even though low as compared to potatoes, the ash content could infer that *amadumbe* has a high mineral content (Kaushal *et al.*, 2012). The nutritional quality of *amadumbe* can be affected by post-harvest losses such as sprouting. According to Burton (1955) and Paul *et al.* (2016), if the weight of sprouts reaches 1 % of the tuber's total weight, then the tuber's respiration increases by 50 %, which causes the hydrolysis of starch to increase.

2.1.3 Post-harvest Losses of *Amadumbe*

Post-harvest losses refer to the unintentional loss of food intended for human consumption throughout the value chain (Bendinelli *et al.*, 2019). The level of post-harvest losses in Africa is estimated to be about 30 – 50 % of the total fresh produce market (Kuyu *et al.*, 2019a). The biggest challenge that causes post-harvest losses of fruits, vegetables, tubers, and root crops is the lack of proper storage infrastructures (Kuyu *et al.*, 2019a). Poor transportation and road networks have also been identified as the leading factors to both quantitative and qualitative food losses (Nourbakhsh *et al.*, 2016). The temperature and relative humidity have been classified as the primary contributor to food losses; hence fresh produce should be kept at the recommended storage temperature (Vigneault *et al.*, 2009). The causes of post-harvest losses are classified into three groups: biological, socio-economic, and environmental (Kader, 2002; Babaremu *et al.*, 2019).

Post-harvest decay of up to 60 % was recorded by Agbor-Egbe and Rickard (1991) after storing *amadumbe* and tannia *(Xanthomosa sagittiform)* for 5 to 6 weeks. This value is higher than the post-harvest loss of potatoes (14.14 – 18.82 %), sweet potatoes (19.3 %), and cassava (40 %) stored for five weeks (Jenkins and PD, 1982; Ray and Ravi, 2005; Naziri *et al.*, 2014; Kuyu *et al.*, 2019b). The significant drivers of post-harvest losses are storage temperature, relative humidity, and storage duration (Kuyu *et al.*, 2019b). Other factors contributing to *amadumbe* post-harvest losses are damage during harvesting, respiration, sprouting, and microbial decay (Baidoo *et al.*, 2014). Compared to potatoes, the information on post-harvest technology for storing *amadumbe* is limited (Lewu *et al.*, 2010). Therefore, there is a need to determine the effect of different storage conditions on the chemical composition of *amadumbe* to develop *amadumbe* post-harvest storage infrastructures.

2.2 Post-harvest Storage Conditions of *Amadumbe*

Post-harvest storage management centres on the control of temperature, relative humidity, and proper packaging. The commonly practiced post-harvest storage technologies of *amadumbe* include mechanical refrigeration, evaporative cooling, and underground pits.

2.2.1 Mechanical refrigeration storage

Mechanical refrigeration results in a reduction in the respiration rate of fruits and vegetables, which reduces their deterioration rate (Jiménez-Zurita *et al.*, 2017). Storing *amadumbe* at temperatures below 10°C can cause chilling injuries and promote starch breaking down into reducing sugars (Mehta *et al.*, 2010; Paull and Ching, 2015). In contrast, Malaki *et al.* (2003) reported that no chilling injury occurred in *amadumbe* when stored below 5°C. This finding is not consistent with studies done on other tubers. Li *et al.* (2018) reported that temperatures below 5°C were not suitable for storing tropical tubers as it increases the reducing sugar content. Niu *et al.* (2019) also reported that tropical tubers stored at temperatures below 10°C are susceptible to chilling injuries. According to Herman *et al.* (2017), for potatoes to have a prolonged shelf life, high specific gravity, and low reducing sugar content, they must be stored at 9°C. Sanchez *et al.* (2013) reported that keeping cassava roots at ambient temperatures of 16.5 – 32.1°C resulted in a decreased weight loss, swelling power, gel clarity, starch content, and an increase in total sugars, respiration rate, and paste viscosity.

Figure 2.2 shows changes in the weight loss of *amadumbe* stored in a refrigerator, evaporative cooler, and ambient storage conditions. It depicts that the smallest weight loss occurred to *amadumbe* stored in refrigerated storage conditions compared to ambient and evaporative storage conditions. The lower weight loss in refrigerated conditions is due to lower temperature and higher relative humidity conditions (Sajeev *et al.*, 2004). Despite the numerous environmental control advantages of mechanical refrigeration systems, it is energy-intensive and requires a high initial capital which most small-scale farmers may not possess (Seweh *et al.*, 2016; Gao *et al.*, 2019). This has prompted researchers and small-scale farmers to resort to low-cost storage technologies such as evaporative coolers and underground storage pits.

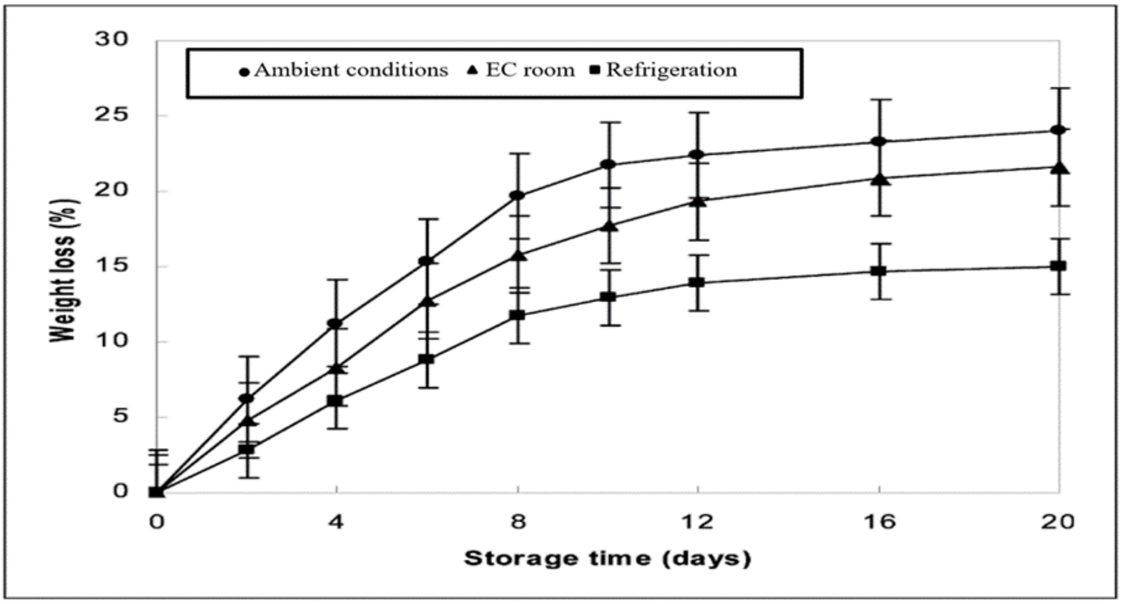

Figure 2.2 Weight loss of *amadumbe* over a 20 day storage period under different storage conditions. EC = evaporative cooler storage (Sajeev et al., 2004).

2.2.2 Evaporative cooler storage

Evaporative coolers (EC) are used to maintain high relative humidity in the storage chamber, which results in a lower weight loss. The key advantage of evaporative coolers is that they are easy to use and affordable to small-scale farmers (Jiménez-Zurita *et al.*, 2017; Babaremu *et al.*, 2019). An EC can keep the temperature between 6 – 12°C below ambient conditions (Singh and Ezekiel, 2003). Tolesa and Workneh (2017) observed that evaporative cooler storage effectively kept the relative humidity at a range of 95.00 – 98.60 %. However, they obtained a temperature of 17 – 22°C, which is above the recommended storage temperature for most fruits and vegetables. To reduce the temperature, they combined CoolBot® air condition and evaporative cooler storage and achieved temperatures in the range of 8 – 15°C (Tolesa and

Workneh, 2017). A CoolBot® system converts an air conditioning system into a cooler by changing the setting of an air conditioner to allow lower temperatures in the range of 0 – 2°C (Saran *et al.*, 2013). These technologies have been created to control environmental properties such as temperature and relative humidity (Babaremu *et al.*, 2018). Presently no work has been done to evaluate the effect of CoolBot® and evaporative cooler storage conditions on the quality of *amadumbe.* In Figure 2.2, an evaporative cooler with environmental conditions of (26.20 – 33.90°C, 59 – 92 %) achieved a lower percentage weight loss of 21.50 % than 23.40 % achieved during ambient storage conditions. Due to the technical challenges relating to the availability, ease of use and designing of evaporative coolers, small-scale farmers still make use of traditional storage methods such as underground storage pits.

2.2.3 Underground storage pits

Storage pits are one of the on-field methods used by farmers for the short-term storage of fruits and vegetables. The on-farm methods are cost-effective and help extend the shelf life of tubers for a short-term of about 2 – 4 months (Paul *et al.*, 2016). These storage pits can keep the temperature and relative humidity in the range of 28 – 30°C and 38 – 66 %, respectively (Singh and Ezekiel, 2003). However, in another study, Mehta et al. (2010) reported that the temperature and relative humidity were in the range of 21 – 32°C and 51 – 95 %, respectively. This difference may be because the experiments were conducted in different climatic conditions.

Traditional storage methods differ in efficiency; as a result, the weight loss of potatoes stored in underground storage pits can range between 15 – 80 % (Ezekiel *et al.*, 1999). The weight loss is influenced by the storage period, the type of storage, and the maturity stage of the tuber (Paul *et al.*, 2016). Obetta *et al.* (2007) studied the effect of ventilation on the storage of *amadumbe*. The results showed that having an improved ventilation system can reduce the temperature by 2.3 °C and increase the relative humidity by 11 %. The percentage weight loss of 13.50 % obtained in refrigeration storage condition (10°C, 65 %) by Sajeev *et al.* (2004) is in the same range of the 8.10 – 20.20 % reported by Obetta *et al.* (2007) in underground storage (28.60 –30.90°C, 72 – 83 %). This is because relative humidity plays a significant role in fruit storage. When kept high, it results in the development of fungal diseases, but when kept low, it results in excessive weight loss (de Oliveira *et al.*, 2016). The loss in weight that occurs when fruits are stored at low relative humidity is due to an increase in the vapour pressure difference, which causes the transpiration rate to increase (Ramaswamy, 2014).

Agbor-Egbe and Rickard (1991) found that increasing relative humidity decreases the respiration rate and results in a lower weight loss of *amadumbe* under controlled temperature. According to Singh and Ezekiel (2003), the dormancy stage influences the weight loss of tubers stored at different relative humidity's. Dormant tubers lose more weight at a low relative humidity between 30 – 35 %, while sprouted tubers lose more at 90 – 95 %. This increased weight loss in sprouted tubers is due to a higher permeability through the sprouts. According to Burton (1955) and Paul *et al.* (2016), if the weight of sprouts reaches 1 % of the tuber's total weight, then the tuber's respiration increases by 50 %. The storage of *amadumbe* in underground pits is a common practice in countries such as Samoa and Egypt (Onwueme and Charles, 1994). However, most of these studies only focused on the shelf life rather than the physicochemical properties and suitability of the tubers for various processing industries. Since different storage environments influence the quality of *amadumbe*, there is a need to quantify these changes from the perspective of physiological, mechanical, and biochemical properties of *amadumbe*.

2.3 Physiological, Mechanical, and Biochemical Properties of *Amadumbe*

Quality is one of the most vital properties of tubers, and it is quantified using both internal and external properties of the tuber. The external properties give the commodity value by attracting the consumer's desire to buy the product. On the other hand, the internal properties are essential to processors because internal properties influence the quality and the profit of the processing product. All these attributes can be grouped into physiological, mechanical, and biochemical factors, which are used to assess the quality of *amadumbe*.

2.3.1 Physiological Properties of *amadumbe*

Amadumbe are living tissues and will continue to respire even after harvest. A higher respiration rate increases tissue aging and limits the tuber's repel of micro-organisms (Tano *et al.*, 2005). To limit post-harvest losses, it is necessary to control the metabolism of *amadumbe* because an increase in respiration rate causes an increase in physiological weight loss.

2.3.1.1 Respiration of *amadumbe*

Respiration is a metabolic process that provides plants with the required energy for biochemical and physiological processes (Fonseca *et al.*, 2002). Respiration is achieved by the breaking down of complex organic molecules into simpler ones that include CO_2, H_2O, and energy releases (González-Buesa and Salvador, 2019). Therefore understanding all the factors that influence respiration is vital to generate strategies to reduce the respiration rate (Guo *et al.*, 2013). The respiration rate of fresh produce is influenced by the produce's genotype, climate, and stage of maturity (Meena and Asrey, 2018). Measuring respiration is very useful when designing modified atmospheric packaging (MAP) (Kahramanoğlu, 2019). Measuring respiration is done by quantifying the amount of O_2 consumed or the CO_2 produced by the product (Bhande *et al.*, 2008).

2.3.1.2 Physiological weight loss of *amadumbe*

Weight loss occurs due to a loss in moisture associated with the storage of fruits and vegetables. Abbasi *et al.* (2016) reported that weight loss occurred at all temperatures during storage, but the weight loss for potatoes stored at 5°C was lower than those held at 15 and 25 °C. Weight loss occurred at all temperatures due to moisture loss by evapotranspiration and loss of dry matter due to respiration (Ghazavi and Houshmand, 2010). There is a direct relationship between storage temperature and loss of moisture because temperature affects the respiration rate. Therefore, there is a need to determine the optimum storage method of *amadumbe* with minimal weight loss while preserving other quality attributes. Other quality attributes include mechanical properties like texture which influences the consumer's acceptability of tubers.

2.3.2 Mechanical properties of *amadumbe*

Physical properties necessary for processing and engineering purposes can be classified as mechanical properties (Masood and Trujillo, 2016). These properties are used in equipment design for storage, transportation, and processing (de Figueiredo *et al.*, 2011). They are some of the factors consumers use to determine the suitability of *amadumbe* for consumption (Sajeev *et al.*, 2004). Specific gravity and dry matter content are used in the crisp-making industry to determine the suitability of the tubers for processing (Abebe *et al.*, 2013). Thus, it becomes crucial to consider the mechanical properties of amadumbe under different storage conditions.

2.3.2.1 Specific gravity

Specific gravity is used as an indicator of tuber quality because of the strong Pearson's correlation to dry matter content and starch content which range from 0.96 – 1 (Mohammed, 2016). The specific gravity should be high for processing purposes, but tubers with high specific gravity are susceptible to bruising (Bekele and Haile, 2019). The current method of measuring and calculating the specific gravity is influenced by all the factors that affect the buoyancy of tubers in water. The skin of *amadumbe* tubers is made of layers of corky cells which trap gas in between the layers, thus affecting the buoyancy of the tuber (Kleinkopf *et al.*, 1987). Hallow heart, which is the cavity at the centre of tubers, also impacts the buoyancy and ability to take accurate measurements of specific gravity.

The specific gravity of tubers also declines from head to tail within an individual tuber, with the central part giving a more accurate representation of the whole tuber (Kleinkopf *et al.*, 1987; Teye *et al.*, 2011). The water and tuber pulp temperatures also impact the buoyancy of tubers. Thus, corrections are needed for temperature if the measurement is carried out at different temperatures (Kleinkopf *et al.*, 1987). The production of potato crisps requires potatoes with a specific gravity higher the 1.08 (Hollyer *et al.*, 2000). The higher the specific gravity, the less oil is absorbed during processing (Kirkman, 2007; Abebe *et al.*, 2013). Thus, a high specific gravity will be suitable for reducing operating costs (Hollyer *et al.*, 2000). Since the processing of *amadumbe* chips is similar to potato chips, the quality must be of comparable levels to produce good quality chips.

Mare (2009) reported the specific gravity of South African *amadumbe* tubers to range between 0.97 – 1.09, making some of them suitable for processing into chips. Since the storage of *amadumbe* has a significant impact on the degradation of starch (Modi and Mare, 2016), there is a need to evaluate whether this will have an impact on the specific gravity. Studies in literature have not reported any study that evaluated the impact of different storage conditions on specific gravity of *amadumbe*.

2.3.2.2 Dry matter content

The dry matter content of tubers is a vital parameter often linked with the product's nutritional value (Nielsen *et al.*, 2016). Determination of dry matter content is crucial for both the processor and researchers who want to monitor the nutrition of potatoes and sweet potatoes (Pinhero *et al.*, 2016). The traditional method for indirectly measuring dry matter content using the density of potatoes, as described by Nissen (1955), is time-consuming. Su and Sun (2017) also attest that conventional dry matter content determination methods are labour intensive, destructive, and inefficient in most cases. To mitigate this, Nielsen *et al.* (2016) used dielectric spectroscopy in the microwave frequency band by looking at the interaction of electric fields and biological tissues to measure the dry matter content. Hoque *et al.* (2018) measured dry matter by heating potatoes in an oven at 65 °C for at least 48 hours till the potatoes reached a constant weight. The same approach was used by Bekele and Haile (2019), at 105°C for 3 hours. Heating at high temperatures needs to be done for a small duration (2 – 3 hours) because drying at temperatures greater than 60°C for longer durations causes chemical changes in the sample that affect subsequent testing (Adegunwa *et al.*, 2011; Bekele and Haile, 2019). Despite the method being old, it is still favoured as it gives reliable results (Mohammed, 2016).

2.3.2.3 Texture

The texture is a vital attribute in determining the overall quality and the consumer acceptability of fruits and vegetables (Sajeev *et al.*, 2004). Afoakwa and Sefa-Dedeh (2002) reported that texture is one of the three main qualities consumers use in determining the acceptability of fruits and vegetables, the others being flavour and appearance. External attributes of food quality include firmness. Thus, preserving this attribute is vital in gaining consumer acceptability (Carputo *et al.*, 2004; Bekele and Haile, 2019). Textural parameters are measured using a texture analyser with test parameters, such as distance, test speed, pre and post-test speeds (Afoakwa and Sefa-Dedeh, 2002). Figure 2.3 illustrates a typical force vs. deformation curve during the compression and cutting of *amadumbe* corms. The peak of the compression test gives the hardness, and the area under the curve gives the toughness. The peak of the cutting test gives the cutting force, whiles the area under the curve gives the cutting energy (Sajeev *et al.*, 2004).

A study by Sajeev *et al.* (2004) reported that the texture parameters such as hardness, cutting force, cutting energy, and toughness, increased during storage of 20. The same results were obtained by Afoakwa and Sefa-Dedeh (2002) on trifoliate yam (*Dioscorea dumetorum*) tubers just after 72 hours of harvest. The increase in texture parameters is due to the thickening of the cell wall concomitant with the lignification of tissues. Biochemical reactions between components present in *amadumbe* corms, such as calcium-induced hardness of pectin and the reduction of moisture, increase the texture parameters (Afoakwa and Sefa-Dedeh, 2002; Sajeev *et al.*, 2004). Therefore, it is important to determine how a loss in moisture will influence biochemical reactions that change the texture properties of the tubers.

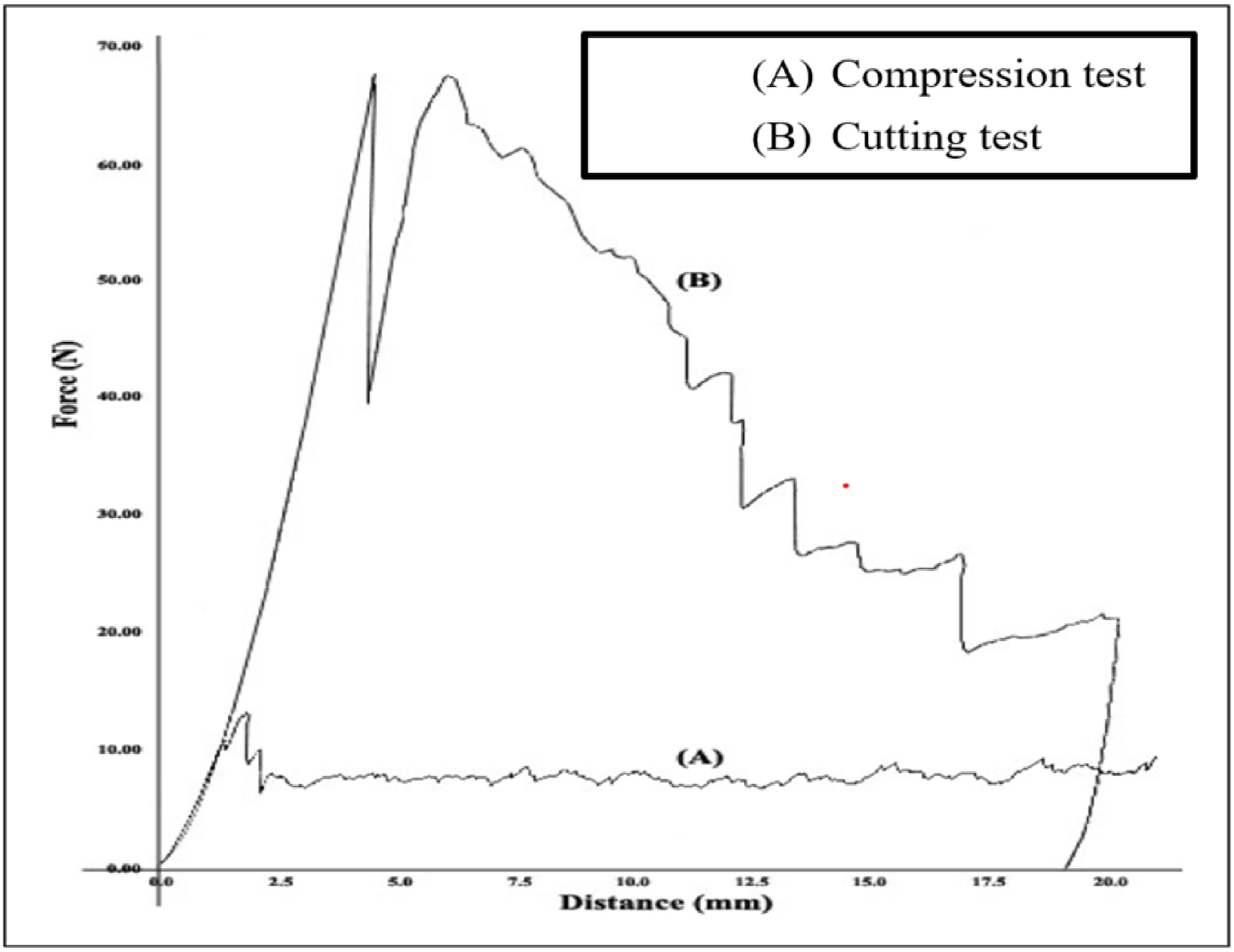

Figure 2.3 Force vs. deformation curve during cutting and penetration of *amadumbe* (Sajeev et al., 2004)

2.3.3 Biochemical properties of *amadumbe*

Biochemical properties are the chemical composition that is found in the tubers. The biochemical properties are used mostly by processors to access the value and suitability of the tuber for processing. Starch quality is one of the crucial factors that processors use to determine the suitability of the flour or starch for various processes. Some of the physicochemical properties of *amadumbe* starch are granular morphology, water, and oil holding capacities, swelling power, and solubility.

2.3.3.1 Reducing sugars

Low-temperature storage is used to prevent sprouting and decay in tubers. However, total sugar accumulation occurs in tubers when stored at temperatures below 10°C (Lin *et al.*, 2019). Kiaitsi *et al.* (2020) also reported that storing potatoes at 1.5°C resulted in the accumulation of reducing sugars. Reducing sugars are responsible for enzymatic browning during the frying of potato crisps which is not desirable for consumers (Xiao *et al.*, 2018). Enzymatic browning is undesirable as it leads to the formation of a cancer-causing substance known as acrylamide due to reactions between reducing sugars and amino acid asparagine (Lin *et al.*, 2017). *Amadumbe* chips also need to have low levels of reducing sugar content to produce good quality chips (Hollyer *et al.*, 2000). Although low-temperature storage can be used as a sprout suppressing technique, the challenge that comes with increased reducing sugar content still needs more scientific attention (Paul *et al.*, 2016). The combination of glucose and fructose makes up the reducing sugar content in tubers (Ngobese *et al.*, 2017). The standard method of measuring sugars is high-pressure liquid chromatography, which separates sugars based on their polarity (Magwaza and Opara, 2015). Baidoo *et al.* (2014) reported that reducing sugar content in *amadumbe* ranged between 1.8 – 1.9 % at room temperature and 1.8 – 2.1 % at cold storage for 21 days. This differs from 0.3 – 0.5 % recorded by Mare (2009) after three months of storage. These differences may be due to differences in *amadumbe* cultivars tested. Thus, there is a need to evaluate how South African *amadumbe* cultivars behave under different storage conditions.

2.3.3.2 Starch

Starch is one of the largest biomass on earth because it is available in abundance, easily accessible, renewable, and biodegradable (Liu *et al.*, 2017). Starch production is expected to increase due to its usage in the textile, paper, and medicinal industries (Abebe *et al.*, 2013). Starch has remarkable properties such as high paste viscosity, freeze-thaw stability, and high paste clarity, making it suitable for use in many industries (Adejumo *et al.*, 2020).

Starch makes up the largest portion of tuber dry matter content, and therefore, proper extraction of it is important for food and other industries that use starch (Raigond *et al.*, 2015). Its granules have a semi-crystalline structure and are composed of amylopectin, which accounts for crystallinity, and amylose, the amorphous component (Ngobese *et al.*, 2017). *Amadumbe* corms have a high starch content, low amylose content, and are small in size (Naidoo *et al.*, 2015). These attributes make *amadumbe* suitable for producing biodegradable starch nanocrystals to make packaging material (Mukurumbira *et al.*, 2017).

According to Agbor-Egbe and Rickard (1991), an increase in temperatures enhances the respiration rate of edible aroids *amadumbe* and tannia. Increasing the temperature also has a significant impact in increasing the reducing sugars of *amadumbe* and promoting the degradation of starch granules during storage (Modi and Mare, 2016). Abbasi *et al.* (2016) reported lower starch content in potatoes stored at 5°C than at 15 and 25°C. The degradation of starch granules is due to an increase in alpha-amylase, which hydrolyses the alpha glycosidic bonds (Zhang *et al.*, 2002). According to Modi and Mare (2016), starch stored for a period of time experiences degradation. Therefore, storing *amadumbe* in different storage environments may result in changes in the physicochemical properties of *amadumbe* flour and their starch due to alpha-amylase activity that is sensitive to temperature.

2.4 Physicochemical Properties of *Amadumbe* Flour and Starch.

Several physicochemical properties are used to measure the quality of amadumbe flour and starch, such as granular morphology, colour, nutritional value, swelling power, solubility, and water and oil absorption capacities. These properties are discussed in the following sections.

2.4.1 Chemical composition of *amadumbe* flour and starch

Table 2.2 shows the proximate composition of flours and starches derived from *amadumbe*, potatoes, sweet potatoes, and cassava. The proximate composition varied with the different tuber sources. The variation is due to differences in the genotype of the tubers (Naidoo *et al.*, 2015). The moisture content of *amadumbe* flour and starch ranged from 7.70 –11.40 % and 7.91 – 14.01 %, respectively. The higher moisture of starch above 9 % indicates that the shelf life of *amadumbe* starch may be less than that of *amadumbe* flour (Kaur *et al.*, 2013). The moisture content of *amadumbe* starch is more than 12 %; thus, it may be susceptible to microbial growth (Aryee *et al.*, 2006). For extended storage of *amadumbe*, it may need to be processed into flour and only processed into starch when required.

The ash content ranged from 0.09 – 0.70 % and 1.0 – 5.70 % for *amadumbe* starch and flour, respectively. Higher ash content in *amadumbe* flour than starch is expected because, during starch extraction, the pulp is discarded (Chisenga *et al.*, 2019a). The discarded pulp contains some of the proximate and mineral compositions of *amadumbe*. The ash content of *amadumbe* starch and flour is > Potato > Cassava > Sweet potatoes. The small presence of non-starch components such as protein, fibre, and lipids in *amadumbe* starch can also indicate proper starch extraction. The protein content of *amadumbe* flour and starches ranged from 0.13 – 5.40 % and 0.38 – 0.70 %, respectively. This range is comparable with the other tubers, but it's inferior compared to other sources of flours and starches such as wheat and corn (Sandhu *et al.*, 2007; Chen *et al.*, 2015).

Table 2.3 proximate composition of *amadumbe*, sweet potato, cassava, and potato flour and starch

Source	Sample	Moisture (%)	Ash (%)	Protein (%)	Lipids (%)	Fibre (%)	References
Amadumbe	Starch	14.01	0.20	0.53	0.27	–	Pérez *et al.* (2005)
Amadumbe	Starch	7.91	0.32	0.66	0.07	–	Himeda *et al.* (2012)
Amadumbe	Starch	11.80	0.09	0.38	–	–	Nwokocha *et al.* (2009)
Amadumbe	Starch	10.40 – 11.40	0.60 – 0.70	0.50 – 0.70	0.30 – 0.40	0.20	Sit *et al.* (2014)
Amadumbe	Flour	8.20 – 9.60	1.30 – 5.50	2.90 – 4.90	0.30 –1.17	–	Njintang *et al.* (2008b)
Amadumbe	Flour	10.20	4.15	0.13	0.50	0,75	Kaushal *et al.* (2012)
Amadumbe	Flour	9.70 – 10.80	3.50 – 5.70	2.70 – 5.40	0.40 – 0.60	0.40 –1.20	Njintang *et al.* (2008a)
Amadumbe	Flour	7.70	1.20	2.00	1.00	–	Kaur *et al.* (2013)
Cassava	Starch	5.51 – 6.91	0.14 – 0.23	0.37 – 0.61	0.03 – 0.17	0.11 – 0.46	Chisenga *et al.* (2019b)
Cassava	Flour	12.02	1.64	1.55	0.84	1.73	Dudu *et al.* (2019)
Sweet Potato	Starch	12.65 –13.80	0.01 – 0.10	0.09 – 0.11	0.42 – 0.55	–	Lee and Lee (2017)
Sweet Potato	Flour	7.30 – 8.00	1.20 – 1.50	2.40 – 2.90	0.60 – 0.90	–	Ndangui *et al.* (2014)
Potato	Starch	10.60	0.80	0.40	0.20	0.10	Sit *et al.* (2014)
Potato	Flour	7.50	1.90	2.20	0.33	–	(Kaur *et al.*, 2013)

(–) Implies that the parameter was not studied.

2.4.2 *Amadumbe* flour and starch granule morphology

Table 2.4 shows the morphology and colour of flours and starches derived from *amadumbe*, potatoes, sweet potatoes, and cassava. In Table 2.4, *amadumbe* starches have been reported to have polygonal and irregular shapes. A scanning electron microscope is commonly used to measure starch morphology (Sit *et al.*, 2014; Oyeyinka *et al.*, 2021). The granule size of *amadumbe* starches ranges between 1.10 – 5. 00 µm. This range was found to be way low in comparison to cassava, potatoes, and sweet potatoes. The granule size and shape are determined by the botanical attributes of the cultivar from which starch is derived (Alcázar-Alay and Meireles, 2015). Therefore, different ranges were observed in the various studies shown in Table 2.4. According to Lindeboom *et al.* (2004), starch granule size less than 5 µm is classed as very small. The small granule size significantly impacts the solubility and water holding capacity of starch (Chisenga *et al.*, 2019c). Small granules have an increased surface area, thus retaining more water (Lindeboom *et al.*, 2004). The small granule size of *amadumbe* is not only favourable for food-related industries. Naidoo *et al.* (2015) and Mukurumbira *et al.* (2017) showed that small granule starches are desirable for forming biodegradable packaging materials. According to Modi and Mare (2016) and Singh *et al.* (2008), starch degradation starts with roughening of the surface followed by indentations, which becomes more profound and causes the granule to break up into smaller pieces. Table 2.4 also shows that the reported studies did not focus on the morphology of flours; therefore, the possible changes in the morphology of flours due to different storage conditions still need to be explored.

2.4.3 *Amadumbe* flour starch colour

The colour can be determined by measuring the L*, a*, and b*. L* represents the degree of whiteness, a* the region of redness for positive values to greenness for negative values, and b* the region of yellowness for positive values to blueness for negative (Oyeyinka *et al.*, 2021). In Table 2.4, *amadumbe* starch has been reported to have a higher degree of whiteness than *amadumbe* flour because of lower fibres and other non-starch components (Kaushal *et al.*, 2015). The whiteness of *amadumbe* starches (93.3 – 96.94) is comparable to other tubers. Baidoo *et al.* (2014) reported that storing *amadumbe* in cold and ambient storage conditions for 21 days showed no significant change in the colour of *amadumbe*. Despite these findings, the impact of longer durations and different storage conditions still need to be eluded.

Table 2.4 The morphology and colour of *amadumbe* flours and their starches

Source	Sample	Shape	Diameter (µm)	L*	a*	b*	References
Amadumbe	Starch	Polygonal and irregular	1.10 – 4.20	93.3 – 94.4	1.90 – 2.20	4.30 – 4.80	Sit *et al.* (2014)
Amadumbe	Starch	Polygonal and irregular	2.00 – 5.00	96.34 – 96.94	0.04 – 0.10	0.89 – 1.14	Oyeyinka and Amonsou (2020)
Amadumbe	Flour	–	–	85.50	1.50	7.50	Kaur *et al.* (2013)
Cassava	Starch	Polyhedral and irregular shape	4.00 – 18.00	90.27	6.45	8.55	Oyeyinka *et al.* (2021)
Cassava	Starch	Spherical, and irregular shape	6.00 – 21.00	93.20 – 96.30	-0.67 – 1.28	4.65 – 4.66	Oyeyinka *et al.* (2019)
Cassava	Flour	–	–	93.88 – 95.71	-0.97- 0.32	5.88 – 10.22	Oduro-Yeboah *et al.* (2010)
Potato	Starch	Oval and spherical	7.60 – 47.60	95.20	1.70	3.10	Sit *et al.* (2014)
Potato	Flour	–	–	86.10	-0.12	12.60	Kaur *et al.* (2013)
Sweet Potato	Starch	round, spherical, and polygonal	18.70 – 22.96	94.67 – 96.29	0.03 – 0.06	1.37 – 2.49	Lee and Lee (2017)
Sweet Potato	Starch	round, polygonal, oval, and hemispherical	1.50 – 84.00	91.40 – 96.83	-0.30 – 0.36	–	(Wang *et al.*, 2020)
Sweet Potato	Flour	–	–	85.84	2.42	25.49	(Ahmed *et al.*, 2010)

(–) Implies that the parameter was not studied.

2.4.4 *Amadumbe* starch and flour water and oil holding capacities

Oil holding capacity indicates the emulsifying ability of starch and shows how much oil will be absorbed during processing (Falade and Okafor, 2013). High water and oil holding capacities are required when producing viscous foods such as soups and gravies (Kaushal *et al.*, 2012). The water and oil holding capacities of *amadumbe* flour ranged between 60 – 250 % and 270 – 350 %, respectively, when conducted at 60 – 80°C (Kaur *et al.*, 2013; Kaushal *et al.*, 2015). Studies have shown that *amadumbe* water and oil holding capacities is a function of temperature (Sit *et al.*, 2014; Chisenga *et al.*, 2019b). This relationship is constant for other tubers such as sweet potatoes and cassava that showed the water and oil holding capacity increase as a function of temperature (Tetchi *et al.*, 2007). Njintang *et al.* (2008b) reported that the water holding capacity of *amadumbe* starch ranged between 60 – 249 %. The higher water absorption capacity of flour than starch is due to other non-starch compounds (Naidoo *et al.*, 2015). The ability of starch to absorb water and swell is determined by the amylose and amylopectin ratio (Himeda *et al.*, 2012). Therefore alteration in the composition of starch affects its ability to retain water and oil (Falade and Okafor, 2013).

2.4.5 *Amadumbe* flour and starch swelling power and solubility

Table 2.5 shows the swelling power and solubility of flours and starches derived from *amadumbe* corms. The swelling power of *amadumbe* ranged between 2.52 – 31.50 and 2.15 – 23.50 $g.g^{-1}$ for starch and flour, respectively. The lower swelling of *amadumbe* flour is due to other non-starchy compounds that reduces their interaction with water (Njintang *et al.*, 2008b). The solubility of *amadumbe* starch and flour ranged between 1.12 – 18.50 and 1.45 – 26.50 %, respectively. An increase in the temperature increases the swelling power of both *amadumbe* flour and starch (Mawoyo *et al.*, 2017). This increase is caused by temperature breaking the hydrogen bonds and exposing more hydroxyl and hydrophilic substances that bind with water. Baidoo *et al.* (2014) reported that the swelling power reduced during storage, with cold storage showing a higher swelling power than ambient storage conditions. Modi and Mare (2016) also found that degradation was higher for *amadumbe* stored in ambient conditions than those held at 12°C. This degradation in starch results in a reduction in the ability of the granule to swell (Dey and Sit, 2017).

Table 2.5 The swelling and solubility of amadumbe flour and their starches at different temperatures

			Temperature					
Source,	Sample	Parameter	50	60	70	80	90	References
Amadumbe	Starch	S	–	2.63	3.09	15.02	22.50	Alam and Hasnain (2009)
Amadumbe	Starch	S	1.12	1.10	1.13	14.48	18.50	Nwokocha *et al.* (2009)
Amadumbe	Flour	S	1.45	2.89	18.90	26.40	–	Mawoyo *et al.* (2017)
Amadumbe	Starch	SP	–	6.20	7.50	26.50	28.00	Alam and Hasnain (2009)
Amadumbe	Starch	SP	2.52	2.30	2.29	14,89	18.60	Nwokocha *et al.* (2009)
Amadumbe	Starch	SP	5.10 – 8.60	7.60 –10.00	10.10 – 13.10	10.95 – 22.25	16.10 – 31.50	Naidoo *et al.* (2015)
Amadumbe	Flour	SP	2.15	9.85	31.50	42.45	–	Mawoyo *et al.* (2017)
Amadumbe	Flour	SP	5.90 – 18.50	7.00 – 19.05	10.10 – 19.98	15.50 – 23.50	19.85 – 23.50	Naidoo *et al.* (2015)

(S) refers to solubility (%),
(–) Implies that the parameter was not studied, and
(SP) refers to swelling power ($g.g^{-1}$)

2.5 Utilisation of *Amadumbe*

Amadumbe cookies can be part of a composite mixture of wheat and *amadumbe* flour. The proportion of the flours influences the consumer acceptability of the cookies (Nip *et al.*, 1994; Adegunwa *et al.*, 2011; Kaushal *et al.*, 2015). The preference for composite bread reduces as the proportion of *amadumbe* is increased in *amadumbe* and wheat flour mixtures. (Sanful, 2011). Physicochemical analysis reveals that as the ratio of *amadumbe* flour is increased; there is a reduction in protein content, fat, carbohydrates, and energy while moisture, ash content, water absorption capacity, water solubility, and swelling power are increased (Sanful, 2011; Himeda *et al.*, 2014). Huang *et al.* (2000) made biscuits using *amadumbe* and soya mixture and found that the addition of soya produced biscuits with better nutritional quality. There are various bakery products that one can explore using *amadumbe* flour. However, limited research has been reported in this area. This review also established that no work had been reported on the impact of storage conditions on the quality of baked *amadumbe* products.

Wheat flour is currently the most used commodity to produce noodles. However, the poor cooking qualities of the end product have caused researchers to look for various methods to improve the end product quality (Mohammed and Bin, 2020). *Amadumbe* and wheat flour blends have been studied to produce noodles with improved quality (Kaushal *et al.*, 2015). Rosarlo *et al.* (1999) found that the addition of *amadumbe* flour increased peak viscosity, final set back values, and cooking weight of noodles. Alcantara *et al.* (2013) reported that the production of *amadumbe* noodles reduced the presence of anti-nutrients such as oxalate and phytates in the tuber. The textural difference amongst various starch noodles was linked with the morphological, thermal, and rheological properties. (Singh *et al.*, 2002). These properties are sensitive to factors such as variety, maturity stage, growth environment, and storage conditions (Sajeev *et al.*, 2004; Njintang *et al.*, 2007; Mawoyo *et al.*, 2017).

The processing of *amadumbe* chips is similar to the processing of potato chips. Therefore, quality properties must be of comparable magnitude to produce good quality chips (Hollyer *et al.*, 2000). Low-temperature storage results in the hydrolysis of starch into reducing sugars. High levels of reducing sugars are responsible for enzymatic browning during the frying of chips which is not desirable (Foukaraki *et al.*, 2016). Reducing sugars is not the only factor that influences crisp quality. The starch content also affects the texture of crisps. Tubers with more than 15 % starch content are ideal for producing good quality chips (Kita, 2002). Other applications of *amadumbe* include its use as a paste commonly known as *achu* in Cameroon (Kaushal *et al.*, 2015). It is prepared by peeling, cooking, and mashing to obtain a smooth paste (Njintang and Mbofung, 2003). Njintang *et al.* (2007) reported that flours with a high water absorption capacity tend to produce a paste with a high level of Newtonian compliance. This quality is desirable when making good viscosity foods such as soups and gravies (Kaushal *et al.*, 2015). *Amadumbe* is also suitable for consumption by infants due to its small granule size and ease of digestion. *Amadumbe* paste is ideal for diabetic people due to its high fibre content and resistant starch. The presence of anti-nutritional factors has also reduced the consumption of *amadumbe*. However, McEwan *et al.* (2014) reported that the production of *amadumbe* paste by boiling reduces all anti-nutritional factors. Other non-food applications include the production of starch nanocrystals used in making biodegradable packaging material (Mukurumbira *et al.*, 2017).

2.6 Discussion and Conclusion

Amadumbe is one of the important species of aroids used as a staple food in tropical and subtropical regions. It has more fibre content than potatoes, sweet potatoes, and cassava, resulting in health-related benefits such as improved digestion and regulating blood sugar levels of consumers (Adepoju and Adejumo, 2015). It has also been reported to have high starch content with a high quantity of resistant starch. Resistant starch resists digestion in the small intestine, which results in lower absorption of glucose which helps in reducing health issues such as diabetes and obesity (Liu *et al.*, 2006). The nutritional composition of *amadumbe* varies with the cultivar, geographical location, maturity stage, planting period, storage, and planting conditions (Sajeev *et al.*, 2004; Naidoo *et al.*, 2015). Therefore, the effect of storage conditions on the nutritional composition of South African *amadumbe* cultivars needs to be established.

Low-temperature storage is one of the technological solutions used to prolong the shelf life of tubers by promoting the inhibition of sprouting and reducing the respiration rate. Despite this benefit, low-temperature storage causes an increase in reducing sugar content, which is not desirable for *amadumbe* that is meant to produce crisps. On the other hand, high-temperature and low relative humidity storage promote an increase in the breakdown of starch into reducing sugars. The reducing sugars promote further sprouting, which results in an accelerated loss of the quality attributes of the tuber. Therefore, high and low-temperature storage conditions may present challenges when storing tubers meant for processing. Farmers use mechanical refrigeration, evaporative cooler, and underground storage pits to control or partially regulate temperature and relative humidity. However, there is limited information on how low-temperature storage and other storage technologies impact the quality of fresh *amadumbe*, flour, and starch.

Mechanical refrigeration reduces the respiration rate of *amadumbe,* which in turn reduces its deterioration rate. However, storing *amadumbe* at temperatures below 10°C can cause chilling injuries and promote starch breaking down into reducing sugars (Mehta *et al.*, 2010; Niu *et al.*, 2019). Despite the environmental control advantages of mechanical refrigeration systems, it is energy-intensive and requires high investment costs, which are out of reach for most small-scale farmers. Thus, small-scale farmers use affordable and easily attainable storage systems such as evaporative coolers (Jiménez-Zurita *et al.*, 2017). Evaporative coolers can keep the temperature in the range of 17 to 22 °C, which is above the recommended storage temperature for many fruits and vegetables. The high temperature prompted Tolesa and Workneh (2017) to combine a CoolBot® and evaporative cooler. The authors found that the combined storage method could lower the temperature while maintaining a high relative humidity. This current review established that no work had been reported on the effect of CoolBot® and evaporative cooler storage conditions on the quality of *amadumbe*. Storage pits are one of the on-field methods used by farmers for short-term storage of 2 to 4 months. However, this method is dependent on the prevailing climatic conditions and has poor control of the temperature and relative humidity. When relative humidity is kept high it results in the development of fungal diseases but when kept low it results in excessive weight loss (de Oliveira *et al.*, 2016). The change in relative humidity has impacts on the physiological, mechanical, and biochemical properties of *amadumbe* corms, flours, and starches.

This review also found that *amadumbe* can be used in various processing industries, such as producing chips, noodles, cookies, and paste. The possibility of using *amadumbe* in these processing industries is dependent on the quality parameters such as colour, texture, dry matter content, swelling power, water and oil holding capacities, solubility, and specific gravity. *Amadumbe* can also be used in non-food industries to produce biodegradable packaging material because of its small granule size. Minimal work concludes on the suitability of *amadumbe* corms stored in various conditions for processing industries. Most of the work has only focused on quantifying the quality of freshly harvested tubers or flour or starch stored over time instead of storing the tuber.

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3. THE PHYSIOLOGICAL AND MECHANICAL PROPERTIES OF *AMADUMBE* CORMS SUBJECTED TO DIFFERENT STORAGE METHODS

Chapter 2 revealed that minimal work has been done to quantify the effect of storage on quality attributes of *amadumbe* corms. So, this chapter will evaluate the changes in the quality of *amadumbe* corms subjected to different storage conditions.

Abstract

This study aimed to investigate the effects of different storage conditions on the mechanical and physiological quality attributes of *amadumbe* corms. In this study, the commonly cultivated *amadumbe* variety (*Dumbe-dumbe*) in South Africa was stored in five different storage conditions: Low-cold storage, High-cold storage, CoolBot® and evaporative cooler storage, Underground storage, and Ambient storage as a control. The corms were stored in three replications using a Completely Randomised Block Design, and sampling was done after 14 days for 70 days. The data were analysed using Duncan's multiple range test with GenStat 18.2.1 software. The results revealed that High-cold storage resulted in the lowest reduction in shear force (24.73 %) and cutting energy (41.24 %). It also had the lowest increase in physiological weight loss (9.76 %), hardness (20.99 %), toughness (9.35 %), specific gravity (10.89), and dry matter content (25.51 %). At the same time, CoolBot® and evaporative resulted in the second-lowest increase in hardness (21.84 %), toughness (11.66 %), specific gravity (11.88 %), and dry matter content (29.45 %). In contrast, Ambient storage resulted in the highest increase in physiological weight loss (27.48 %) and hardness (47.33 %), while Low-cold storage resulted in the highest increase in toughness (20.48 %), specific gravity (18.81 %), and dry matter content (44.42 %). Ambient storage also resulted in the highest decrease in shear force (38.90 %), while Low-cold storage resulted in the highest decrease in cutting energy (57.81 %). Storage period had a significant impact in increasing the physiological weight loss (0 –18 %), hardness (14.2 – 18.68 N), toughness (71.3 – 84.5 N.s), dry matter content (27.6 – 36.9 %), specific gravity (1.0 – 1.2) and a significant impact in the reduction of the shear force (18.6 – 12.7 $N.g^{-1}$) and cutting energy (82.9 – 39.9 N.s). High-cold storage maintained the quality attributes better than all other storage conditions. However, to preserve the quality of

amadumbe at an affordable price, the micro-environment inside a CoolBot® and evaporative cooler be improved. The improvements can be made by lowering the temperature to 10°C and increasing the ventilation.

3.1 Introduction

Amadumbe (*Colocasia esculenta L. Schott*), also known as Taro, is a vital source of carbohydrates grown in tropical and subtropical regions (Oyeyinka and Amonsou, 2020). Tubers have a high moisture content which makes them susceptible to microbial spoilage. Therefore, they need to be stored immediately or adequately processed (Naziri *et al.*, 2014). Quantitative and qualitative food losses occur during harvest and post-harvest stages due to poor temperature and relative humidity management, and improper packaging (Prusky, 2011; Zhang *et al.*, 2022). According to Morris *et al.* (2019) and Kuyu *et al.* (2019), post-harvest losses are mainly influenced by poor management skills and a lack of proper infrastructure. To prevent post-harvest losses, it is essential to use technologies that will promote and preserve the shelf life of fruits and vegetables (Nkolisa *et al.*, 2018; Zhang *et al.*, 2021).

Mechanical refrigeration is one of the post-harvest technology methods used to reduce the deterioration rate by slowing down the respiration of fruits and vegetables (Jiménez-Zurita *et al.*, 2017). Refrigeration units allow temperature and relative humidity control to be executed effectively (Gao *et al.*, 2019). Some challenges come with cold storage of tubers, like chilling injuries, accumulation of reducing sugars, and a high energy cost to operate the refrigeration system (Herman *et al.*, 2017; Pang *et al.*, 2021). Small-scale farmers are the significant producers of *amadumbe* in South Africa, and they make use of affordable alternative methods to store *amadumbe* (Mehta *et al.*, 2010; Mngadi *et al.*, 2015). The methods include evaporative coolers and underground storage pits, which can reduce temperature and increase the relative humidity of the storage environment (Paul *et al.*, 2016; Babaremu *et al.*, 2019). These different storage conditions influence the post-harvest losses of *amadumbe* (Zeng *et al.*, 2019). Therefore, it is vital to understand how *amadumbe* responds to different environmental conditions.

This chapter aims to assess the effect of storing *amadumbe* in different environmental conditions on the mechanical and physiological properties of *amadumbe* and to study relations that exist between internal attributes of *amadumbe*. This section hypothesised that cold storage maintains the mechanical and physiological properties of *amadumbe* better than all storage conditions (Oyeyinka *et al.*, 2020).

3.2 Materials and Methods

The following methods were used to conduct this research.

3.2.1 Location and description of *amadumbe* sampling site

The most cultivated *amadumbe* variety in South Africa (*Dumbe-dumbe*) was used for analysis. *Dumbe-dumbe* was sourced from Dienyane Projects, a small-scale farmer in Swayimane, Pietermaritzburg, South Africa. The farm is located at 29.4878° S, 30.6603° E, at an elevation of about 610 m. It receives an annual rainfall in the range of 832-910 mm per year. The mean annual minimum temperature is 11.5˚C, and the maximum temperature is 26.5˚C.

3.2.2 *Amadumbe* storage conditions and post-harvest sample preparations

The tubers were harvested after ten months. After that, *amadumbe* corms were washed using tap water and allowed to dry at ambient conditions. After drying, the corms with defects and harvest injuries were discarded. After preparations, the tubers were stored in five storage methods: (1) Low-cold storage (LC), (2) High-cold storage (HC), (3) CoolBot® and evaporative cooler storage (CBEC), (4) Underground storage (U), and (5) Ambient storage (A) as a control. The tubers were left unpackaged throughout the storage period. Table 3.1 shows the average, minimum, and maximum obtained temperature, and relative humidity values throughout the storage period. One data logger was used per storage method to measure the temperature and relative humidity (Texture HOBO U23 Pro v2, Onset, United States of America). The data loggers were kept randomly in the different storage conditions. The Underground pit had the following dimensions 2 m x 1 m x 1 m and was lined with grass and covered with a galvanized sheet to prevent rain from entering the pit see Figure 3.1a-d.

Table 3.1 Temperature and relative humidity values of different storage conditions over 70 days.

	Storage Method									
	A		**U**		**CBEC**		**HC**		**LC**	
Stats	Temp (°C)	RH (%)	Temp (°C)	RH (%)	Temp (°C)	RH (%)	Temp (°C)	RH (%)	Temp (°C)	RH (%)
Average	20.44	75.08	19.99	88.66	14.03	78.76	10.40	98.79	3.98	92.20
Min	17.30	75.02	17.51	78.02	12.34	64.75	9.26	97.57	3.80	89.71
Max	23.59	75.15	22.47	99.30	15.72	92.76	11.54	100.00	4.20	94.69

A = Ambient storage
CBEC = CoolBot® and evaporative cooler storage
HC = High-cold storage
U = Underground storage
LC = Low-cold storage

Temp = Temperature and RH = Relative humidity

(a)

(b)

(c)

(d)

Figure 3.1 Illustration of the underground storage pit used to store *amadumbe* corms

3.2.3 Experimental design

The experimental design can be found in Figure 3.2. The experiments were conducted using a Completely Randomised Block Design. A Randomised Block Design is achieved by setting up each experiment in groups called blocks and ensuring that each treatment appears in each block. The experiments had two factors (storage conditions and storage period). Sampling was done every 14th day for 70 days using three replications. *Amadumbe* corms were stored in five different storage conditions: Low-cold storage, High-cold storage, CoolBot® and evaporative cooler storage, Underground storage, and Ambient as a control. Sampling was done on days 0, 14, 28, 42, 56, and 70.

3.2.4 Data collection

Evaluation of all mechanical and physiological properties was done at the Food Science and Agricultural Engineering Laboratory, University of KwaZulu-Natal, South Africa. A total of 1700 tubers was required but considering that some of the samples were damaged and had to be discarded a total of 2500 tubers was procured. The total sample was calculated based on all the experiments that will be conducted. A large tuber weighs about 80-100 g, therefore, about 112.5 kg of *amadumbe* will be required to conduct the experiments.

3.2.5 Physiological weight loss

The method used by Sajeev *et al.* (2004) was adopted for determining physiological weight loss. The physiological weight loss was measured by taking the weight (ALS-A; KERN, Germany) loss of *amadumbe*. The same tuber was used for measuring weight loss throughout the storage period. The physiological weight loss was calculated using Equation 3.1

$$PWL = \frac{W_i - W_t}{W_i} \times 100 \tag{3.1}$$

where

PWL = Physiological weight loss (%),

W_i = initial weight of fresh *amadumbe* corm(g), and

W_t = weight of fresh *amadumbe* corm at any time (g).

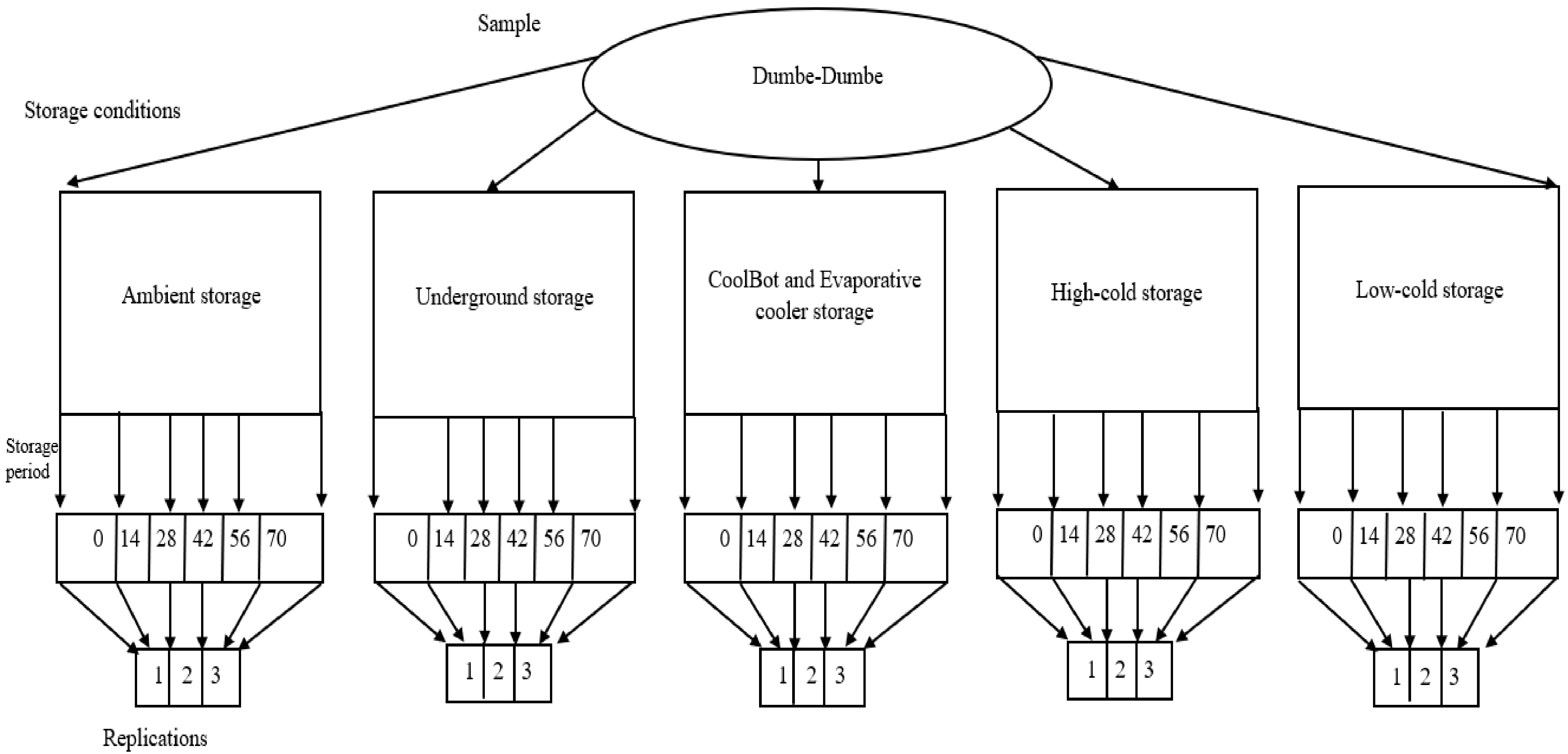


Figure 3.2 Experimental design to determine mechanical and physiological properties of amadumbe corms

3.2.6 Hardness and toughness

The method used by Sajeev *et al.* (2004) was adopted for puncture analysis with minor modification of the analyser settings. A texture analyser (TA.XTplus, Texture Technologies Company, United States of America) was used at the following settings: Option-return to start, pre speed = 1.5 $mm.s^{-1}$, speed = 1 $mm.s^{-1}$, post speed = 10 $mm.s^{-1}$, distance = 12 mm, trigger force = 0.02 kg, acquisition rate = 20 pps. The texture analyser gave an output graph which was used to read the firmness and toughness. Firmness was determined to be the peak of the puncture test, while toughness was the area of the puncture test.

3.2.7 Shear force and cutting energy

The method used by Harker et al. (1997) was adopted for shear analysis. Kramer shear was measured using a texture analyser (TA.XTplus, Texture Technologies Company, United States of America). However, a shear press-fitting was used as opposed to a puncture probe. The *amadumbe* corms were cut into 10 mm round slices using a knife for each sample, and the slices were measured using a Vainer caliper. The slices were weighed before being positioned in the sample chamber. The shear press plate was set to press the slices at a 1 $mm.min^{-1}$ speed. The maximum force applied was recorded and divided by the weight of the *amadumbe* slice to account for the difference in the area of the slice cut by the plates. The texture analyser gave an output graph which was used to read the cutting force and cutting energy. Cutting force was determined to be the peak of the shear test, while cutting energy was the area of the shear test.

3.2.8 Specific gravity

The specific gravity was determined by measuring the weight of *amadumbe* in air and water after modification of the method used by Haase (2003). The amendment was necessary because temperature corrections factors have not been calculated for *amadumbe* corms. For this experiment, the water temperature was kept at 25.5°C. The same KERN ALS-A analytical scale with a maximum weight of 250 g was used for measurements. Then finally, the SG was calculated using the ratio of weight in water to the weight in the air (Equation 3.2)

$$SG = \frac{W_{AW}}{W_{AA}} \tag{3.2}$$

where

SG = Specific gravity ($g.g^{-1}$),

W_{AW} = weight of fresh *amadumbe* slice in water (g), and

W_{AA} = weight of fresh *amadumbe* slice in the air (g).

3.2.9 Dry matter content

The destructive method used by Bekele and Haile (2019) was adopted with minor modifications for temperature and heating duration. The amendment was necessary due to the availability of one oven. The tubers were peeled, washed, sliced, and mixed, and 200 g samples were dried at 35°C for 48 hours and further dried at 105°C for 3 hours. Finally, the dry matter was determined by taking the ratio of the final weight to the initial weight measured using a KERN ALS-A analytical scale (Equation 3.3).

$$DMC = \frac{W_{f^-} - W_d}{W_f} \times 100 \tag{3.3}$$

where

DMC = Dry matter content (%),

W_f = weight of fresh *amadumbe* slice (g), and

W_d = weight of dried *amadumbe* slice (g).

3.2.10 Data analysis

Data analysis was performed using the GenStat 18.2.1 software, analysis of variance (ANOVA) was used to test for differences. The separation of means was determined using Duncan's multiple range test at the 5 % significant level. The relationship between the quality attributes was determined using linear regression analysis (Chisenga *et al.*, 2019).

3.3 Results and Discussion

This Section will analyse the physiological and mechanical properties of *amadumbe* corms such as weight loss, shear force, cutting energy, hardness, toughness, dry matter content, and specific gravity. Table 3.2 shows the correlation between mechanical and physiological properties of *amadumbe*.

3.3.1 Physiological weight loss

Figure 3.3 illustrates the change in physiological weight loss of *amadumbe* corms subjected to different storage conditions and storage period. The physiological weight loss ranged from 0.00 to 27.48 %. The range obtained in this study is comparable to the range reported by other authors such as Sajeev *et al.* (2004) (0.00 – 24.00 %) and Obetta *et al.* (2007) (1.00 – 16 .00 %) and low compared to the range reported by Agbor-Egbe and Rickard. (1991) (0.00 – 60 .00 %). The change in weight loss is influenced by post-harvest handling techniques such as storage and packaging (Chang and Kim, 2015; Haffez *et al.*, 2020).

Storage conditions had a significant impact ($p < 0.001$) on the physiological weight of *amadumbe* corms. High-cold storage resulted in the lowest physiological weight loss of 9.76 % than all the storage conditions. In comparison, ambient storage conditions resulted in the highest physiological weight of 27.48 % after 70 days of storage. Figure 3.3 also shows that the more controlled storage environment, such as High and Low-cold storage conditions, can reduce weight loss more than the uncontrolled storage environments. This reduction is caused by low temperature, which reduces the respiration and transpiration of *amadumbe* corms. Agbor-Egbe and Rickard (1991) showed that storing *amadumbe* at 30°C resulted in a higher respiration rate of 8.60 –13.30 $mL.kg^{-1}.h^{-1}$ compared to 5.00 – 11.00 $mL.kg^{-1}.h^{-1}$ at 15°C.

Agbor-Egbe and Rickard (1991) also showed that low relative humidity results in a higher respiration rate of *amadumbe*. The lower average relative humidity of 78.76 % in CoolBot® and evaporative storage conditions than 88.66 % in Underground storage is why this storage condition had a higher weight loss than Underground storage. When fruits are stored at low relative humidity, there is an increase in the vapour pressure difference which, causes the transpiration rate to increase (Ramaswamy, 2014).

The storage period had a significant impact ($p < 0.001$) on the physiological weight of *amadumbe* corms. The physiological weight loss increased from 0.00 to 18 .00 % on days 0 and 70, respectively. There was a faster loss in weight during the first 14 days, as evident by the sharper gradient that occurred during the first 14 days. This sharp gradient started to flatten for all storage conditions except Ambient storage conditions. Sajeev et al. (2004) also reported a higher weight loss during the first ten days of storage. The reduction in weight shows a decrease in quality and will produce fewer chips, bread, paste, and noodles (Kaushal *et al.*, 2015; Dite Hunjek *et al.*, 2020).

As shown in Table 3.2, the physiological weight loss showed a weak positive correlation with hardness ($r = 0.473$, $p < 0.001$) and toughness ($r = 0.399$, $p < 0.001$). This correlation occurs due to moisture loss during storage because of evapotranspiration. The loss of moisture causes a reduction in the weight loss of *amadumbe*, which increases the hardness and toughness of the tuber (Paniagua *et al.*, 2013; Dite Hunjek *et al.*, 2020). The physiological weight loss also had a moderately strong positive correlation with specific gravity ($r = 0.607$, $p < 0.001$) and dry matter content ($r = 0.676$, $p < 0.001$). Specific gravity and dry matter content increase as moisture is lost throughout the storage period. It also had showed a moderately strong negative correlation with shear force ($r = 0.-593$, $p < 0.001$) and cutting energy ($r = -0.754$, $p < 0.001$). The negative correlation occurs because cutting energy and shear force reduce due to processes such as starch degradation (Shapawi *et al.*, 2021).

The interaction of storage conditions and storage period had a significant impact ($p < 0.001$) on the physiological weight loss of *amadumbe* corms. High-cold storage had the lowest increase in physiological weight loss of 9.76 % from days 0 to 70 while, and Ambient storage had the highest increase of 27.48 %.

Table 3.2 Pearson correlation coefficients of *amadumbe* properties

Parameter	Physiological weigh loss	Hardness	Toughness	Shear force	Cutting energy	Specific gravity	Dry matter content
PWL	1.000						
Hardness	0.473***	1.000					
Toughness	0.399***	0.235**	1.000				
Shear Force	-0.593***	-0.271**	-0.537***	1.000			
Cutting Energy	-0.754***	-0.479***	-0.521***	0.728***	1.000		
Specific gravity	0.607***	0.383***	0.440***	-0.448***	-0.662***	1.000	
Dry Matter Content	0.676***	0.469***	0.469***	-0.441***	-0.707***	0.596***	1.000

p > 0.05*, p < 0.05**, p < 0.001**

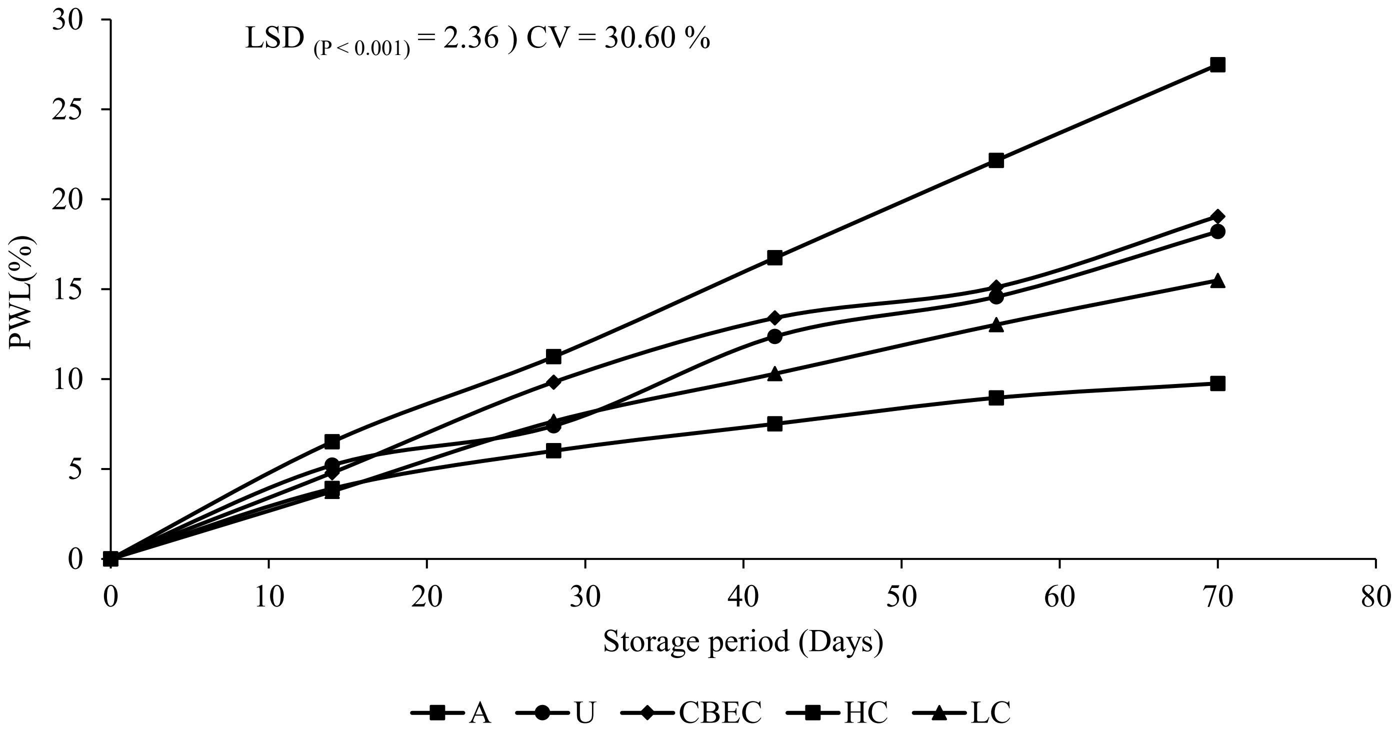


Figure 3.3 Change in physiological weight loss of *amadumbe* stored in different conditions. A = Ambient storage, U = Underground storage, EC = CoolBot® and evaporative cooler storage, HC = High-cold, and LC = low-cold storage

3.3.2 Hardness and toughness

The texture is one of the quality parameters used by consumers to assess the suitability of a commodity for consumption (Paniagua *et al.*, 2013). Figure 3.4a-b illustrates the change in hardness of *amadumbe* corms subjected to different storage conditions and storage period. The hardness ranged from 14.25 to 20.98 N. The range obtained in this study is comparable to the range reported by Sajeev *et al.* (2004) (12.26 – 18.45 N). The hardness of a tuber is influenced by post-harvest storage conditions, storage time, and packaging (Dite Hunjek *et al.*, 2020).

Figure 3.4b illustrates the change in hardness of *amadumbe* subjected to different storage conditions. The results show that storage conditions had no significant impact ($p > 0.05$) on the hardness of *amadumbe* corms. However, Ambient storage conditions had the highest hardness of 18.35 N, while High-cold storage had the lowest of 16.67 N. Sajeev *et al.* (2004) also reported higher firmness for *amadumbe* stored in ambient storage conditions as compared to those stored in an evaporative cooler and a refrigerator. The increase in hardness in this study is contrary to the work reported by Chang and Kim (2015) and Sanchez et al. (2021), who found a reduction in firmness of *amadumbe* and sweet potatoes during storage. Both these authors had peeled the tubers before conducting the textural analysis. The increase reported in this present work may be due to an increase in elasticity of *amadumbe* peels during storage which requires a higher force for penetration to be achieved (Paniagua et al., 2013).

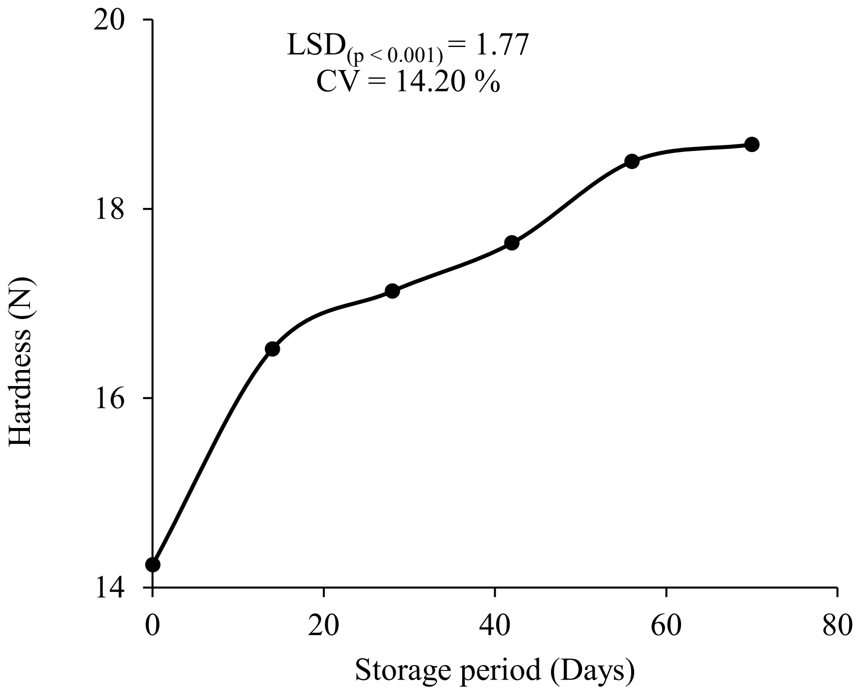
Figure 3.4a illustrates the change in hardness of *amadumbe* as the storage period is increased. The results show that the storage period had a significant impact ($p < 0.001$) on the hardness of *amadumbe* corms. *Amadumbe* hardness increased from 14.24 to 18.68 N on day 0 and day 70, respectively. Dite Hunjek et al. (2020) also reported an increase in potato firmness during storage. Rocculi *et al.* (2009) reported that the firmness of potatoes increases over time due to moisture loss, wounding response, and cross-linking of cell substances. Hardness showed a weak positive correlation with toughness ($r = 0.473$, $p < 0.001$), specific gravity ($r = 0.383$, $p < 0.001$) and dry matter content ($r = 0.469$, $p < 0.001$). Sanchez *et al.* (2021) also reported a strong positive correlation between texture and dry matter content during the storage of sweet potatoes. Hardness also showed a weak negative correlation with shear force ($r = -0.271$, $p < 0.009$) and cutting energy ($r = 0.-479$, $p < 0.001$).

The interaction of storage conditions and storage period had a significant impact ($p < 0.05$) on the hardness of *amadumbe* corms. High-cold storage had the lowest increase in hardness of 20.99 % from days 0 to 70 while, and Ambient storage had the highest increase of 47.33 %. Therefore, High-cold storage is the best storage method in preserving the hardness of *amadumbe* corms, while Ambient storage was the worst storage method.

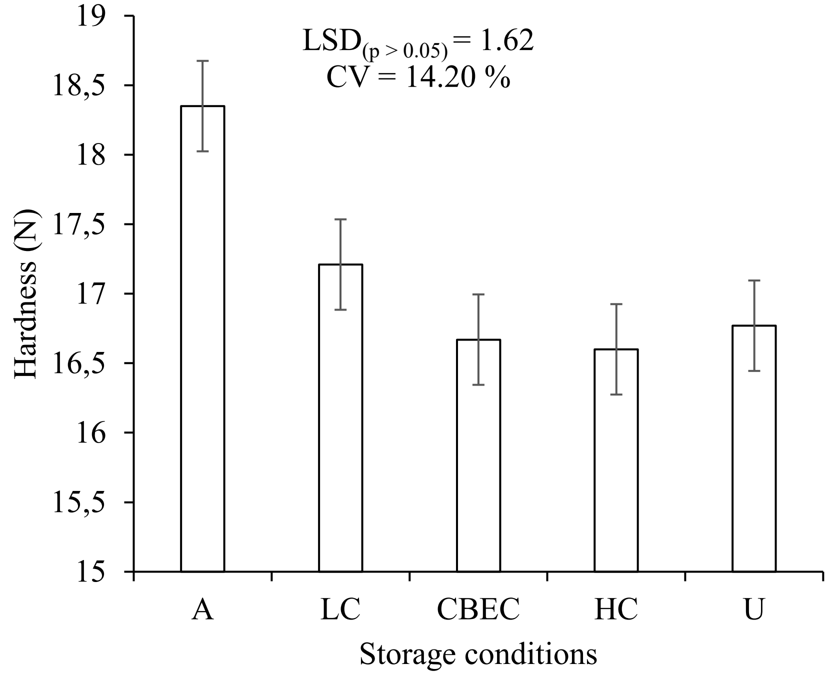
Figure 3.4c-d illustrates the change in the toughness of *amadumbe* corms subjected to different storage conditions and storage period. The toughness ranged from 70.92 to 93.68 N. Figure 3.4d illustrates the change in toughness of *amadumbe* subjected to different storage conditions. The results show that storage conditions had a significant impact ($p < 0.001$) on the toughness of *amadumbe* corms. Low and High-cold storage conditions had the highest and lowest toughness of 82.97 and 79.62 N.s, respectively (Figure 3.4d). The high toughness of cold storage still needs to be elucidated. The possible hypothesis for this increase in toughness may be due to lignification of the cell wall due to biochemical reactions during cold-induced sweetening (Afoakwa and Sefa-Dedeh, 2002; Paniagua *et al.*, 2013).

Figure 3.4c illustrates the change in toughness of *amadumbe* as the storage period is increased. The results shows that the storage period had a significant impact ($P < 0.01$) on the toughness of *amadumbe* corms. The toughness of *amadumbe* increased from 71.33 to 84.51 N.s on day 0 and day 70, respectively (Figure 3.4c). Toughness showed a weak positive correlation with specific gravity ($r = 0.440$, $p < 0.001$) and dry matter content ($r = 0.469$, $p < 0.001$). The fact that there is no correlation may be due to the elasticity of *amadumbe* peels, which may have caused toughness to increase, just as Paniagua *et al.* (2013) concluded. The toughness was also found to have a moderately strong negative correlation with shear force ($r = -0.537$, $p < 0.001$) and cutting energy ($r = 0.-521$, $p < 0.001$).

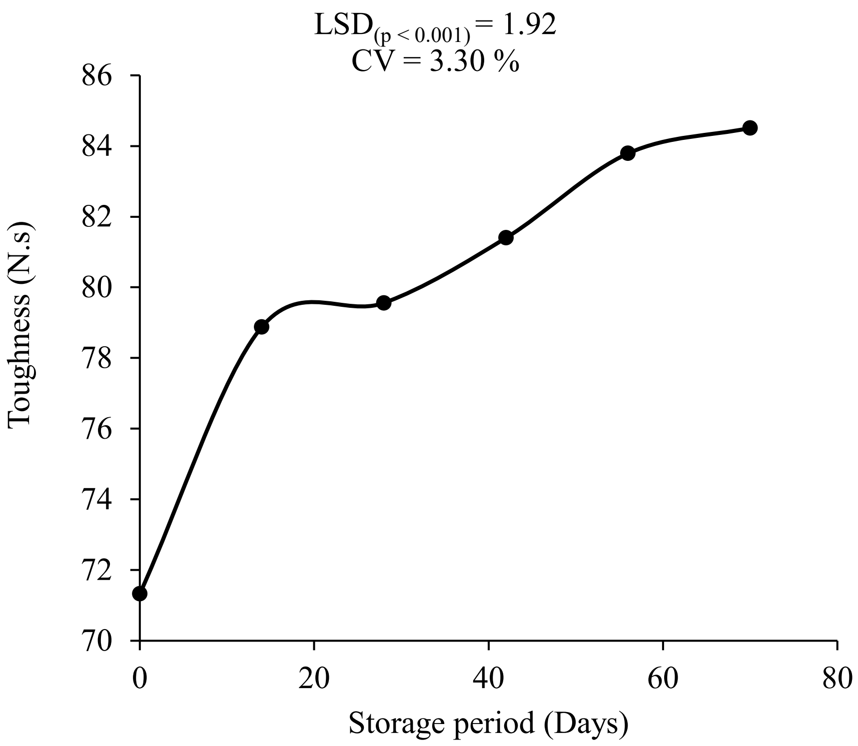
The interaction of storage conditions and storage period had a significant impact ($p < 0.001$) on the toughness of *amadumbe* corms. High-cold storage had the lowest increase in toughness of 9.35 % from days 0 to 70 while, Low-cold storage had the highest increase of 20.48%. Therefore, High-cold storage is the best storage method in preserving the toughness of *amadumbe* corms, while Low-cold storage was the worst storage method.

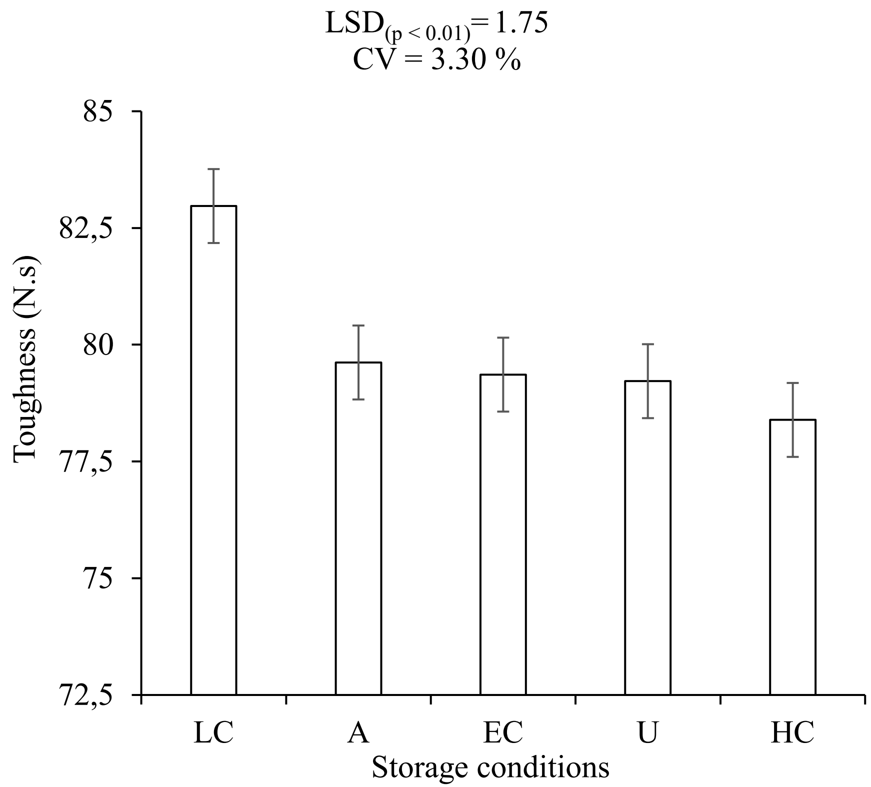

LSD(p < 0.001) = 1.77
CV = 14.20 %
Hardness (N)
20
18
16
14
0
20
40
60
80
Storage period (Days)

(a)


LSD(p > 0.05) = 1.62
CV = 14.20 %
Hardness (N)
19
18,5
18
17,5
17
16,5
16
15,5
15
A
LC
CBEC
HC
U
Storage conditions

(b)





(d)

(c)

Figure 3.4 The effect of storage on the hardness and toughness of *amadumbe*. A = Ambient storage, U = Underground storage, EC = CoolBot® and evaporative cooler storage, HC = High-cold, and LC = low-cold storage.

3.3.3 Shear force and cutting energy

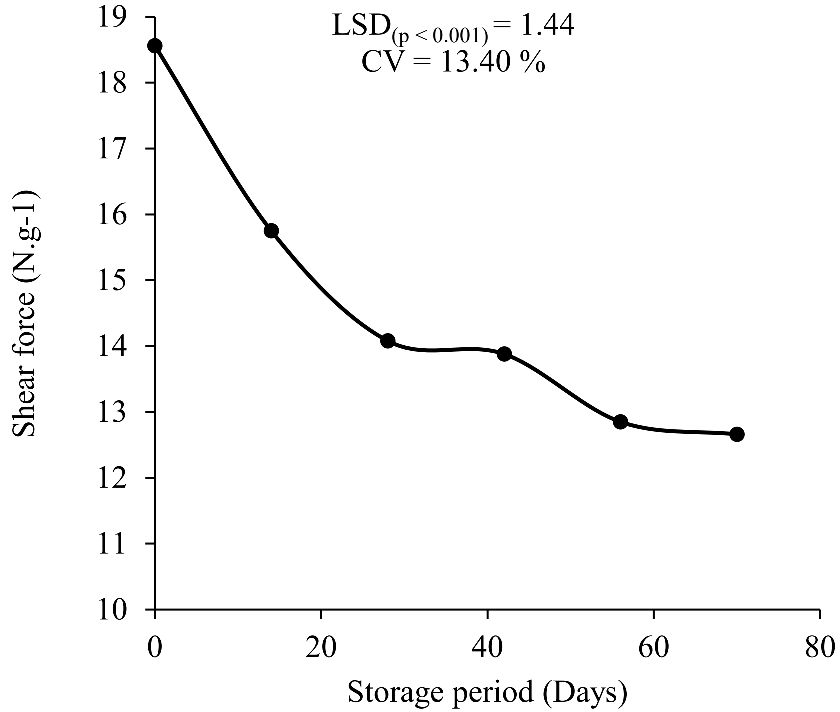
Figure 3.5a-b illustrates the change in the shear force of *amadumbe* corms subjected to different storage conditions and storage period. The shear force ranged from 10.92 to 18.56 $N.g^{-1}$. Figure 3.5b illustrates the change in shear force of *amadumbe* subjected to different storage conditions. The results show that storage conditions had no significant impact ($p > 0.05$) on the shear force of *amadumbe* corms. High-cold storage had the highest shear force of 14.93 $N.g^{-1}$, while Low-cold had the lowest shear force of 14.25 $N.g^{-1}$. The high shear force in High-cold storage shows less structural degradation than other storage conditions (Shapawi et al., 2021). The low shear force in low-cold storage may be due to the breaking down of starch into reducing sugars which affects the structural integrity of the tuber (Modi and Mare, 2016).

Figure 3.5b illustrates the change in shear force of *amadumbe* flour as the storage period is increased. The results shows that the storage period had a significant difference ($p < 0.001$) on the shear force of *amadumbe* corms. The shear force of *amadumbe* corms reduced from 18.56 to 12.66 $N.g^{-1}$ on days 0 and 70, respectively. Ghosh and Das (2014) reported a decrease in the shear force of potatoes stored for six months. The reduction in shear force is due to physicochemical changes because of the degradation of tuber structural elements. The shear force showed a weak negative correlation with specific gravity ($r = -0.448$, $p < 0.001$) and dry matter content ($r = -0.441$, $p < 0.001$). During storage, *amadumbe* loses moisture due to respiration and loses structural integrity due to processes such as starch degradation, which reduces the shear force (Modi and Mare, 2016). The shear force also showed a moderately strong positive correlation with cutting energy ($r = 0.728$, $p < 0.001$). The correlation of shear force and cutting energy was expected because cutting energy is the energy required for shear to occur (Sajeev *et al.*, 2004).

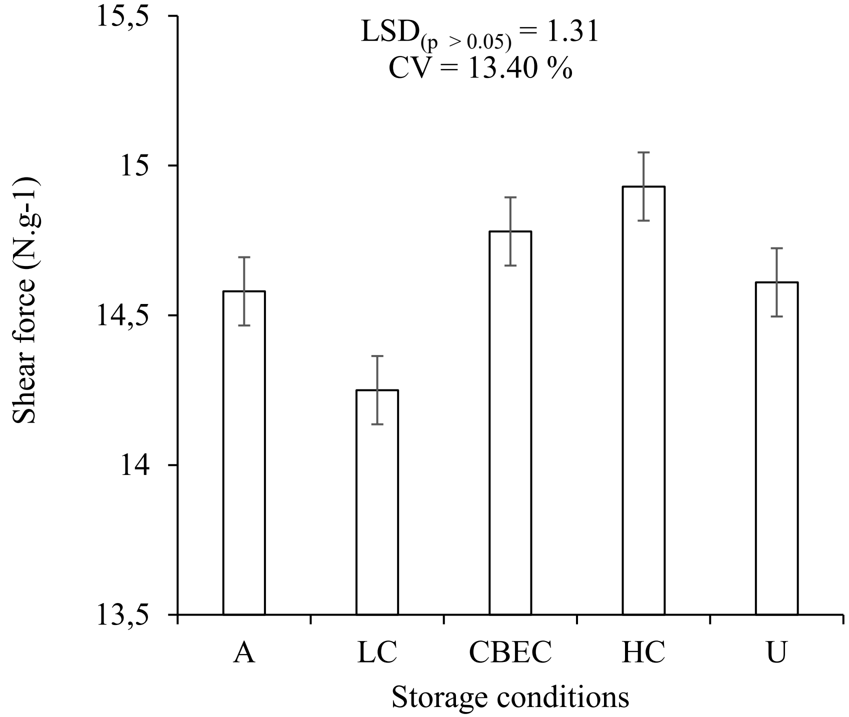
Figure 3.5c-d illustrates the change in cutting energy of *amadumbe* corms subjected to different storage conditions and storage period. The cutting energy ranged from 34.99 to 82.95 N.s. Figure 3.5d illustrates the change in cutting energy of *amadumbe* subjected to different storage conditions. The results shows that storage conditions had a significant impact ($p < 0.001$) on the cutting energy of *amadumbe*. High-cold storage had the highest cutting energy of 62.76 N.s, while low-cold storage had the lowest cutting energy of 53.86 N.s. Therefore, storing *amadumbe* in High-cold storage results in better retention of the structural integrity (Shapawi et al., 2021).

Figure 3.5c illustrates the change in cutting energy of *amadumbe* as the storage period is increased. The results show that the storage period also had a significant impact ($p < 0.001$) on the cutting of energy *amadumbe*. The cutting energy of *amadumbe* corms reduced from 82.95 to 39.92 N.s on days 0 and 70, respectively. This reduction in the cutting energy of *amadumbe* may be desirable when designing equipment that may be used to cut *amadumbe* crisps because less energy will be needed to cut the slices. The cutting energy showed a moderately strong negative correlation with specific gravity ($r = 0.-0.662$, $p < 0.001$) and dry matter content ($r = 0.707$, $p < 0.001$). Since crisp production requires tubers with high dry matter content and specific gravity, this correlation is favourable because the cutting energy reduces as the specific gravity and dry matter content increases (Hollyer *et al.*, 2000; Paull and Ching, 2015). However, a subjective quality analysis experiment that focuses on colour, taste, appearance, and texture may be required to index the storage time where *amadumbe* crisp will still be regarded as palatable.

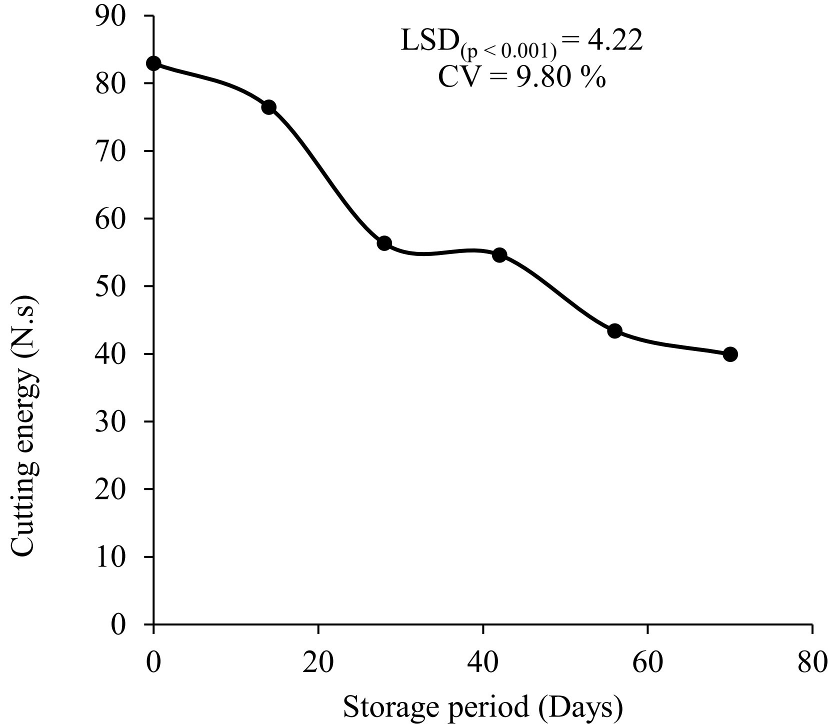
The interaction of storage conditions and storage period had a significant impact ($p < 0.05$) on the cutting energy of *amadumbe* corms. High-cold storage had the lowest reduction in cutting energy of 41.24 % from days 0 to 70, and Ambient storage had the highest reduction of 49.70 %. Therefore, High-cold storage is the best storage method in preserving the cutting energy of *amadumbe* corms, while Ambient storage was the worst storage method.


LSD(p < 0.001) = 1.44
CV = 13.40 %
Shear force (N.g-1)
19
18
17
16
15
14
13
12
11
10
0
20
40
60
80
Storage period (Days)

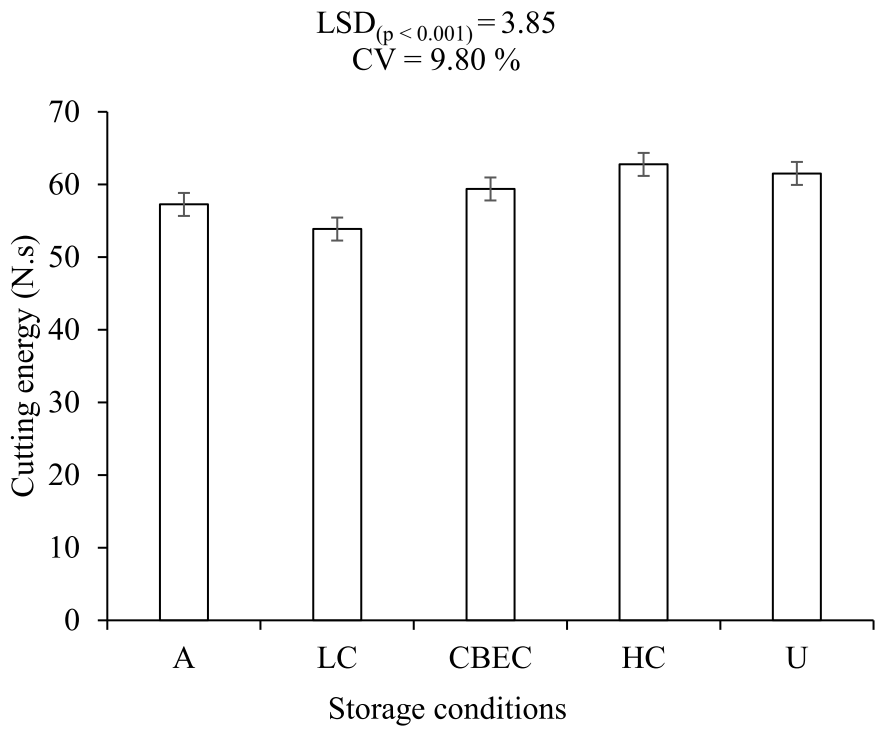
(a)


LSD(p > 0.05) = 1.31
CV = 13.40 %
Shear force (N.g-1)
15,5
15
14,5
14
13,5
A
LC
CBEC
HC
U
Storage conditions

(b)



(c)



(d)

Figure 3.5 The effect of storage on the shear force and cutting energy of *amadumbe*. A = Ambient storage, U = Underground storage, EC = CoolBot® and evaporative cooler storage, HC = High-cold, and LC = low-cold storage.

3.3.4 Specific gravity

Table 3.3 illustrates the change in specific gravity of *amadumbe* corms subjected to different storage conditions and storage period. The specific gravity of *amadumbe* corms ranged between 1.01 and 1.20. The range obtained in this work is comparable to the work done by other authors such as Buragohain *et al.* (2013), that reported that the specific gravity of 20 *amadumbe* cultivars ranged between 1.08 to 1.58, and Mare (2009), who reported that the specific gravity of South African *amadumbe* corms to range between 0.97 to 1.09.

Storage conditions had no significant impact ($p > 0.05$) on the specific gravity of *amadumbe* corms. However, High-cold storage resulted in the lowest specific gravity of 1.08, while Low-cold storage had the highest specific gravity of 1.11. The low specific gravity in High-cold storage is due to lower moisture loss because of evaporation (Paull and Ching, 2015). It also indicates that this storage method results in less structural degradation than other storage conditions (Shapawi et al., 2021). High-cold storage can reduce the respiration rate of *amadumbe,* which results in less loss of structural integrity (Dite Hunjek *et al.*, 2020).

The storage period had a significant difference ($p < 0.001$) on the specific gravity of *amadumbe* corms. The specific gravity of *amadumbe* corms increased from 1.01 to 1.16 on days 0 and 70, respectively. Table 3.3 shows that the specific gravity of *amadumbe* reduced throughout the storage period in all storage conditions except for High-cold storage, where the specific gravity remained relatively constant between days 28 and 56. Hollyer *et al.* (2000) reported that potatoes with a specific gravity greater than 1.08 produce good quality crisps. After 28 days of storage, the specific gravity of *amadumbe* is greater than or equal to 1.08 in all storage conditions. Therefore it can be inferred that after 28 days, the oil uptake of *amadumbe* is reduced, thus resulting in good quality crisp (Golmohammadi and Afkari-Sayyah, 2013).

Specific gravity showed a moderately strong positive correlation with and dry matter content ($r = 0.596$, $p < 0.001$). Mohammed (2016) and Abebe *et al.* (2013) also found a strong positive correlation between specific gravity and dry matter content. The correlations reported in their studies were around 0.9; therefore, these authors could generate accurate linear regression models. In this present study the correlation for day 0 was ($r = 0.826$, $p < 0.001$). However, the correlation drops once the tubers are stored in different storage environments. The different storage conditions may cause the reduction in correlation because the stored tubers may have different pulp temperatures, thus affecting the specific gravity readings (Kleinkopf *et al.*, 1987; Bekele and Haile, 2019).

Table 3.3 The specific gravity of *amadumbe* subjected to different storage conditions

Storage period (Days)	A	U	CBEC	HC	LC
0	1.01(0.01)^{a}	1.01(0.01)^{a}	1.01(0.01)^{a}	1.01(0.01)^{a}	1.01(0.01)^{a}
14	1.07(0.04)^{abc}	1.08(0.03)^{abc}	1.02(0.07)^{ab}	1.02(0.01)^{ab}	1.09(0.06)^{abc}
28	1.09(0.00)^{abc}	1.08(0.06)^{abc}	1.09(0.06)^{abc}	1.10(0.04)^{abc}	1.11(0.02)$^{a-e}$
42	1.10(0.03)^{abc}	1.09(0.04)^{abc}	1.13(0.03)^{cde}	1.10(0.03)$^{a-d}$	1.12(0.04)$^{b-e}$
56	1.11(0.01)$^{b-e}$	1.13(0.05)^{cde}	1.14(0.04)^{cde}	1.11(0.02)$^{b-e}$	1.16(0.02)^{cde}
70	1.13(0.02)^{cde}	1.20(0.16)^{e}	1.16(0.07)^{cde}	1.12(0.06)$^{b-e}$	1.20(0.06)^{de}

Storage conditions (A)	0.275	LSD	0.079
Storage period (B)	< 0.001	SE	0.049
Storage conditions * Storage period (A*B)	0.885	CV (%)	4.500

All values are means of three replications. Data in the parenthesis are the standard deviations. The values with different letters are significantly different at $p < 0.05$ by LSD test. A = Ambient storage, U = Underground storage, EC = CoolBot® and evaporative cooler storage, HC = High-cold, and LC = low-cold storage.

3.3.5 Dry matter content

Table 3.4 illustrates the change in dry matter content of *amadumbe* corms subjected to different storage conditions and storage period. The dry matter content of *amadumbe* corms ranged between 27.64 and 37.29 %. This range is comparable to the range obtained by other authors such as Kristl *et al.* (2021) (27.80 – 30.20 %), Mare (2009) (23.50 – 32.50 %), and Buragohain *et al.* (2013) (19.91 – 36.91 %). The dry matter content is influenced by harvest time, cultivar, storage period, and storage temperature (Krochmal-Marczak *et al.*, 2020; Kristl *et al.*, 2021).

Storage conditions had no significant impact ($p > 0.05$) on the dry matter content of *amadumbe*. However, Low-cold storage resulted in the highest dry matter content of 32.36 %, while High-cold storage had the lowest of 31.73 %. Krochmal-Marczak *et al.* (2020) also reported lower dry matter content for sweet potatoes stored at 5°C as compared to those held at 15°C. Kaaber *et al.* (2001) also found that the dry matter content increased for tubers stored at 8°C and reduced for tubers stored at 4°C. This increase in dry matter content is due to a loss in moisture content due to evaporation.

The storage period had a significant difference ($p < 0.001$) on the dry matter content of *amadumbe*. Table 3.4 illustrates that the dry matter of *amadumbe* increased throughout the storage period in all storage conditions. Kaur *et al.* (2007) reported that an increase in temperature and storage period increased the dry matter content of potatoes. However, the increase was only significant for potatoes stored at 16 and 20°C. The increase is due to loss of moisture during storage and an increase in the respiration rate when tubers are stored at high temperatures (Ezekiel *et al.*, 1999; Kaur *et al.*, 2007). The increase in dry matter content is beneficial when making crisps because it lowers oil uptake (Kaur *et al.*, 2008). Therefore, the Low dry matter content in High and low-cold storage conditions may result in lower quality crisp.

Table 3.4 Dry matter content of *amadumbe* subjected to different storage conditions

Storage period (Days)	A	U	CBEC	HC	LC
0	27.64(1.69)[a]	27.64(1.69)[a]	27.64(1.69)[a]	27.64(1.69)[a]	27.64(1.69)[a]
14	30.72(1.22)[a-e]	28.50(1.70)[abc]	29.40(7.18)[a-d]	31.39(2.89)[a-e]	30.94(2.18)[a-e]
28	31.22(0.96)[a-e]	30.30(2.62) [a-e]	30.79(1.80)[a-e]	32.39(0.23)[a-f]	31.09(0.57)[a-e]
42	32.31(2.26)[a-f]	34.19(0.55)[c-f]	33.33(3.27)[a-f]	32.78(1.53)[a-f]	32.09(1.80)[a-f]
56	34.99(0.14)[d-g]	34.23(0.81)[def]	33.69(1.31)[c-f]	32.98[(a-e)]	33.73(3.38)[c-f]
70	37.29(4.42)[fg]	37.29(3.73)[fg]	35.78(0.63)[efg]	34.59(1.40)[def]	39.92(3.05)[g]

Storage conditions (A)	0.879	LSD	4.680
Storage period (B)	<0.001	SE	2.865
Storage conditions * Storage period (A*B)	0.929	CV (%)	8.900

All values are means of three replications. Data in the parenthesis are the standard deviations. The values with different letters are significantly different at $p<0.05$ by LSD test. A = Ambient storage, U = Underground storage, EC = CoolBot® and evaporative cooler storage, HC = High-cold, and LC = low-cold storage.

3.4 Conclusion

This research investigated the effect of storing *amadumbe* in different environmental conditions on the mechanical and physiological properties of *amadumbe*. The study affirms the null hypothesis that High-cold storage conditions (9.26 – 11.54℃, 97.57 – 100.00 %) will preserve the quality attributes of *amadumbe* better than all storage conditions. The study revealed that the physiological and mechanical properties of *amadumbe* corms are influenced by storage conditions, storage period, and the interaction of storage conditions and storage period. All studied parameters, namely: physiological weight loss, hardness, toughness, shear force, cutting energy, specific gravity, and dry matter content, showed a significant correlation with each other. A short shelf-life and massive quality changes were observed in all corms stored in Ambient storage conditions (17.30 – 23.59℃, 75.02 – 75.15 %). Ambient storage had the highest increase in physiological weight loss, hardness, toughness, specific gravity, and dry matter content. It also had the lowest decrease in shear force and cutting energy. While High-cold storage followed by CoolBot® and evaporative cooler storage (12.32 – 15.72℃, 64.75 – 92.76 %) seemed to have a slow quality change. The study revealed that the storage period resulted in an increase in physiological weight loss (0 –18 %), hardness (14.2 – 18.68 N), toughness (71.3 – 84.5 N.s), dry matter content (27.6 – 36.9 %), specific gravity (1.0 – 1.2) and a significant impact in the reduction of the shear force (18.6 – 12.7 $N.g^{-1}$) and cutting energy (82.9 – 39.9 N.s).

This study shows that high-cold storage can preserve quality attributes of *amadumbe* more than all studied storage conditions. However, storing *amadumbe* at high-cold storage can be costly, so to maintain the quality of *amadumbe* for longer durations at an affordable price, it is recommended that the micro-environment inside a CoolBot® and evaporative cooler be improved by lowering the temperature to 10℃ and increasing the ventilation.

3.5 References

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4. PHYSICOCHEMICAL PROPERTIES OF *AMADUMBE* FLOUR DERIVED FROM AMDUMBE CORMS SUBJECTED TO DIFFERENT STORAGE METHODS

Amadumbe has a high moisture content, so it is necessary to process it into flour to extend its shelf life. Chapter 3 revealed that storage conditions influenced the physiological and mechanical properties of *amadumbe* corms. So, this chapter will evaluate the changes in the quality of *amadumbe* flour derived from *amadumbe* corms subjected to different storage conditions.

Abstract

This study aimed to investigate the effects of different storage conditions on the proximate composition, functional and morphological quality attributes of *amadumbe* flour. *Amadumbe* flour was derived from corms subjected to five storage conditions: Low-cold storage, High-cold storage, CoolBot® and evaporative cooler storage, Underground storage, and Ambient storage as a control. The corms were stored in three replications using a completely Randomised Block Design. Three different experimental designs were used in this chapter. The first two experimental designs had two treatments: storage conditions and storage period. However, sampling was done every 14th day for 70 days in experiment one and on days 0 and 70 in experiment two. The third experimental design had three treatments: storage conditions, storage period, and temperature, and sampling was done every 14th day for 70 days. The data were analysed using the Duncan multiple range test at a 5 % significance level. The results obtained in this study showed that storage conditions and storage period had a significant impact ($p < 0.05$) in increasing the crude fat, reducing sugar content, water holding capacity, and oil holding capacity, and decreasing the swelling power and solubility of amadumbe flour. High-cold storage was the best method in preserving the quality attributes of *amadumbe* flour. It resulted in the lowest reduction in moisture content (2.67 %), crude protein (5.89 %), swelling power (16.44 %), solubility (20.41 %), L* (0.04 %), degradation of *amadumbe* flour starch granules. It also resulted in the highest increase in crude fat (55. 56 %), oil holding capacity (94.58 %), and a* (137.28). Ambient storage was the worst storage method in preserving the quality attributes of *amadumbe* flour. It resulted in the highest decrease in

moisture (7.02 %), solubility (31.59 %), and L* (2.51 %). It also resulted in the lowest increase in crude fat (2.78 %), reducing sugar content (91.75 %), water holding capacity (70.85 %), and oil holding capacity (85.99 %). The microscopic morphologies of *amadumbe* flour were irregular and polygonal in shape. On day 0, the flours exhibited larger densely packed granular particles connected by fibrous materials. After 70 days of storage, there was a reduction in the size and compactness of the granular particles. This study found that CoolBot® and evaporative cooler storage is the second-best storage method after High-cold storage. Therefore, it can be used as an alternate method in cases where a refrigerator cannot be afforded.

4.1 Introduction

Amadumbe has a high moisture content which limits its shelf life, one of the ways used to preserve the shelf life is processing it into flour (Pérez et al., 2005). The processing of *amadumbe* into flour reduces its size and makes storage more convenient (Shi et al., 2017). Besides size reduction and extended shelf life, *amadumbe* has been gaining more scientific attention because it has health-related benefits such as aiding with digestion and reducing blood sugar levels (Kaushal *et al.*, 2015; Wongsagonsup *et al.*, 2021).

The performance of flour as a food ingredient is dependent on its nutritional and functional properties (Njintang *et al.*, 2008b). According to Chandra et al. (2015), *amadumbe* with a high water holding capacity is suitable for producing dough, processed cheese, and baked products. The ability to hold water makes *amadumbe* suitable for producing foods that require a thick viscosity, such as soups and gravies (Kaur et al., 2013; Kaushal et al., 2015). High oil holding capacity is suitable for industries where fat absorption is desired, like bakery and meat products (Chandra et al., 2015). The small granule size of *amadumbe* flour makes it suitable for producing biodegradable polyethylene film (Naidoo et al., 2015; Mukurumbira et al., 2017).

The composition of *amadumbe* flour is influenced by factors such as storage, cultivar, and geographical location (Sit et al., 2014). Previous studies in South Africa have focused on the water use and drought tolerance of locally grown varieties (Mabhaudhi and Modi, 2015), starch properties of cultivated and wild *amadumbe* types (Naidoo *et al.*, 2015). The impact of genotype and growth location on composition and functionality of *amadumbe* flour (Mawoyo *et al.*, 2017) and recently, the composition, pasting, and thermal properties of flour and starch derived from *amadumbe* with different corm sizes (Oyeyinka and Amonsou, 2020). Modi and Mare (2016) studied the impact of temperatures on the short-term storage of South African *amadumbe* corms. However, the study only had two storage conditions and did not focus on the functional properties of *amadumbe* flour. Therefore, this study was conducted to quantify the impact of various storage environments on the functional properties of flour derived from stored *amadumbe* corms.

4.2 Materials and Methods

This section contains all materials and methods used to quantify the impact of different storage conditions on the quality properties of *amadumbe* flour.

4.2.1 Post-harvest sample preparations

The tubers were harvested after ten months. After that, the tubers were washed using tap water and allowed to dry at ambient conditions. The corms with defects and harvest injuries were discarded immediately after drying.

4.2.2 Data Collection

Evaluation of all physicochemical properties of *amadumbe* flour was done at the Food Science and Agricultural Engineering Laboratory, University of KwaZulu-Natal, South Africa.

4.2.3 Experimental design

Three experimental designs were used in this chapter. The difference between experimental designs 1 and 2 was due to financial constraints, which resulted in sampling for experimental design 2 only being done on days 0 and 70. Experimental design 3 differed because temperature becomes an additional treatment when calculating swelling power and solubility.

4.2.3.1 Experiment design 1

The experimental design to determine flour yield, water holding capacity, and oil holding capacity was conducted using a Completely Randomised Block Design. The experimental design had two factors (storage conditions and storage period). Sampling was done every 14th day for 70 days using three replications (The graphical illustration of the experimental design can be found in Figure 3.2 of Section 3.2.3).

4.2.3.2 Experiment design 2

The experimental design to determine flour morphology and proximate composition were similar to Experiment design 1. However, sampling was only done on days 0 and 70. (The graphical illustration of the experimental design can be found in Figure 4.1)

4.2.3.3 Experiment design 3

The experimental design to determine swelling power and solubility was conducted using a Completely Randomised Block Design. The experimental design had three factors (storage conditions, storage period, and temperature). Sampling was done every 14th day for 70 days using three replications (The graphical illustration of the experimental design can be found in Figure 4.2).

4.2.4 Flour extraction and yield

The method used by Naidoo et al. (2015) was used with minor modification to extract the flour. The *amadumbe* were brought to the laboratory for analysis immediately after harvest. The tubers were washed, peeled, chopped into small pieces, and then milled using a blender. The resultant pulp was oven-dried at 35°C for 48 h. The flour yield was calculated as the ratio of the flour obtained to the weight of the tuber used (Equation 4.1).

$$\mathrm{FY} = \frac{\mathrm{W}_{fa}}{\mathrm{W}_{t}} \mathrm{x}100 \tag{4.1}$$

where

FY = Flour yield (%),

W_{fa} = weight of flour obtained after drying (g), and

W_t = weight of the tuber used (g).

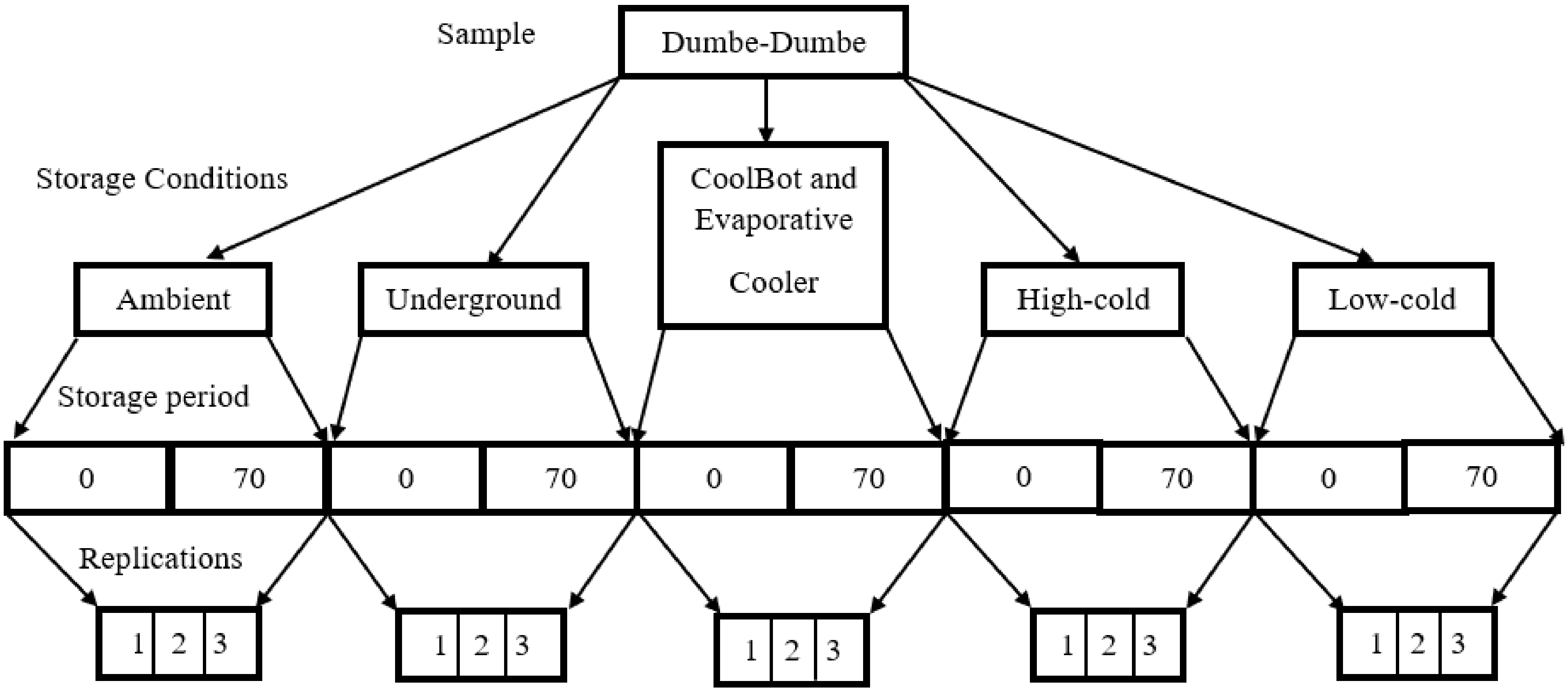


Figure 4.1 Experimental design to determine the proximate composition and morphology of *amadumbe* flour

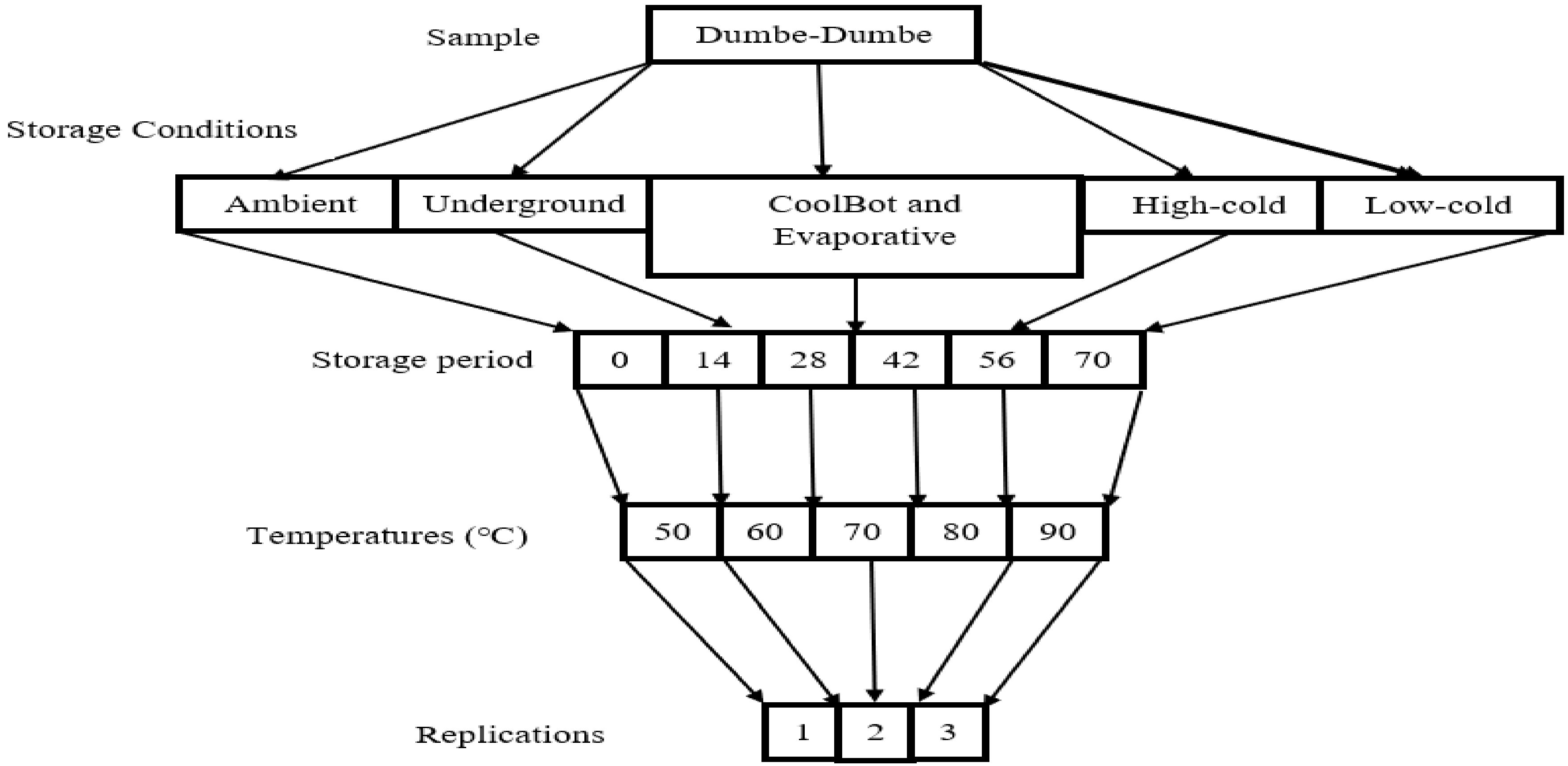


Figure 4.2 Experimental design to determine swelling power and solubility of *amadumbe* flour

4.2.5 *Amadumbe* flour proximate composition

The proximate composition of *amadumbe* was determined using the following methods:

4.2.5.1 Moisture content

The moisture content of the *amadumbe* flour sample was determined in a triplicate using the AOAC (2012) method 925.10 by drying a 5.0 g flour sample at 95°C for 72 hours. The moisture content was then calculated using Equation 4.2.

$$MC = \frac{W_{bd} - W_{ad}}{W_{bd}} x100 \tag{4.2}$$

where

MC = Moisture content (%),

W_{bd} = weight of *amadumbe* flour before drying (g), and

W_{ad} = weight of *amadumbe* flour after drying (g).

4.2.5.2 Ash content

The ash content of *amadumbe* flour sample was determined in a triplicate using the AOAC (2012) method 923.03 by taking about 1.0 g flour sample and igniting it at 550 °C for 6 h in a furnace (J M Ney furnace; Gesswein, United States of America). The ash content was then calculated using Equation 4.3

$$AC = \frac{W_{ba} - W_{a}}{W_{ba}} x100 \tag{4.3}$$

where

AC = Ash content (%),

W_{ba} = weight of *amadumbe* flour before ashing (g), and

W_{a} = weight of *amadumbe* ash (g).

4.2.5.3 Crude protein

The crude protein was determined according to the method used by Chisenga *et al.* (2019a). The Dumas combustion method of nitrogen content analysis was performed using a (Leco Truspec FP-528; LECO Corporation, United States America) by taking about a 0.2 g flour sample and analysing it using Leco Truspec. The percentage protein was then calculated by multiplying the obtained nitrogen content by 6.25.

4.2.5.4 Crude fibre

The crude fibre was measured according to the AOAC (2012) method No 962.09 by weighing 5 g flour sample then boiling it in 50 mL of 0.3M sulphuric acid (Labsupply; South Africa) under reflux for 40 min, followed by filtering under suction pressure. The obtained residue was then washed with hot distilled water to get rid of the acid. The remaining residue was then boiled in 100 mL, 0.25M of sodium hydroxide (Labsupply; South Africa) under reflux for 40 min and filtered under suction. The remaining residue was washed with hot distilled water to get rid of the sodium hydroxide. The residue was dried to the constant weight in the oven at 95°C for 2 h, then cooled in a desiccator (Labsupply; South Africa). The sample was then heated using a blue Bunsen burner and then ashed in a furnace (J M Ney furnace; Gesswein, United States of America) to remove ash from the fibre. The crude fibre was then calculated using Equation 4.4.

$$\mathrm{CF} = \frac{(\mathrm{W}_d - \mathrm{W}_a) - \mathrm{W}_c}{\mathrm{W}_i} \mathrm{x}100 \qquad (4.4)$$

where

CF = Crude Fibre (%),

W_i = Initial weight of *amadumbe* flour (g),

W_c = Weight of crucible (g),

W_d = Weight of residue after drying at 95°C for 2 h (g), and

W_a = Weight of residue ashing (g).

4.2.5.5 Crude fat

The AOAC (2012) method 920.39 was used to determine the crude fat. The crude fat was determined by putting about 5 g of flour sample in a Soxhlet extraction unit (Büchi, Switzerland) using petroleum ether (LabSupply; South Africa) as a solvent. The crude fat was then calculated using Equation 4.5.

$$F = \frac{W_r - W_b}{W_i} x100 \tag{4.5}$$

where

F = Crude fat content (%),

W_i = Initial weight of *amadumbe* flour (g),

W_b = Weight of the beaker (g), and

W_r = Weight of the beaker and residue remaining after extraction.

4.2.6 *Amadumbe* flour sugar content

The method used by Ngobese et al. (2017) was used with minor modification to determine the sugar content. *Amadumbe* flour weighing 100 mg was measured using a digital scale (KERN ALS-A; KERN & SOHN GmbH, Germany). Fifteen millilitres of 80 % ethanol (99.9 %; Laboratory Supplies, South Africa) was added to the flour and homogenised (T 18 digital Ultra-Turrax; IKA, China) for 1 min. The mixture was then incubated for 1 hour in an 80°C shaking water bath (Faithful FWS-30; Huanghua Faithful Instruments Co., Ltd, China), after which the mixture was left to stand overnight at 4°C. The mixture was then centrifuged (Avanti J-26S XP; Beckman Coulter, United States of America) at 10,000 rpm for 15 minutes in a refrigerated centrifuge operating at 4°C. The obtained supernatant was filtered through a glass wool. The filtrate was dried overnight in an evaporator (EZ-2 Plus; SP Industries, United States of America). The dried extracts were made up to 2 mL using ultrapure water. The mixture was then filtered using a 0.45 µm pore size Ascrodisc nylon filter (Analytical Technology, South Africa). Glucose, sucrose, and fructose were separated using a High-Performance-Liquid-Chromatography system (LC-20AT; Shimadzu, Japan) equipped with a refractive index detector (RID-10A; Shimadzu, Japan). Soluble sugars were separated using a phenomenex monosaccharide column (300 × 7.8 mm 300 Phenomenex; Torance, United States of America) at 85 °C. Double-distilled water was used as the mobile phase at a flow rate of 1 $mL.min^{-1}$. Three 20 µL injection volumes were analysed, and each one was read three times, and average reading was used. The content of individual sugars was determined using an equation obtained from glucose and fructose (Labsupply, South Africa) standard curves (which were prepared from reading 0,0.1, 0.2, 0.4, 0.5, 1, 2.5, 5, 10, and $mg.mL^{-1}$ solutions) and be expressed relative to the fresh weight.

4.2.7 *Amadumbe* flour swelling power and solubility

The swelling power and solubility were determined using the method used by Chisenga *et al.* (2019b) with minor modifications. The swelling power and solubility were determined at 50, 60, 70, 80, and 90°C. A 0.5 g dry flour sample was suspended in 20 mL deionised water in a 50 mL centrifuge tube with a known weight. The centrifugal tube was heated using a water bath (Faithful FWS-30; Huanghua Faithful Instruments Co., Ltd, China) at 50, 60, 70, 80, and 90°C for 30 min and spiralling was done every 5 min. The centrifugal tube was allowed to cool to ambient temperature and centrifuged (Avanti J-26S XP; Beckman Coulter, United States of America) at 1867 × g for 20 min. The supernatant obtained was used for the solubility test. The sediment mass was measured, and the swelling power ($g.g^{-1}$) was calculated as the ratio of the sediment mass to the original sample weight (Equation 4.6.) The collected supernatant was placed on a pre-weighed evaporating crucible dish and oven-dried at 105°C for 12 h, and the dried mass was measured. The solubility (%) was calculated as the ratio of dried mass to the original sample weight (Equation 4.7).

$$SP = \frac{W_S}{W_O} \qquad (4.6)$$

$$S = \frac{W_{ds}}{W_0} \qquad (4.7)$$

where

SP = Swelling power ($g.g^{-1}$),

S = Swelling power ($g.g^{-1}$),

W_O = weight of original *amadumbe* flour (g),

W_s = weight of wet *amadumbe* flour sediment (g), and

W_{ds} = weight of dry *amadumbe* flour supernatant (g).

4.2.8 *Amadumbe* flour water and oil holding capacities

The water and oil holding capacities were determined using the method used by Ngobese et al. (2017). A 0.5 g of flour was placed in a 15 mL conical pre-weighed centrifuge tube. Five millilitres of deionised water or canola with a density of 1 and 0.89 g cm^{-3} respectively at the ambient temperature was added to the flour. The mixture was stirred with a stainless-steel spatula and allowed to stand at ambient temperature for two hours before being centrifuged at 350 × g (Avanti J-26S XP; Beckman Coulter, United States of America) for 30 min. The supernatant was discarded, and the sample was reweighed. The absorption capacity was calculated by taking the ratio of the difference between the initial and final weight to the weight of the initial flour portion used (Equation 4.8).

$$\mathrm{HC} = \frac{W_i - W_f}{W_i} \tag{4.8}$$

where

HC = Water or Oil holding capacity (%),

W_i = initial weight of *amadumbe* flour (g), and

W_f = final weight of *amadumbe* flour (g).

4.2.9 *Amadumbe* flour colour

The colour of flour was determined using the method used by Oyeyinka and Amonsou (2020). The data was obtained using a colorimeter after standardisation using Hunter Lab colour standards (ColorFlexEZ; Hunter Associate Laboratories Inc, United States of America). The colour of the flour was measured by reading L*, a*, and b*. L*, a*, and b* refer to (degree of lightness), (redness to greenness), and (yellowness to blueness), respectively. Flour was poured into a glass cup (04-7209-00 glass sample cup; Hunter Associate Laboratories Inc, United States of America) until it completely covered the bottom part of the cup.

4.2.10 *Amadumbe* flour granule morphology

The granule morphology was determined using the method used by Ngobese et al. (2017). Granule morphology was determined using a scanning electron microscope (ZEISS EVO LS15; Carl Zeiss Microscopy, United States of America), set at a magnification of 1.50kX with signal A at SEI, I Probe = 59 pA, and EHT = 20.00kV. The flour was splashed on a double-sided silver tape attached to a 10 mm diameter specimen stub. The samples were coated with gold, using an ion sputter coater Q150 €S; Quorumtech, United Kingdom). The obtained granules from scanning electron microscope were then subjected to image analysis (Soft Imaging System GmbH; Olympus America Inc, United States of America) at the Microscopic analysis laboratory (University of KwaZulu Natal, Pietermaritzburg, South Africa).

4.2.11 Statistical analysis

Data analysis was performed using the GenStat 18.2.1 software, analysis of variance (ANOVA) was used to test for differences. The separation of means was determined using Duncan's multiple range test at the 5 % significant level. The relationship between the quality attributes was determined using linear regression analysis (Chisenga *et al.*, 2019).

4.3 Results and Discussion

This section will analyse and discuss the quality properties of *amadumbe* flour subjected to different storage environments. Table 4.3 shows the relationship between all the measured quality properties.

4.3.1 Flour yield

Table 4.1 shows the impact of storage conditions and storage period on the yield of *amadumbe* flour. Storage conditions had no significant effect ($p > 0.05$) on the yield of *amadumbe* flour.

The flour yield ranged from 31.58 to 32.26 %, with High-cold and Ambient storages having the lowest and highest flour yield, respectively. The range obtained in this study is comparable to the flour yield obtained by authors such as Tattiyakul *et al.* (2006) and Hoyos-Leyva *et al.* (2017), which reported a yield of (37.10-39.20 %) and (18.40-33.40%), respectively. The yield may be reduced due to milling losses (Pérez *et al.*, 2005).

The storage period had a significant impact ($p < 0.001$) on the yield of *amadumbe* flour. The flour yield increased from 24.96 to 36.60 % on days 0 and 70, respectively. The increase in flour yield may be due to the reduction in moisture during storage, as a result of respiration. This is evident by the strong negative correlation ($r = -0.728$, $p < 0.001$) between flour yield and moisture content. Flour yield had a positive correlation with reducing sugar content ($r = 0.855$, $p < 0.001$), water holding capacity ($r = 0.832$, $p < 0.001$), oil holding capacity ($r = 0.864$, $p < 0.001$), a* ($r = 0.485$, $p < 0.05$) and b* ($r = 0.415$, $p < 0.05$). Flour yield also had a negative correlation with swelling power ($r = -0.860$, $p < 0.001$) and solubility ($r = -0.828$, $p < 0.001$).

Table 4.1 The yield of flour from amadumbe subjected to different storage conditions

Storage period (days)	A	U	CBEC	HC	LC
0	24.96(4.20)^{a}	24.96(4.20)^{a}	24.96(4.20)^{a}	24.96(4.20)^{ab}	24.96(4.20)^{a}
14	32.97(1.60)^{cd}	32.95(2.25)^{cd}	34.00(2.19)^{cd}	30.56(5.31)^{ac}	32.20(0.5)^{c}
28	32.91(2.17)^{cd}	34.49(2.05)^{cd}	32.48(0.97)^{cd}	32.66(1.51)^{c}	33.52(0.83)^{cd}
42	35.66(0.30)^{cd}	34.35(2.56)^{cd}	32.67(1.20)^{c}	32.15(2.95)^{c}	32.90(1.39)^{cd}
56	36.22(0.58)^{cd}	35.32(1.66)^{cd}	33.96(0.62)^{c}	32.98(1.76)^{cd}	33.49(1.33)^{cd}
70	39.47(0.51)^{d}	35.66(1.39)^{cd}	36.25(0.99)^{cd}	35.41(0.43)^{cd}	36.22(1.76)^{cd}

	Storage conditions (A)	Storage period (B)	(A*B)
Level of significance	$p > 0.05$	$P < 0.001$	$p > 0.05$

All values are means of three values. Data contained in the parenthesis are the standard deviations. The means with different letters are significantly different at $p<0.05$ by LSD test. A = Ambient storage, U = Underground storage, EC = CoolBot® and evaporative cooler storage, HC = High-cold, and LC = low-cold storage.

4.3.2 *Amadumbe* flour proximate composition

Table 4.2 shows the change in proximate composition of *amadumbe* flour subjected to different storage conditions for 70 days.

4.3.2.1 Moisture

Storage conditions had no significant impact ($p > 0.05$) on the moisture content of *amadumbe* flour. The moisture content ranged from 11.46 to 11.72 %, with Ambient and High-cold storages having the lowest and highest moisture content, respectively. The high moisture content in flour stored in High-cold storage coincides with the reduced physiological weight loss of *amadumbe* corms kept in the same storage conditions. The range obtained in this study is comparable to the moisture content found by other authors such as Njintang *et al.* (2008b) (8.20 – 9.60 %), Kaushal *et al.* (2012) (10.2%), and Njintang *et al.* (2008a) (9.70 – 10.80 %). The moisture content is essential in determining flour storability, and levels above 12 % make the flour susceptible to microbial growth (Aryee *et al.*, 2006). The moisture content obtained in this study makes *amadumbe* flour suitable for prolonged storage. The storage period had a significant impact ($p < 0.001$) on the moisture content of *amadumbe* flour. The moisture content decreased from 11.88 to 11.04 % in day 0 and 70 respectively.

Moisture content correlated positively with crude protein ($r = 0.474$, $p < 0.05$), swelling power ($r = 0.816$, $p < 0.001$) and solubility ($r = 0.853$, $p < 0.001$). Protein has both hydrophobic and hydrophilic proteins and therefore they can interact with water in foods (Kaushal *et al.*, 2012). The positive corelation between moisture content and protein may be attributed to the hydrophilic nature of protein that make it attract water, therefore flours with high hydrophilic protein tend to absorb more water (Naidoo *et al.*, 2015). The reduction in moisture with time may cause a reduction in the polarity of the proteins as a result of degradation. Moisture content correlated negatively with crude fibre ($r = -0.410$, $p < 0.05$), flour yield ($r = -0,728$, $p < 0.001$), reducing sugar content ($r = -0.694$, $p < 0.001$), water holding capacity ($r = -0.700$, $p < 0.001$), oil holding capacity ($r = -0.765$, $p < 0.001$), L* ($r = -0.404$, $p < 0.05$). Furthermore, no correlation was found between moisture content, crude fat ($r = -0.068$, $p >0.05$) and a* (r = -

0.050, $p > 0.05$). The reason why there is no correlation between crude fat and moisture content is because of the low water binding capacity of fats (Chisenga *et al.*, 2019a).

4.3.2.2 Ash content

Ash content is used as an indicator of the mineral content of *amadumbe* flour (Ogunlakin *et al.*, 2012). Storage conditions had no significant impact ($p > 0.05$) on the ash content of *amadumbe* flour. The ash content ranged from 3.17 to 3.23 %, with Low-cold and High cold storage having the lowest ash content, while Ambient storage conditions had the highest. The high ash content in Ambient storage conditions can be attributed to the high dry matter content of *amadumbe* corms stored in Ambient storage conditions (Chisenga *et al.*, 2019a). The range obtained in this study is comparable to the ash content reported by other authors such as Ogunlakin *et al.* (2012) (2.47 – 2.87%) and Njintang *et al.* (2008a) (3.50 – 5.70 %). The storage period had no significant impact ($p > 0.05$) on the ash content of *amadumbe* flour. Ash content showed no significant relationship ($p > 0.05$) with all the studied properties.

4.3.2.3 Crude protein

Storage conditions had no significant impact ($p > 0.05$) on the crude protein of *amadumbe* flour. The crude protein ranged from 7.65 to 8.23 %, with Low-cold and High-cold storage conditions having the lowest and highest crude protein, respectively. The higher crude protein in High-cold storage indicates that this storage can reduce protein loss during storage. The range obtained in this study is alarmingly high compared to the crude protein obtained by other authors such as Njintang *et al.* (2008a) (2.70 – 5.40 %), Kaur *et al.* (2013) (2.00 %), Ogunlakin *et al.* (2012) (4.90 – 5.17 %), and (McEwan *et al.*, 2014) (4.5 – 5.04 %). The difference in protein content may be due to agronomic management factors such as fertiliser application and environmental conditions (Agiriga and Iwe, 2016; Chisenga *et al.*, 2019a).

The storage period had a significant impact ($p < 0.001$) on the crude protein of *amadumbe* flour. The crude protein decreased from 8.48 to 7.47 % on days 0 and 70. The crude protein correlated positively with moisture content ($r = 0.474$, $p < 0.05$), swelling power ($r = 0.595$, $p < 0.001$), and solubility ($r = 0.593$, $p < 0.001$). Crude protein correlated negatively with crude fat ($r = -0.523$, $p < 0.05$), flour yield ($r = -0.513$, $p < 0.001$), reducing sugar content ($r = -0.732$,

$p < 0.001$), water holding capacity ($r = -0.665$, $p < 0.001$), oil holding capacity ($r = -0.707$, $p < 0.001$), and crude fibre ($r = -0.576$, $p < 0.001$). This negative relation shows that crude fibre, flour yield, reducing sugar content, water holding capacity, oil holding capacity, and crude fat increased throughout the storage period while protein reduced. The reduction in the crude protein will impact the dough quality due to decreased water retention ability of *amadumbe* starch (Lu and Lu, 2012). Therefore, storing *amadumbe* for longer periods may result in a dough that is not suitable to produce bread due to reduced protein but more suitable for producing foods that require soft flour such as pies, biscuits, and other baked products (Njintang *et al.*, 2008a).

4.3.2.4 Crude fibre

Storage conditions had no significant impact ($p > 0.05$) on the crude fibre of *amadumbe* flour. The crude fibre ranged from 0.92 to 1.14 %, with High-cold and Low-cold storage conditions having the lowest and highest crude fibre, respectively. The crude fibre comprises of lignin, cellulose and hemicellulose, pectin, and gum. It is essential to regulate blood sugar levels and improve digestion (Adepoju and Adejumo, 2015). The high fibre content in Low-cold storage is suitable to produce healthy food products (Ogunlakin *et al.*, 2012). The range obtained in this study is comparable to the crude fibre obtained by other authors such as Njintang *et al.* (2008a) (0.40 – 1.20 %), Kaushal *et al.* (2012) (0.75 %), and low compared to authors such as Ogunlakin *et al.* (2012) (2.70 – 2.97 %), and Naidoo *et al.* (2015) (1.9 %). This difference in fibre content may be due to variety, growth conditions, and agronomic practices (Svanberg *et al.*, 1997; Naidoo *et al.*, 2015).

Storage period had a significant impact ($p < 0.001$) on the crude fibre of *amadumbe* flour. The crude fibre increased from 0.89 to 1.13 % in days 0 and 70 respectively. The crude fibre had a positive correlation with reducing sugar content ($r = 0.498$, $p < 0.05$), water holding capacity ($r = 0.458$, $p < 0.05$), and oil holding capacity ($r = 0.467$, $p < 0.05$). The crude fibre also correlated negatively with crude protein ($r = -0.576$, $p < 0.001$), swelling power ($r = -0.422$, $p < 0.05$), and solubility ($r = -0.481$, $p < 0.05$). This negative correlation shows that crude fibre increased throughout the storage period while crude protein, swelling power, and solubility decreased.

4.3.2.5 Crude fat

Storage conditions had a significant impact ($p < 0.05$) on the crude fat of *amadumbe* flour. The crude fat ranged from 0.36 to 0.46 %, with Ambient and High-cold storage conditions having the lowest and highest crude fat content, respectively. The range obtained in this study is comparable to the crude fat obtained by other authors such as Njintang *et al.* (2008a) (0.400 – 0.60 %), Kaushal *et al.* (2012) (0.5 %), Ogunlakin *et al.* (2012) (0.50 – 0.57 %), and Kaur *et al.* (2013) (1.90 %). Crude fat is responsible for flavour and texture softening; therefore, flours with increased crude fat content result in baked products with improved taste (Paramita *et al.*, 2021). High-cold storage is recommended for better-quality food due to its high crude fat content compared to all tested storage conditions.

The storage period had a significant impact ($p < 0.001$) on the crude fat of *amadumbe* flour. The crude fat increased from 0.36 to 0.44 % on days 0 and 70. The crude fat had a negative correlation ($r = -0.523$, $p < 0.05$) with crude protein. Park and Baik (2004) also found a negative correlation between crude protein and crude fat of wheat flour used to produce noodles. The crude fat also had a positive with ($r = 0.391$, $p < 0.05$), water holding capacity ($r = 0.365$, $p < 0.05$), and a* ($r = 0.624$, $p < 0.001$).

Table 4.2 Proximate composition of flour from *amadumbe* stored in different storage conditions

Storage period (Days)	Storage conditions	MC (%)	AC (%)	CP (%)	CF (%)	F (%)
0	A	11.88(0.09)^{c}	3.17(0.04)^{a}	8.48(0.52)^{c}	0.89(0.22)^{a}	0.36(0.02)^{b}
	U	11.88(0.09)^{c}	3.17(0.04)^{a}	8.48(0.52)^{c}	0.89(0.22)^{a}	0.36(0.02)^{b}
	CBEC	11.88(0.09)^{c}	3.17(0.04)^{a}	8.48(0.52)^{c}	0.89(0.22)^{a}	0.36(0.02)^{b}
	HC	11.88(0.09)^{c}	3.17(0.04)^{a}	8.48(0.52)^{c}	0.89(0.22)^{a}	0.36(0.02)^{b}
	LC	11.88(0.09)^{c}	3.17(0.04)^{a}	8.48(0.52)^{c}	0.89(0.22)^{a}	0.36(0.02)^{b}
70	A	11.04(0.09)^{a}	3.29(0.15)^{a}	7.40(0.40)^{ab}	1.27(0.23)^{ab}	0.37(0.04)^{ab}
	U	11.46(0.23)^{b}	3.19(0.20)^{a}	7.77(0.93)^{abc}	1.04(0.23)^{ab}	0.38(0.02)^{a}
	CBEC	11.38(0.40)^{b}	3.18(0.20)^{a}	7.35(0.30)^{ab}	0.98(0.15)^{ab}	0.38(0.09)^{b}
	HC	11.56(0.30)^{bc}	3.17(0.43)^{a}	7.98(0.26)^{bc}	0.95(0.23)^{a}	0.56(0.03)^{c}
	LC	11.54(0.07)^{bc}	3.17(0.09)^{a}	6.83(0.62)^{a}	1.39(0.28)^{b}	0.50(0.10)^{c}
Level of significance	Storage conditions (A)	$p > 0.05$	$p > 0.05$	$p > 0.05$	$p > 0.05$	$p < 0.001$
	Storage period (B)	$p < 0.001$	$p > 0.05$	$p < 0.001$	$p < 0.05$	$p < 0.05$
	(A*B)	$p > 0.05$	$p > 0.05$	$p > 0.05$	$p > 0.05$	$p < 0.001$

All values are means of three values. Data contained in the parenthesis are the standard deviations. The means with different letters are significantly different at $p<0.05$ by LSD test. A = Ambient storage, U = Underground storage, EC = CoolBot® and evaporative cooler storage, HC = High-cold, and LC = low-cold storage. MC= Moisture content, AC = Ash content, CP = Crude protein, CF = Crude fibre, and F = Crude Fat

Table 4.3 Correlation between proximate and physicochemical properties of of flour from *amadumbe* subjected to different storage conditions

Parameter	MC (%)	AC (%)	CP (%)	CF (%)	F (%)	FY (%)	RS (%)	SP (g.g-1)	S (%)	WHC (%)	OHC (%)	L*	a*	b*
MC (%)	1.000													
AC (%)	-0.022*	1.000												
CP (%)	0.474**	0.242*	1.000											
CF (%)	-0.410**	0.224*	-0.576***	1.000										
F (%)	-0.068*	-0.220*	-0.523**	0.268*	1.000									
FY (%)	-0.728***	0.041*	-0.513**	0.280*	0.207*	1.000								
RS (%)	-0.694***	0.055*	-0.732***	0.498**	0.391**	0.855***	1.000							
SP ($g.g^{-1}$)	0.816***	-0.062*	0.595***	-0.422**	-0.113*	-0.860***	-0.877***	1.000						
S (%)	0.853***	-0.195*	0.593***	-0.481**	0.011*	-0.828***	-0.775***	0.871***	1.000					
WHC (%)	-0.700***	0.000*	-0.665***	0.458**	0.365**	0.832***	0.958***	-0.861***	-0.724***	1.000				
OHC (%)	-0.765***	0.084*	-0.707***	0.467**	0.230*	0.864***	0.955***	-0.933***	-0.879***	0.936***	1.000			
L*	-0.404**	-0.197*	-0.117*	0.041*	-0.310*	0.000*	-0.007*	-0.300*	-0.230*	0.057*	0.131*	1.000		
a*	-0.121*	-0.199*	-0.198*	-0.016*	0.624***	0.485**	0.452*	-0.244*	-0.119*	0.480**	0.340**	-0.628***	1.000	
b*	-0.050*	0.534**	0.207*	-0.132*	-0.152*	0.415**	0.182*	-0.238*	-0.296*	0.203*	0.254*	-0.382**	0.344**	1.000

MC = Moisture content, AC = Ash content, CP = Crude protein, CF = Crude fibre, F= Crude fat, FY = Flour yield, RS = Reducing sugars, SP = Swelling power, S = Solubility, WHC = water holding capacity and OHC = Oil holding capacity. Level of significance p > 0.05*, p < 0.05**, p < 0.001***

4.3.3 *Amadumbe* flour sugar content

The change in the reducing sugar content of *amadumbe* flour during storage can be found in Table 4.4. The reducing sugar content of *amadumbe* flour ranged between 0.97 and 2.23 %. The range obtained in this study is comparable to the reducing sugar content obtained by other authors, such as Momin *et al.* (2021) (1.31 – 3.36 %), Njintang *et al.* (2007) (1.30 – 2.33 %). However, the reducing sugar content is high compared to those reported by other authors such as Modi and Mare (2016) (0.30 – 0.50 %) and Amon *et al.* (2014) (0.35 – 0.73 %). The difference in reducing sugars may be due to agronomic management factors. Mare (2009) reported that the sugar content was reduced by not applying fertiliser to *amadumbe*.

Storage conditions had a significant impact ($p < 0.001$) on the reducing sugar content of *amadumbe* flour. The reducing sugar content ranged from 1.26 to 1.48 %, with Ambient and Low-cold storages having the lowest and highest reducing sugar content, respectively. Baidoo *et al.* (2010) also reported a higher reducing sugar content in *amadumbe* stored in cold storage (2.10 %) with a temperature of 4-5 °C as compared to ambient storage conditions (1.80 %) with a temperature of 28±3 °C. The increase in reducing sugar content in cold storage is due to starch breaking down into reducing sugars (Kiaitsi *et al.*, 2020). Hollyer *et al.* (2000) reported that you need to have low levels of reducing sugar content to produce good quality crisps. Reducing sugars are responsible for enzymatic browning during the frying of crisps (Xiao *et al.*, 2018). Therefore, to prevent enzymatic brown during processing, reducing sugar levels must be kept below 2% (Van Hal, 2000).

The storage period had a significant impact ($p < 0.001$) on the reducing sugar content of *amadumbe* flour. The reducing sugar content increased from 0.97 to 2.00 % on days 0 and 70, respectively. Baidoo *et al.* (2010) also reported an increase in the reducing sugar content of *amadumbe* stored for three weeks from 1.90 to 2.10 %. The breakdown of starch causes an increase in sugars throughout the storage period. Reducing sugar content had a strong positive correlation with water holding capacity ($r = 0.958$, $p < 0.001$) and oil holding capacity ($r = 0.955$, $p < 0.001$) and a strong negative correlation with swelling power ($r = -0.877$, $p < 0.001$), and solubility ($r = -0.775$, $p < 0.001$). This negative correlation shows that as reducing sugars increase, the swelling power and solubility of *amadumbe* flour are reduced.

The interaction of storage conditions and storage period had a significant impact ($p < 0.001$) on the reducing sugar content of *amadumbe* flour. Low-cold storage had the highest reducing sugar content increase of 129.89 % from day 0 to day 70, while Ambient storage had the lowest reducing sugar content increase of 91.75 %. The high sugar content in Low-cold storage is suitable for producing cakes because the sugars are used in fermentation to raise the dough (Van Hal, 2000). The low, reducing sugar content of Ambient storage below 2% is suitable to produce good quality crisps (Hollyer *et al.*, 2000; Van Hal, 2000).

Table 4.4 The reducing sugar content of flour from *amadumbe* subjected to different storage conditions

Storage period (Days)	A	U	CBEC	HC	LC
0	0.97(0.00)^{a}	0.97(0.00)^{a}	0.97(0.00)^{a}	0.97(0.00)^{a}	0.97(0.00)^{a}
14	1.00(0.00)^{ab}	1.01(0.05)^{ab}	1.04(0.02)^{abc}	1.05(0.06)^{abc}	1.10(0.01)^{abc}
28	1.10(0.03)$^{a-d}$	1.12(0.02)$^{a-d}$	1.31(0.05)^{def}	1.35(0.04)^{ef}	1.23(0.03)^{cde}
42	1.21(0.02)$^{b-e}$	1.35(0.13)^{ef}	1.41(0.43)^{ef}	1.40(0.35)^{ef}	1.39(0.04)^{ef}
56	1.42(0.07)^{ef}	1.49(0.05)^{fg}	1.65(0.12)^{g}	1.88(0.11)^{h}	1.94(0.04)^{hi}
70	1.86(0.11)^{h}	1.88(0.03)^{h}	1.96(0.05)^{hi}	2.09(0.02)^{ij}	2.23(0.07)^{j}

	Storage conditions (A)	Storage period (B)	(A*B)
Level of significance	$p < 0.001$	$p < 0.001$	$p < 0.05$

All values are means of three values. Data contained in the parenthesis are the standard deviations. The means with different letters are significantly different at $p<0.05$ by LSD test. A = Ambient storage, U = Underground storage, EC = CoolBot® and evaporative cooler storage, HC = High-cold, and LC = low-cold storage.

4.3.4 *Amadumbe* flour swelling power and solubility

Figure 4.3a-c illustrates the effect of storage conditions and storage period on the swelling power of *amadumbe* flour. The swelling power ranged between 2.42 and 9.78 $g.g^{-1}$. The range obtained in this study is low compared to the swelling power obtained by other authors such as

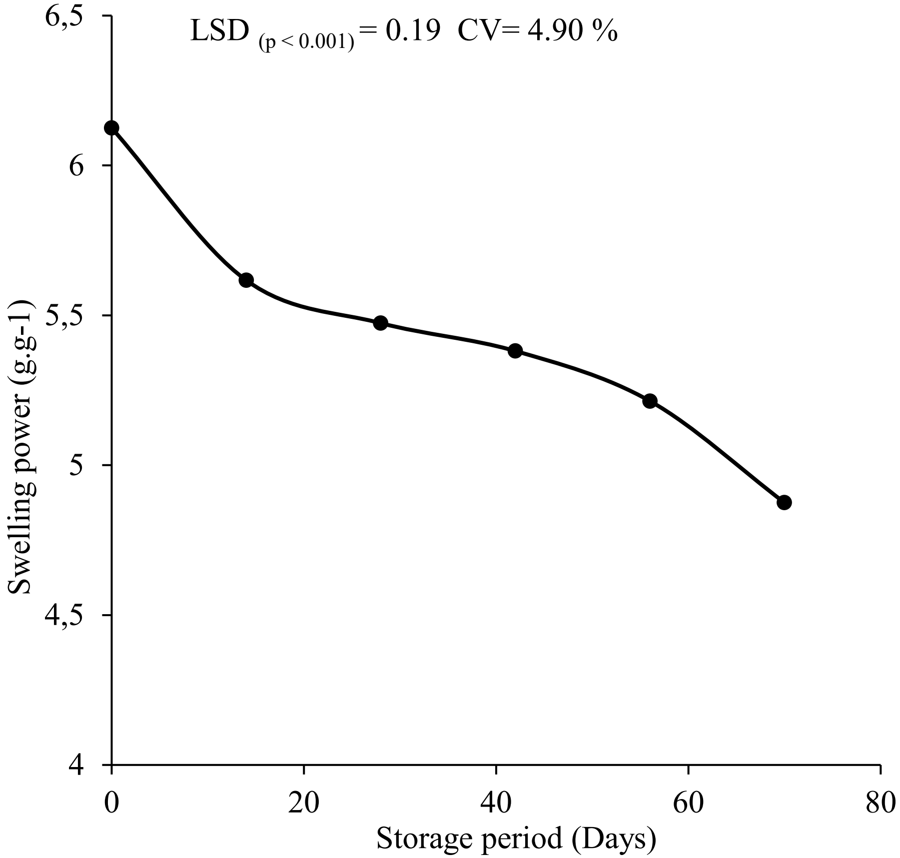
Aprianita *et al.* (2014) (5.45 – 30.12 $g.g^{-1}$), Alam and Hasnain (2009) (6.20 –28.00 $g.g^{-1}$), and Nwokocha *et al.* (2009) (2.52 –18.60 $g.g^{-1}$). The low swelling power of *amadumbe* flour may be attributed to higher protein levels because protein forms a stiff matrix by embedding in the starch granule, restricting the water from accessing the granules (Lewu *et al.*, 2010).

Figure 4.3b illustrates the change in swelling power of *amadumbe* stored in different storage conditions. Storage conditions had a significant impact ($p < 0.001$) on the swelling power of *amadumbe* flour. The swelling power ranged between 5.31 to 5.62 $g.g^{-1}$, with Ambient and High-cold storage conditions having the lowest and highest swelling power, respectively. Baidoo *et al.* (2010) also reported a higher reduction in swelling power of *amadumbe* stored in cold storage (24.90 – 18.50 $g.g^{-1}$) as compared to ambient storage (24.90 – 14.85 $g.g^{-1}$). The high swelling power in High-cold storage may be attributed to the reduced degradation in starch granules which interns result in granules with improved ability to retain water (Chiranthika *et al.*, 2021). CoolBot® and Evaporative cooler storage conditions had a swelling power of 5.47 $g.g^{-1}$, comparable to the swelling power obtained in High-cold storage. Therefore, both these storage conditions would be suitable to produce foods where high pasting viscosity is required (Buckman *et al.*, 2018).

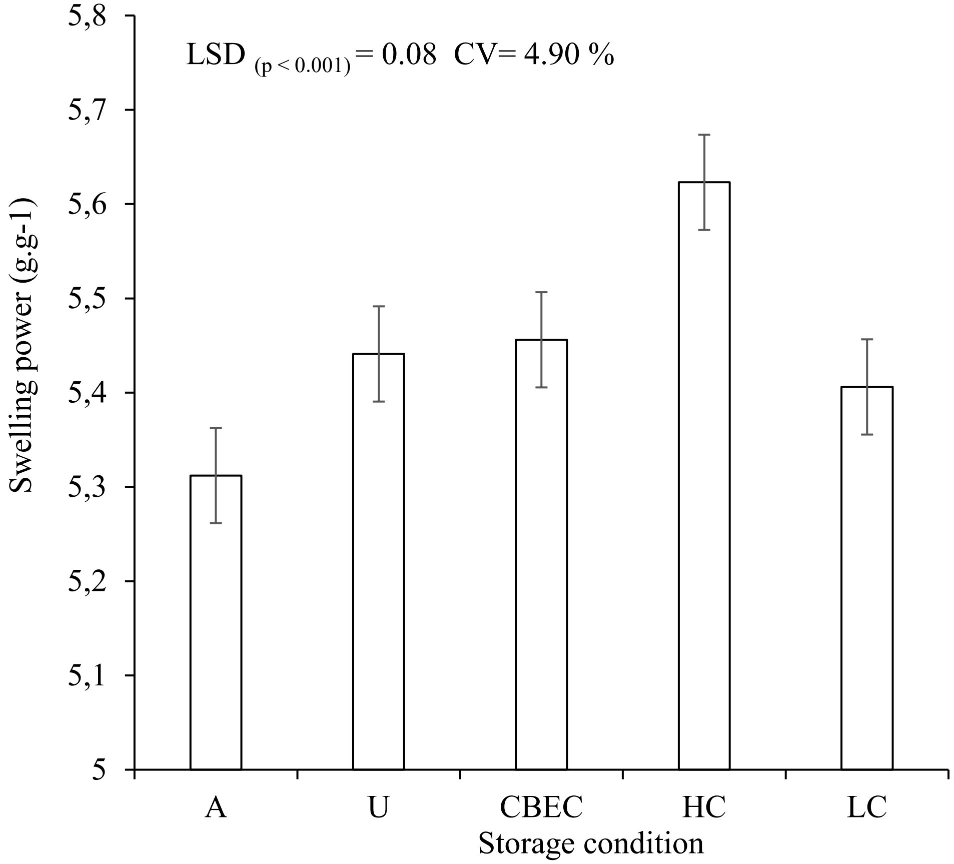
Figure 4.3a illustrates the change in swelling power of *amadumbe* flour as the storage period is increased. The figure illustrates that the swelling power of *amadumbe* flour decreased throughout the storage period. The storage period had a significant impact ($p < 0.001$) on the swelling power of *amadumbe* flour. The swelling power decreased from 6.13 to 4.88 $g.g^{-1}$ on days 0 and 70, respectively. Others authors, such as Bamidele and Akanbi (2013), reported a decrease in the swelling power of pigeon pea flour stored for ten weeks from 2.31 to 2.27 $mL.100g^{-1}$. Baidoo *et al.* (2010) also reported a decrease in the swelling power of *amadumbe* stored for three weeks from 20.50 to 14.85 $g.g^{-1}$. The reduction in swelling power throughout the storage may be attributed to the degradation of starch granules and a reduction in other non-starch components such as phosphorus content. Phosphorous has a negative charge which improves its ability to retain water (Kaur *et al.*, 2009; Kayode *et al.*, 2021). The swelling power correlated positively with solubility ($r = 0.871$, $p < 0.001$) and correlated negatively with water holding capacity ($r = -0.861$, $p < 0.001$) and oil holding capacity ($r = -0.933$, $p < 0.001$). The negative correlation shows that water and oil holding capacities increase as swelling power decreases.

Figure 4.3c illustrates the change in swelling power of *amadumbe* flour due to temperature changes. The figure shows that the swelling power of *amadumbe* flour increases as the temperature increases. The temperature had a significant impact ($p < 0.001$) on the swelling power of *amadumbe* flour. The swelling power increased from 3.20 to 8.45 $g.g^{-1}$ at 50 and 90°C, respectively. The increase in swelling power may be attributed to heat energy breaking the hydrogen bonds and exposing more of the hydroxyl and hydrophilic substances that bind with water (Kaur *et al.*, 2013). At temperatures below 60°C, the swelling power was relatively low across all storage conditions. The swelling power increased rapidly as a function of temperature beyond 60°C, as a result of gelatinisation of starch present in the flour (Mawoyo *et al.*, 2017). Aprianita *et al.* (2014) also reported that *amadumbe* flour undergoes a rapid increase in swelling power at temperatures above 60°C.

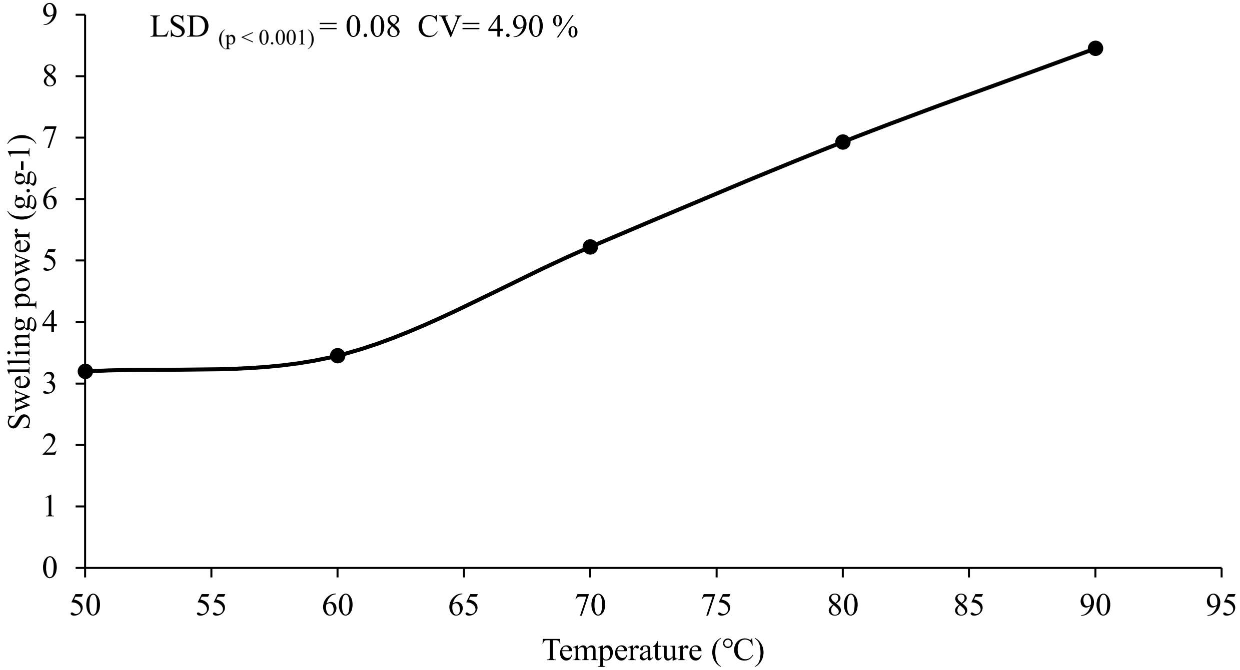
The interaction of storage conditions and storage period had a significant impact ($p < 0.001$) on the swelling power of *amadumbe*. Ambient storage conditions had the highest reduction in swelling power of 24.36 %, while High-cold storage conditions had the lowest reduction of 16.44 % from day 0 to day 70. The interaction of storage conditions and the temperature had a significant impact ($p < 0.001$) on the swelling power of *amadumbe*. High-cold storage had the highest swelling power increase of 211.31 % from 50 to 90 °C, while Ambient storage had the lowest swelling power increase of 134.39 %. The interaction of storage period and the temperature also had a significant impact ($p < 0.001$) on the swelling power of *amadumbe* flour. Day 0 had the highest increase in swelling power of 180.85 %, while day 70 had the lowest increase of 139.65 %. Therefore, storing *amadumbe* for an extended period reduces its ability to swell. The interaction of storage conditions, storage period and temperature, had a significant impact ($p < 0.001$) on the swelling power of *amadumbe*. High-cold storage had the highest swelling power on day 0 at 90°C, while ambient storage conditions showed the lowest swelling power on day 70 at 50°C. According to Falade and Okafor (2013), food-eating quality is related to the retention ability of the flour. Therefore, High-cold storage has an increased ability to maintain swelling power.


LSD (p < 0.001) = 0.19 CV= 4.90 %
6,5
6
5,5
5
4,5
4
Swelling power (g.g-1)
0
20
40
60
80
Storage period (Days)

a)


LSD (p < 0.001) = 0.08 CV= 4.90 %
5,8
5,7
5,6
5,5
5,4
5,3
5,2
5,1
5
Swelling power (g.g-1)
A
U
CBEC
HC
LC
Storage condition

b)



c)

Figure 4.3 The effect of storage period (a), storage conditions (b), and temperature (c) on the swelling power of *amadumbe* flour.

A = Ambient storage, U = Underground storage, EC = CoolBot® and evaporative cooler storage, HC = High-cold, and LC = low-cold storage.

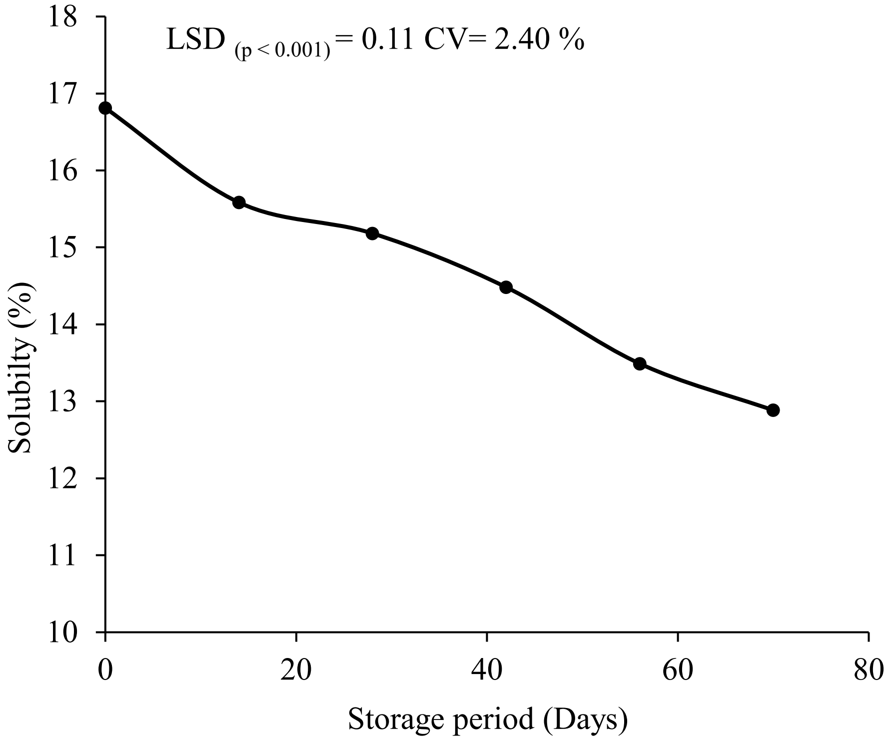
Figure 4.4a-c illustrates the change in solubility of *amadumbe* flour stored in different storage conditions. The solubility ranged between 7.62 and 20.46 %. The range obtained in this study is comparable to the solubility obtained by Mawoyo *et al.* (2017) (1.45 – 26.40 %), low compared to the range reported by (Njintang *et al.*, 2008b) (15.85 – 35.50 %), and high compared to the range obtained by (Falade and Okafor, 2013) (2.67 – 8.19 %). The variation in solubility may be due to differences in non-starch components such as mucilage and phosphorous content, which influences the interaction of flour with water (Bao *et al.*, 2021). The variations were also due to the solubilities being determined at different temperatures (Chisenga *et al.*, 2019a).

Figure 4.4b illustrates the change in solubility of *amadumbe* stored in different storage conditions. Storage conditions had a significant impact ($p < 0.001$) on the solubility of *amadumbe* flour. The solubility ranged between 12.89 to 15.84 %, with Ambient and High-cold storage conditions having the lowest and highest solubility, respectively. According to Naidoo *et al.* (2015), flours with small granules have lower solubility. The low solubility in Ambient storage conditions may be attributed to the degradation of starch granules of *amadumbe* flour. Modi and Mare (2016) also found that starch degradation was higher for *amadumbe* stored in ambient conditions than those held at 12 °C. The high soluble sugar content in High-cold storage may have also contributed to the higher solubility (Dereje *et al.*, 2020). CoolBot® and Evaporative cooler storage conditions had a solubility of 15.51 %, comparable to the solubility obtained in High-cold storage. Therefore, these storage conditions would be suitable for producing baked products because of their higher ability to swell (Kusumayanti *et al.*, 2015).

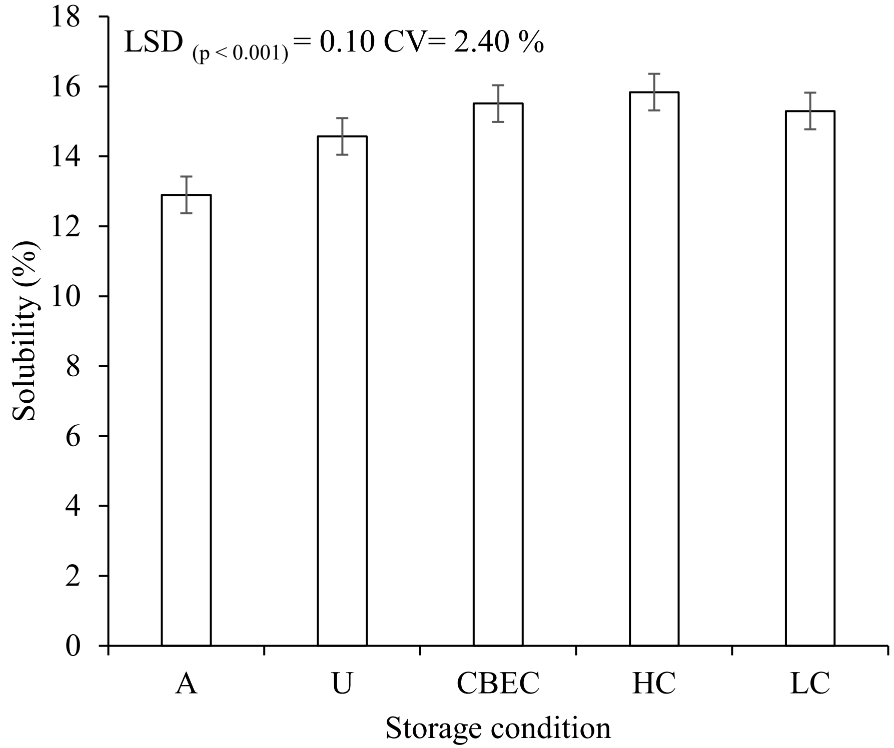
Figure 4.4a illustrates the change in the solubility of *amadumbe* flour as the storage period is increased. The figure illustrates that the solubility of *amadumbe* decreased throughout the storage period. The storage period had a significant impact ($p <0.001$) on the solubility of *amadumbe* flour. The solubility of *amadumbe* flour decreased from 16.81 to 12.88 % on days 0 and 70, respectively. The reduction in solubility throughout the storage may be attributed to the reduction in phosphate groups which are known to increase swelling by weakening the extent of bonding within the crystalline region of starch granules (Bao *et al.*, 2021). The reduction in swelling leads to reduced loss of amylose through leaching thus, reducing the solubility. Furthermore, the solubility of *amadumbe* flour correlated negatively with water holding capacity ($r = -0.724$, $p < 0.001$) and oil holding capacity ($r = -0.879$, $p < 0.001$). Therefore, flours with high solubility have a reduced ability to hold both water and oil.

Figure 4.4c illustrates that the solubility of *amadumbe* increased as the temperature was increased. The temperature had a significant impact ($p < 0.001$) on the solubility of *amadumbe* flour. The solubility of *amadumbe* flour increased from 12.16 to 17.51 % at 50 and 90°C, respectively. The increase in solubility may be attributed to heat causing the bonding forces to relax, making the granules swell, resulting in amylose leaching (Nwokocha *et al.*, 2009; Kaur *et al.*, 2013). Solubility had a strong positive correlation ($r = 0.871$, $p < 0.001$) with swelling power. Therefore, as the temperature increases, the swelling of *amadumbe* flour increases, which causes the amylose to leach out of the starch granules (Chisenga *et al.*, 2019a). The solubility increased rapidly as a function of temperature beyond 60°C because of increased swelling of starch granules (Mawoyo *et al.*, 2017).

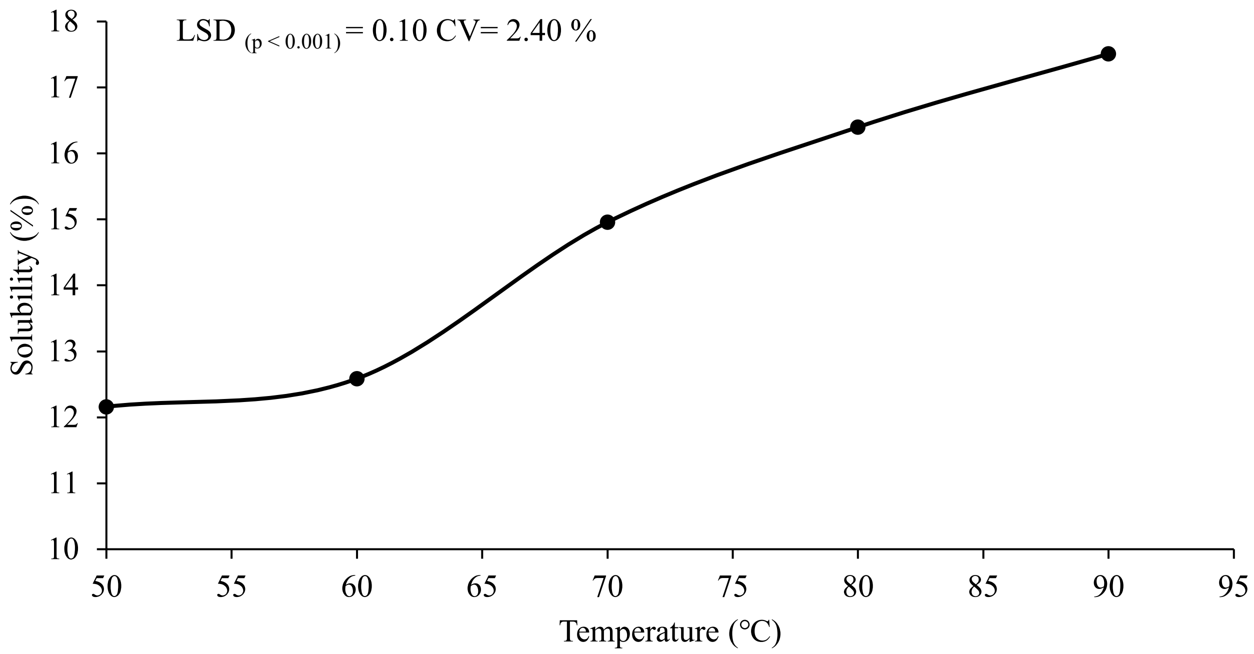
The interaction of storage conditions and storage period had a significant impact ($p < 0.001$) on the solubility of *amadumbe*. Ambient storage conditions had the highest reduction in solubility of 40.25 %, while High-cold storage had the lowest reduction of 15.14 % from day 0 to day 70. The interaction of storage conditions and the temperature had a significant impact ($p < 0.001$) on the solubility of *amadumbe* flour. High-cold storage had the highest solubility increase of 53.42 % from 50 to 90 °C, while Ambient storage had the lowest increase of 35.33 %. The interaction of storage period and the temperature had a significant impact ($p < 0.001$) on the solubility of *amadumbe*. Day 0 had the highest increase in solubility of 52.52 % from 50 to 90 °C, while day 70 had the lowest increase of 51.98 %. Therefore, storing *amadumbe* results in reduced solubility. The interaction of storage conditions, storage period, and temperature had a significant impact ($p < 0.001$) on the solubility of *amadumbe*. The highest solubility was found on day 0 at 90°C across all storage conditions, while the lowest was found in Ambient storage conditions on day 70 at 50°C.


LSD (p < 0.001) = 0.11 CV= 2.40 %
Solubilty (%)
Storage period (Days)
18
17
16
15
14
13
12
11
10
0
20
40
60
80

a)


LSD (p < 0.001) = 0.10 CV= 2.40 %
Solubility (%)
Storage condition
18
16
14
12
10
8
6
4
2
0
A
U
CBEC
HC
LC

b)



c)

Figure 4.4 The effect of storage period (a), storage conditions (b), and temperature (c) on the solubility of *amadumbe* flour. A = Ambient storage, U = Underground storage, EC = CoolBot® and evaporative cooler storage, HC = High-cold, and LC = low-cold storage.

4.3.5 *Amadumbe* flour water and oil holding capacities

The change in the water holding capacity of *amadumbe* flour during storage can be found in Table 4.5. The water holding capacity ranged between 196.60 and 422.50 %. The range obtained in this study is comparable to the water holding capacity obtained by other authors such as Kaur *et al.* (2013) (60 – 250%), Njintang *et al.* (2008b) (270 – 375%), Hendek Ertop *et al.* (2019) (360 %), and Kaushal *et al.* (2012) (244.70 %).

Storage conditions had a significant impact ($p < 0.05$) on the water holding capacity of *amadumbe* flour. The water holding capacity ranged from 281.50 to 308.56 %, with Ambient and High-cold storage conditions having the lowest and highest water holding capacity, respectively. Baidoo *et al.* (2010) also reported a higher water holding capacity in *amadumbe* stored in cold storage (222.50 %) with a temperature of 4 – 5 °C as compared to ambient storage conditions (170 %) with a temperature of 28±3 °C. The low water holding capacity in Ambient storage conditions may be attributed to lower protein content and the degradation of starch granules, which reduces the amylose content and starch crystalline (Kaushal *et al.*, 2012). CoolBot® and Evaporative cooler storage had the second-highest water holding capacity of 307.71%, comparable to the water holding capacity obtained in High-cold storage. Therefore, both these storage conditions would be suitable to produce foods such as baked goods, sausages, gravies, and soups where high viscosity is required (Kaushal *et al.*, 2015).

The storage period had a significant impact ($p < 0.001$) on the water holding capacity of *amadumbe* flour. The water holding capacity increased from 190.59 to 377.02 % on days 0 and 70. Baidoo *et al.* (2010) reported an increase in the water holding capacity of *amadumbe* stored for three weeks from 177 to 235.50 %. Medoua *et al.* (2005) also reported an increase in the water holding capacity of trifoliate yam (*Dioscorea dumetorum*) stored for 56 days from 182.30 to 390.70 %. The increase may be attributed to increased polysaccharides such as mucilage which are hydrophilic (Njintang *et al.*, 2008b; Kaushal *et al.*, 2015). Njintang *et al.* (2014) reported that mucilage has a strong positive correlation ($r = 0.77$, $p < 0.05$) with carbohydrates, while Kaushal *et al.* (2015) reported that the high water holding capacity of *amadumbe* flour could be attributed to the presence of a higher amount of carbohydrates. The water holding capacity of *amadumbe* correlated positively with oil holding capacity ($r = 0.936$, $p < 0.001$)

and a* ($r = 0.480$, $p < 0.05$). The positive correlation shows that as water holding capacity increases the oil holding capacity and a* also increase.

The interaction of storage conditions and storage period had a significant impact ($p < 0.05$) on the water holding capacity of *amadumbe* flour. High-cold storage had the highest water holding capacity, which increased by 99.42 % from day 0 to day 70 while, Ambient storage conditions had the lowest water holding capacity, which increased by 76.27 %. Despite High-cold having the highest average water holding capacity, CoolBot® and Evaporative cooler storage had the highest increase in water holding capacity of 121.70 % from day 0 to day 70.

The change in the oil holding capacity of *amadumbe* flour during storage can be found in Table 4.5. The oil holding capacity ranged between 214.10 and 427.10 %. The range obtained in this study is alarmingly high compared to the oil holding capacity obtained by other authors such as Kaur *et al.* (2013) (270 – 350 %), Hendek Ertop *et al.* (2019) (107.00 %), and Kaushal *et al.* (2012) (188.80 %). This present study's high oil holding capacity may be due to the high crude protein content. The protein binds with lipids due to the interaction of the non-polar side chains of protein and the hydrocarbon side chains of the oil (Kaushal *et al.*, 2012).

Storage conditions had a significant impact ($p < 0.05$) on the oil holding capacity of *amadumbe* flour. The oil holding capacity ranged from 326.46 to 352.19 %, with Ambient and High-cold storage conditions having the lowest and highest water capacity, respectively. The low oil holding capacity in Ambient storage may be attributed to lower protein content (Adebowale and Lawal, 2004).

The storage period had a significant impact ($p < 0.001$) on the oil holding capacity of *amadumbe* flour. The oil holding capacity increased from 214.09 to 418.30 % on days 0 and 70. Medoua *et al.* (2005) also reported an increase in the oil holding capacity of trifoliate yam (*Dioscorea dumetorum*) stored for 56 days from 72.30 to 94.80 %. The author concluded that the increase in oil holding capacity is due to sprouting and post-harvest hardening. Sprouting indicates food losses, leading to size reduction due to water loss and remobilisation of storage compounds such as protein, sugars, and starch (Coleman, 1987; Sonnewald and Sonnewald, 2014). The increase in oil holding capacity may also be attributed to a reduction in polarity of the protein as it degrades throughout the storage period. Lawal (2004) reported that noncovalent bonds such as hydrophobic and hydrogen bonds are the forces involved in protein-lipid reactions. The oil holding capacity of *amadumbe* flour had a positive correlation ($r = 0.340$, $p < 0.05$) with a* which shows that as the oil holding capacity increases the a* also increases.

The interaction of storage conditions and storage period had a significant impact ($p < 0.05$) on the oil holding capacity of *amadumbe* flour. High-cold storage had the highest increase in oil holding capacity of 94.61 % from day 0 to day 70, while Ambient storage had the lowest increase of 85.99 %. The oil holding capacity obtained in CoolBot® and evaporative cooler storage of 94.11 % is comparable to the one obtained in High-cold storage. The similar oil holding capacity shows that both storage conditions are good at retaining the oil of *amadumbe* flour. High oil holding capacity is necessary because fat is used to maintain flavour and increase the mouthfeel of foods (Adebowale and Lawal, 2004). Therefore, flours with high oil holding capacity will be suitable to produce foods such as sausages, mayonnaise, sponge cakes, and chiffon deserts (Kaushal *et al.*, 2015).

4.3.6 *Amadumbe* flour colour

Table 4.6 shows the impact of storage conditions and storage period on the colour of *amadumbe* flour. Both storage period and conditions had no significant impact ($p > 0.05$) on the L* of *amadumbe* flour. The L* ranged from 82.01 to 88.44, the range obtained in this study is comparable to the L* values reported by other authors such as Kaur *et al.* (2013) (85.50), Njintang *et al.* (2008b) (84.40 – 93.63). Baidoo *et al.* (2014) also reported that storing *amadumbe* in cold storage and ambient storage for 21 days showed no significant change ($p > 0.05$) on the colour of *amadumbe*. The major influence of colour difference is the pigments, which depend on the botanical origin of the tuber (Njintang *et al.*, 2008b). Therefore, since the same variety was used in this study, this may have been why the change in whiteness was not significant. L* had a negative correlation with a*($r = -0.628$, $p < 0.001$) and b* ($r = -0.382$, $p < 0.05$) which shows that as a* and b* increases the L* reduces.

Storage conditions and storage period had a significant impact ($p < 0.05$) on the a* of *amadumbe* flour. The a* ranged between 3.02 and 3.58, with Low-cold storage and High-cold storage conditions having the lowest and highest a*, respectively. The high a*in High-cold storage still needs to be elucidated. A possible reason for the high a* could be other non-starch components in the flour, such as mucilage and protein, due to less protein degradation during High-cold storage (Wongsagonsup *et al.*, 2021). The a* increased during storage from 3.03 to 3.48 on days 0 and 70. The increase may be attributed to rotting because a dark brown substance is formed as *amadumbe* rots. The value of a* showed a positive correlation with crude fat ($r = 0.624$, $p < 0.001$) and a negative correlation with b* ($r = -0.628$, $p < 0.001$) and moisture content ($r = -0.404$, $p < 0.05$).

The b* of *amadumbe* flour ranged from 9.11 to 11.14, and this range is comparable to the b* reported by other authors such as Kaushal *et al.* (2012) (8.16), Wongsagonsup *et al.* (2021) (7.50 – 8.69), and Njintang *et al.* (2008b) (7.50 – 31.6). Storage conditions had no significant impact ($p > 0.05$) on the b* of *amadumbe* flour; however, the storage period had a significant impact ($p < 0.05$). The b* increased from 9.80 to 10.14 on days 0 and 70. The increase in b* may be attributed to oxidation caused by moisture loss during storage. The moisture loss causes the substrate and enzymes such as polyphenol oxidase to mix, thus causing oxidation (Van Hal, 2000). These enzymes are responsible for enzymatic browning, leading to the formation of dark compounds (Nascimento and Canteri, 2018). Jamin and Flores (1998) hypothesised that high b* values might be due to a higher level of protein; however, this present study showed that b* has an insignificant positive correlation ($r = 0.207$, $p > 0.05$) with crude protein. The b* was also found to have no significant correlation with all *amadumbe* proximate composition parameters.

The high L* and low a* and b* obtained in this study are similar to the results obtained by Njintang *et al.* (2008b), who reported *amadumbe* flour to be white, less red, and less yellow. Bhat *et al.* (2016) reported that wheat flour's L*, a*, and b* are 84.10, 0,29, and 23.1, respectively. These values are comparable to the colour parameters obtained in this present study which means that mixing *amadumbe* and wheat could improve nutritional benefits without changing the colour of the flours (Wang *et al.*, 2020).

Table 4.5 The water and oil holding capacities of flour from *amadumbe* subjected to different storage conditions

Capacity	Storage period (Days)	A	U	CBEC	HC	LC
Water holding	0	196.60(2.73)[a]	196.60(2.73)[a]	196.60(2.73)[a]	196.60(2.73)[a]	196.60(2.73)[a]
	14	242.70(31.57)[bc]	241.70(6.71)[bc]	201.50(2.15)[a]	256.60(26.15)[bc]	213.10(8.51)[ab]
	28	259.30(23.67)[c]	269.10(7.79)[c]	333.20(24.59)[d-g]	318.80(16.05)[de]	314.50(10.73)[d]
	42	329.5(27.37)[def]	317.30(17.96)[d]	346.60(3.04)[d-h]	338.90(31.73)[d-g]	348.70(23.35)[d-h]
	56	331.40(4.92)[def]	355.0(31.01)[d-h]	361.90(21.56)[d-h]	367.30(70.69)[fhg]	365.40(31.74)[e-h]
	70	335.90(20.54)[d-g]	356.10(13.28)[d-h]	422.50(59.67)[i]	380.10(9.33)[gh]	390.40(13.38)[hi]
Oil holding	0	214.10(19.49)[a]	214.10(19.49)[a]	214.10(19.49)[a]	214.10(19.49)[a]	214.10(19.49)[a]
	14	266.90(0.70)[b]	278.30(9.41)[b]	329.90(32.13)[c]	353.10(34.40)[cde]	345.10(33.99)[cd]
	28	328.80(9.05)[c]	346.10(39.17)[cd]	358.60(21.87)[c-f]	367.60(27.46)[c-g]	361.90(22.40)[c-f]
	42	372.70(42.86)[d-g]	379.30(17.73)[d-h]	381.10(12.19)[d-h]	380.20(15.58)[d-h]	371.00(27.70)[d-g]
	56	377.90(12.75)[d-h]	391.60(5.56)[e-i]	405.70(2.79)[g-j]	382.20(4.98)[d-h]	378.60(9.12)[d-h]
	70	398.20(35.78)[f-j]	407.10(5.63)[g-j]	415.60(4.80)[hij]	416.60(7.29)[hij]	397.90(3.61)[f-j]

	Level of significance		
Capacity	Storage conditions (A)	Storage period (B)	A*B
Water holding	$p < 0.05$	$p < 0.001$	$p < 0.05$
Oil holding	$p < 0.05$	$p < 0.001$	$p < 0.05$

All values are means of three values. Data contained in the parenthesis are the standard deviations. The means with different letters are significantly different at $p < 0.05$ by LSD test. A = Ambient storage, U = Underground storage, EC = CoolBot® and evaporative cooler storage, HC = High-cold, and LC = low-cold storage.

Table 4.6 The colour of flour from *amadumbe* subjected to different storage conditions

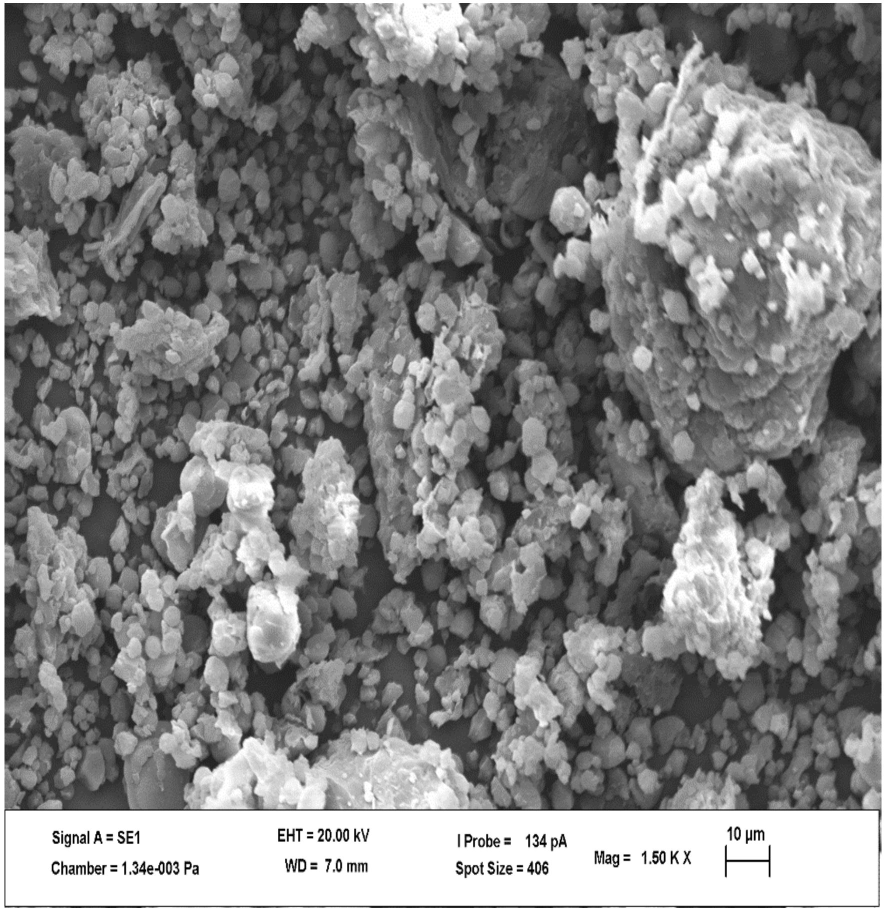
Colour parameter	Storage period (Days)	A	U	CBEC	HC	LC
L*	0	83.26(1.77)^{ab}	83.26(1.77)^{ab}	83.26(1.77)^{ab}	83.26(1.77)^{ab}	83.26(1.77)^{ab}
	14	83.13(2.22)^{ab}	83.96(0.68)^{ab}	85.67(1.56)^{abc}	83.33(2.78)^{ab}	85.48(0.06)^{abc}
	28	83.25(1.50)^{ab}	83.05(2.05)^{ab}	84.70(1.82)^{ab}	83.46(0.30)^{abc}	88.44(0.86)^{c}
	42	82.63(1.87)^{abc}	82.02(2.89)^{ab}	83.03(2.71)^{ab}	83.81(2.34)^{ab}	86.35(2.91)^{abc}
	56	82.18(2.54)^{ab}	82.81(0.38)^{ab}	82.31(2.02)^{ab}	83.60(2.71)^{ab}	85.48(0.66)^{abc}
	70	81.17(2.52)^{ab}	82.14(0.58)^{ab}	83.20(1.52)^{ab}	83.25(2.17)^{abc}	82.01(1.67)^{ab}
a*	0	3.03(0.48)^{abc}	3.03(0.48)^{abc}	3.03(0.48)^{abc}	3.03(0.48)^{abc}	3.03(0.48)^{abc}
	14	4.09(0.86)^{cd}	3.32(0.39)^{bcd}	3.21(0.69)^{bcd}	3.81(0.53)^{bcd}	3.28(0.05)^{bcd}
	28	3.17(0.80)^{bcd}	3.52(0.58)^{bcd}	3.28(0.40)^{bcd}	3.46(0.32)^{bcd}	2.09(0.14)^{a}
	42	3.30(0.39)^{bcd}	3.10(0.44)^{abc}	3.70(0.78)^{bcd}	3.18(0.93)^{bcd}	2.97(0.91)^{bcd}
	56	3.53(0.29)^{bcd}	3.60(0.23)^{bcd}	3.96(0.59)^{bcd}	3.79(0.86)^{bcd}	3.20(0.29)^{bcd}
	70	3.92(0.29)^{ab}	3.23(0.28)^{bcd}	3.35(0.84)^{bcd}	4.19(0.26)^{d}	3.55(0.45 ^{bcd}
b*	0	9.80(0.76)^{abc}	9.80(0.76)^{abc}	9.80(0.76)^{abc}	9.80(0.76)^{abc}	9.80(0.76)^{abc}
	14	9.90(0.21)$^{a-d}$	9.78(0.57)^{abc}	9.62(0.28)^{abc}	9.92(0.29)$^{a-d}$	9.11(0.21)^{a}
	28	10.07(0.30)$^{a-d}$	10.10(1.09) $^{a-d}$	10.76(0.84)$^{a-d}$	10.51(1.07)^{bcd}	9.30(0.81)^{ab}
	42	10.18(0.46)$^{a-d}$	10.11(0.43) $^{a-d}$	10.40(0.33)$^{a-d}$	10.70(0.74)^{cd}	9.16(0.36)^{a}
	56	10.28(0.74)$^{a-d}$	10.14(0.36)$^{a-d}$	10.86(1.03)^{cd}	10.79(1.22)^{cd}	9.16(0.03)^{a}
	70	10.53(0.46)^{bcd}	10.57(0.59)^{bcd}	11.14(0.68)^{d}	10.90(0.42)^{cd}	9.97(0.21)^{abc}

	Level of significance		
Colour parameter	Storage condition (A)	Storage period (B)	A*B
L*	$p > 0.05$	$p > 0.05$	$p > 0.05$
a*	$p < 0.05$	$p < 0.05$	$p > 0.05$
b*	$p > 0.05$	$p < 0.05$	$p > 0.05$

All values are means of three values. Data contained in the parenthesis are the standard deviations. The means with different letters are significantly different at $p < 0.05$ by LSD test. A = Ambient storage, U = Underground storage, EC = CoolBot® and evaporative cooler storage, HC = High-cold, and LC = low-cold storage.

4.3.7 *Amadumbe* flour morphology

The morphology of *amadumbe* flour can be found in Figure 4.5a-f. The flour of *amadumbe* is made up of small starch granules connected by fibrous materials. The shape of the granules is predominantly irregular and polygonal, while the fibrous material has no distinct shape. This finding is consistent with the work of other authors such as Hendek Ertop *et al.* (2019) and Wang *et al.* (2020), that reported that *amadumbe* flour is mainly composed of starch granules that are polygonal and irregular in shape. Figure 4.5a illustrates the micrograph of *amadumbe* flour before storage. The particles appear tightly packed and have large granules. After 70 days, the flour in Ambient (Figure 4.5b), Underground (Figure 4.5c), CoolBot® and Evaporative cooler (Figure 4.5d), and Low-cold (Figure 4.5f) storage conditions appear less packed and have small granular particles. However, High-cold storage (Figure 4.5e) is similar to the initial micrograph. The reduction in compaction and granular size indicates degradation in the granules of the flour. The degradation in Figure 4.5b-d may have occurred due to alpha-amylase, which causes *amadumbe* starch to hydrolyse (Modi and Mare, 2016). The degradation in Figure 4.5f may be due to the breakdown of starch into reducing sugars during cold storage (Krochmal-Marczak *et al.*, 2020).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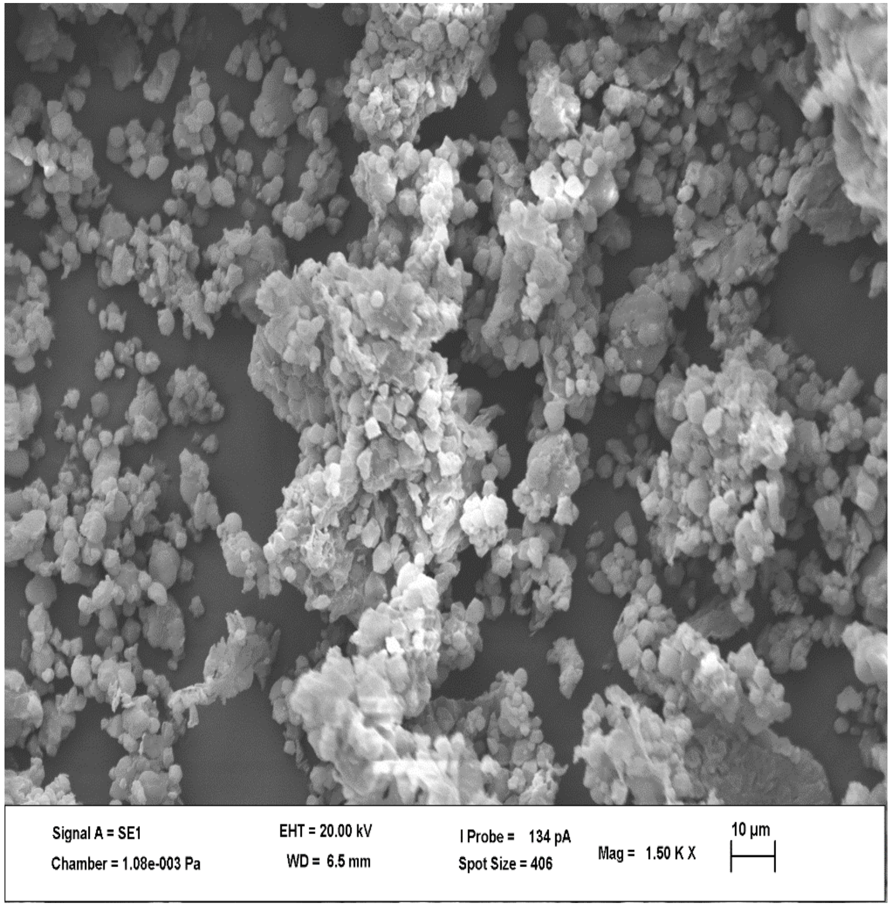
10 µm

a)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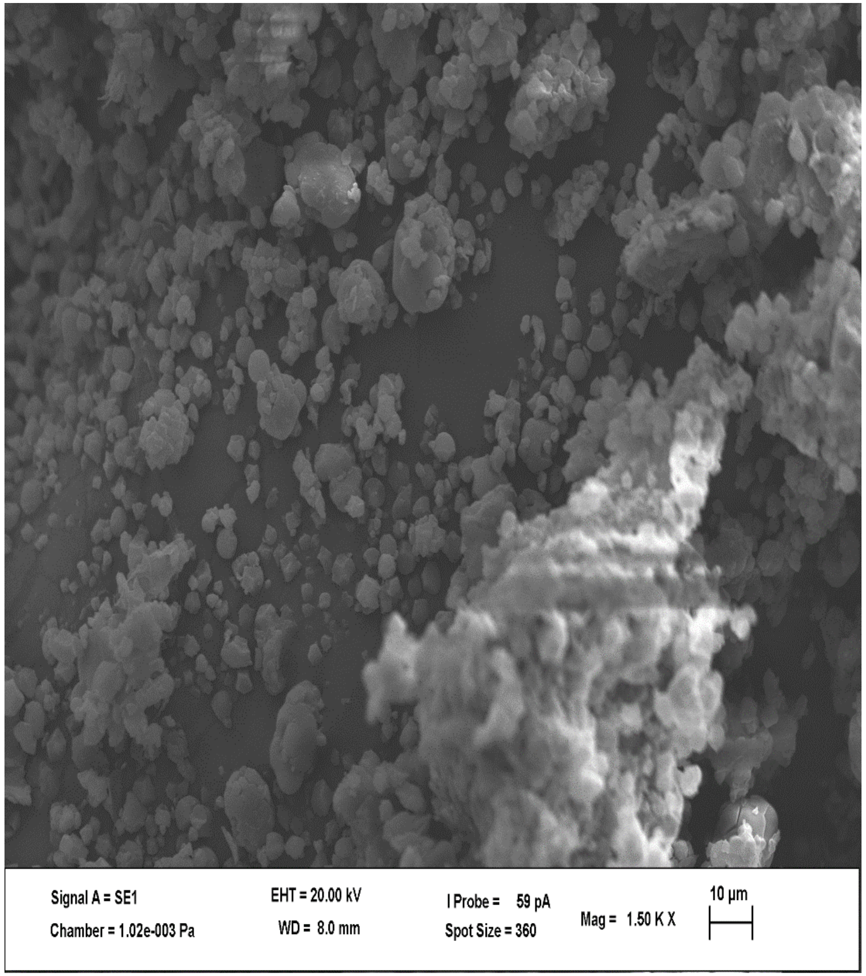
10 µm

b)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WD = 8.0 mm
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Spot Size = 360
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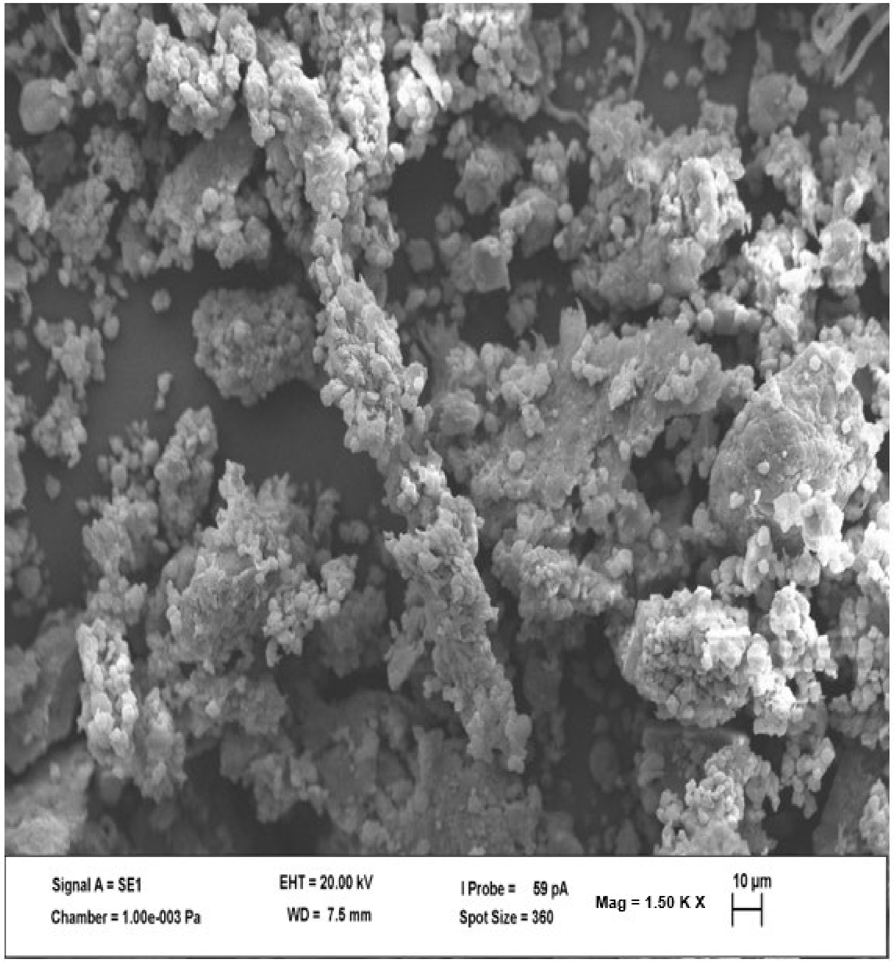
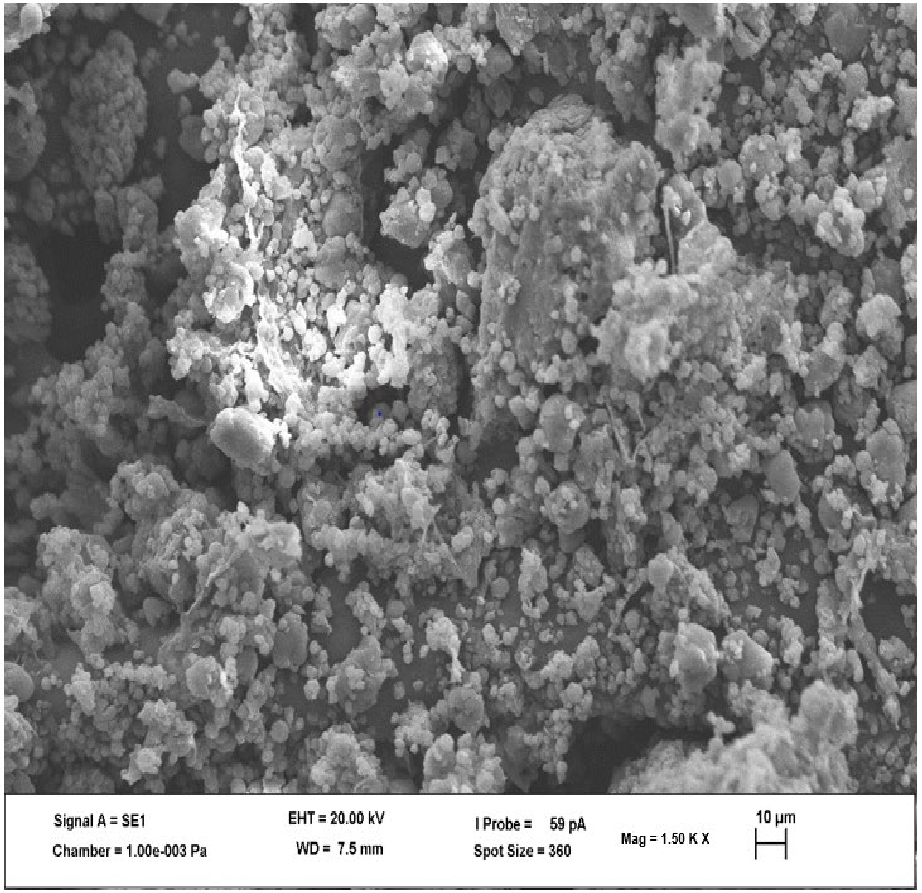
10 µm

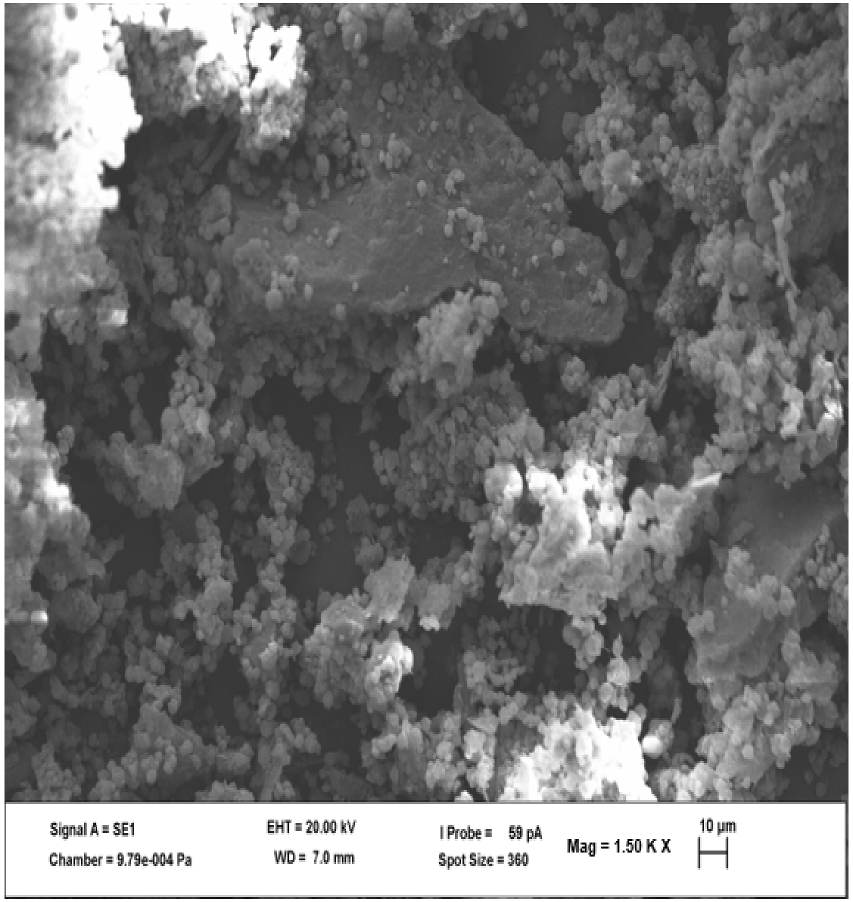
c)


Signal A = SE1
Chamber = 1.00e-003 Pa
EHT = 20.00 kV
WD = 7.5 mm
I Probe = 59 pA
Spot Size = 360
Mag = 1.50 K X
10 µm

d)



e)



f)

Figure 4.5 The effect of storage conditions on the morphology of *amadumbe* flour (a) Flour before storage, (b) Ambient storage, (c) Underground storage, (d) CoolBot® and Evaporative cooler storage, (e) High-cold storage (f) Low-cold storage after 70 days

4.4 Conclusion

This study aimed to determine the effect of storage conditions and storage period on the quality attributes of flour derived from stored *amadumbe* corms. The outcome of this study revealed that the physicochemical properties of *amadumbe* flour are influenced by storage conditions, storage period, and the combined effect of storage conditions and storage period. Flour derived from corms stored in High-cold storage conditions (9.26 – 11.54°C, 97.57 – 100.00 %) were of better quality. It had minimal reductions in (moisture content, swelling power, solubility, and protein content), minimal increase in (a* and b*), and the highest increase in the (oil holding and water holding capacities). While Ambient storage conditions (17.30 – 23.59°C, 75.02 – 75.15 %) showed a massive loss in quality attributes.

The study revealed that High-cold storage was the best method in preserving the quality attributes of *amadumbe* flour. It resulted in the lowest reduction in moisture content (2.67 %), crude protein (5.89 %), swelling power (16.44 %), solubility (20.41 %), L* (0.04 %), degradation of *amadumbe* flour starch granules. It also resulted in the highest increase in crude fat (55. 56 %), oil holding capacity (94.58 %), and a* (137.28). Ambient storage was the worst storage method in preserving the quality attributes of *amadumbe* flour. It resulted in the highest decrease in moisture (7.02 %), solubility (31.59 %), and L* (2.51 %). It also resulted in the lowest increase in crude fat (2.78 %), reducing sugar content (91.75 %), water holding capacity (70.85 %), and oil holding capacity (85.99 %).

The microscopic morphologies of *amadumbe* flour were irregular and polygonal in shape. The flours exhibited larger densely packed granular particles connected by fibrous materials on day 0. After 70 days of storage, there was a reduction in the size and compactness of the granular particles. However, these reductions were more profound in Ambient, Underground, Low-cold, and CoolBot® and evaporative storage conditions. High-cold storage showed less reduction in granular size and resulted in densely packed flour compared to all studied storage conditions.

This chapter revealed that Ambient storage conditions resulted in the worst ability to maintain *amadumbe* flour quality attributes. Therefore, for short-term storage, this method is not recommended. However, High-cold storage conditions, followed by CoolBot® and evaporative cooler storage conditions, were the best storage method in preserving the quality attributes of *amadumbe* flour. Therefore, some adjustments would need to be made to the storage conditions of CoolBot® and evaporative cooler for it to have an improved ability to preserve quality attributes of *amadumbe* flour. The minimal loss in quality attributes in High-cold storage conditions can infer that *amadumbe* flour will have improved uses in food and non-food industries. Therefore, it is also recommended that the end-use products be made using corms stored in High-cold storage to assess the impact of this storage method on end-use quality.

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5. PHYSICOCHEMICAL PROPERTIES OF *AMADUMBE* STARCH DERIVED FROM AMDUMBE CORMS SUBJECTED TO DIFFERENT STORAGE METHODS

Section 4 revealed that storage conditions had a significant impact on the physicochemical properties of *amadumbe* flour. This chapter will evaluate the changes in the quality of *amadumbe* starch subjected to different storage conditions.

Abstract

This study aimed to investigate the effects of different storage conditions on the functional and morphological attributes of *amadumbe* starch. *Amadumbe* starch was derived from corms subjected to five storage conditions: Low-cold storage, High-cold storage, CoolBot® and evaporative cooler storage, Underground storage, and Ambient storage as a control. The corms were stored in three replications using a completely Randomised Block Design. Three different experimental designs were used in this study. The first two experimental designs had two treatments: storage conditions and storage period. However, sampling was done every 14th day for 70 days in experiment one and on days 0 and 70 in experiment two. The third experimental design had three treatments: storage conditions, storage period, and temperature, and sampling was done every 14th day for 70 days. The data were analysed using the Duncan multiple range test at a 5 % level significance. The results obtained in this study showed that storage conditions and storage period had a significant impact ($p < 0.05$) in reducing the granular starch size, swelling power, solubility, and L* and increasing water holding capacity, oil holding capacity, and a*. High-cold storage resulted in the lowest reduction in starch yield (10.37 %), granular starch size (6.21 %), swelling power (12.31 %), solubility (20.99 %), L* (1.08 %). It also resulted in the highest increase in water holding capacity (60.02 %) and oil holding capacity (107.17 %). While Ambient storage resulted in the highest decrease in starch yield (10.37 %), granular starch size (6.21 %), swelling power (12.31 %), solubility (20.99 %), L* (1.08 %). It also resulted in the highest increase in water holding capacity (60.02 %) and oil holding capacity (107.17 %). The starch morphology study revealed that the granules of *amadumbe* starch are predominantly irregular and polygonal shapes with a smooth texture. The granules of starch were densely packed and large on day 0; however, after 70 days of storage, the

granules became loosely packed and reduce in size. This study revealed that High-cold, followed by CoolBot® and evaporative cooler storages, were the best storage method in preserving the quality attributes of *amadumbe* starch. In contrast, Ambient storage conditions resulted in the worst ability to maintain *amadumbe* starch quality attributes. Therefore, for short-term storage, ambient storage is not recommended.

5.1 Introduction

The global native starch market has reached 88.2 million tons, mainly because starch has many uses in the food and non-food industries (Singla *et al.*, 2020). *Amadumbe* starch is preferred by most consumers due to its health-related benefits, as a result of having high resistant starch and being gluten-free (Arici *et al.*, 2020). Native *amadumbe* starch is also preferred in most industries because very little modification is required to its physicochemical properties before being used (Singla *et al.*, 2020).

Amadumbe starch has small granules that range between 1 to 5 µm. This unique small size makes *amadumbe* starch beneficial to produce biodegradable packaging material and easily digestible formulas for infants (Wongsagonsup *et al.*, 2021). According to Falade and Okafor (2013) and Kaushal *et al.* (2015), *amadumbe* starch is suitable for producing baked products, soups, gravies, mayonnaise, and sausages because it has high water and oil holding capacities. Buckman *et al.* (2018) reported that the high swelling power and solubility of *amadumbe* starch are beneficial when producing foods with high pasting viscosity. The physicochemical properties of starch are influenced by amylose and amylopectin content (Gercekaslan, 2020). Modi and Mare (2016) showed changes in granular starch morphology during storage due to alpha-amylase. These changes may impact the amylose and amylopectin content and ultimately influence the physicochemical properties of *amadumbe* starch (Labuschagne *et al.*, 2014).

Previous studies focused on the effect of *amadumbe* starch nanocrystals on physicochemical properties of starch bio-composite films (Mukurumbira *et al.*, 2017b) and the effect of corm size on the composition, pasting, and thermal properties of *amadumbe* flours and starches (Oyeyinka and Amonsou, 2020). While Modi and Mare (2016) only looked at the effect of temperature and packaging on the morphological properties of *amadumbe* starch. Therefore, this study will characterise the impact of different storage conditions on the physicochemical properties of *amadumbe* starch.

5.2 Materials and Methods

This section contains all materials and methods used to determine the impact of different storage conditions on the quality properties of *amadumbe* starch.

5.2.1 Post-harvest sample preparations

The tubers were harvested after ten months. The *amadumbe* tubers were then washed using tap water and allowed to dry at ambient conditions. The corms with defects and harvest injuries were discarded immediately after drying.

5.2.2 Data Collection

Evaluation of all physicochemical properties of *amadumbe* starch was done at the Food Science and Agricultural Engineering Laboratory, University of KwaZulu-Natal, South Africa.

5.2.3 Experimental design

Three experimental designs were used in this study. The difference between experiments 1 and 2 was due to financial constraints. Experiment 3 differed because temperature becomes an additional treatment when calculating the swelling power and solubility of *amadumbe* starch.

5.2.3.1 Experimental design 1

The experimental design to determine starch yield, water holding capacity, and oil holding capacity was conducted using a Completely Randomised Block Design. The experimental design had two factors (storage conditions and storage period). Sampling was done every 14th day for 70 days using three replications (The graphical illustration of the experimental design can be found in Figure 3.2 of Section 3.2.3).

5.2.3.2 Experimental design 2

The experimental design to determine morphology was similar to Experimental design 1. However, sampling was only done on days 0 and 70 (The graphical illustration of the experimental design can be found in Figure 4.1 of Section 4.2.3.2)

5.2.3.3 Experimental design 3

The experimental design to determine swelling power and solubility was conducted using a Completely Randomised Block Design. The experimental design had three factors (storage conditions, storage period, and temperature). Sampling was done every 14th day for 70 days using three replications (The graphical illustration of the experimental design can be found in Figure 4.2 of Section 4.2.3.3).

5.2.4 Starch extraction and yield

The method used by Naidoo et al. (2015) was used with minor modification to extract the starch. The *amadumbe* were brought to the laboratory for analysis immediately after harvest. The 400g tubers were washed, peeled, chopped into small pieces, and then milled using a blender. The resultant pulp was dispersed in water (1:5), stirred at room temperature for five hours. A double cheesecloth was used to filter the non-starchy components. The resulting filtrate was allowed to settle at room temperature for 48 h. The supernatant was decarded, and the remaining residue was oven-dried at 35°C for 48 h. The dried residue was sieved (screen size: 180 µm) to obtain starch. The starch yield was calculated as the ratio of the starch obtained to the weight of the tuber used (Equation 5.1).

$$SY = \frac{W_{fa}}{W_t} x100 \qquad (5.1)$$

where

SY = Starch yield (%),

W_{fa} = weight of starch obtained after drying (g), and

W_t = weight of the tuber used (g).

5.2.5 *Amadumbe* starch granule morphology

The granule morphology was determined using the method used by Ngobese et al. (2017). Granule morphology was determined using a scanning electron microscope (ZEISS EVO LS15; Carl Zeiss Microscopy, United States of America), set at a magnification of 4.50 KX with signal A at SEI, I Probe = 59 pA, and EHT = 20.00kV. The starch was splashed on a double-sided silver tape attached to a 10 mm diameter specimen stub. The samples were coated with gold, using an ion sputter coater Q150 €S; Quorumtech, United Kingdom). The obtained granules from scanning electron microscope were then subjected to image analysis (Soft Imaging System GmbH; Olympus America Inc, United States of America) at the Microscopic analysis laboratory (University of KwaZulu Natal, Pietermaritzburg, South Africa).

5.2.6 *Amadumbe* starch swelling power and solubility

The swelling power and solubility were determined using the method used by Chisenga *et al.* (2019c) with minor modifications. The swelling power and solubility were determined at 50, 60, 70, 80, and 90°C. A 0.5 g dry starch sample was suspended in 20 mL deionised water in a 50 mL centrifuge tube with a known weight. The centrifugal tube was heated using a water bath (Faithful FWS-30; Huanghua Faithful Instruments Co., Ltd, China) at 50, 60, 70, 80, and 90°C for 30 min and spiralling was done every 5 min. The centrifugal tube was allowed to cool to ambient temperature and centrifuged (Avanti J-26S XP; Beckman Coulter, United States of America) at 1867 × g for 20 min. The supernatant obtained was used for the solubility test. The sediment mass was measured, and the swelling power ($g.g^{-1}$) was calculated as the ratio of the sediment mass to the original sample weight (Equation 5.2.) The collected supernatant was placed on a pre-weighed evaporating crucible dish and oven-dried at 105°C for 12 h, and the dried mass was measured. The solubility (%) was calculated as the ratio of dried mass to the original sample weight (Equation 5.3).

$$SP = \frac{W_S}{W_O} \qquad (5.2)$$

$$S = \frac{W_{ds}}{W_0} \times 100 \tag{5.3}$$

where

SP = Swelling power ($g.g^{-1}$),

S = Solubility (%),

W_O = weight of original *amadumbe* starch (g),

W_s = weight of wet *amadumbe* starch sediment (g), and

W_{ds} = weight of dry *amadumbe* starch supernatant (g).

5.2.7 *Amadumbe* starch water and oil holding capacities

The water and oil holding capacities were determined using the method used by Ngobese et al. (2017). A 0.5 g of starch was placed in a 15 mL conical pre-weighed centrifuge tube. Five millilitres of deionised water or canola with a density of 1 and 0.89 g cm^{-3}, respectively, at ambient temperature, was added to the starch. The mixture was stirred with a stainless-steel spatula and allowed to stand at ambient temperature for two hours before being centrifuged at 350 × g (Avanti J-26S XP; Beckman Coulter, United States of America) for 30 min. The supernatant was discarded, and the sample was reweighed. The absorption capacity was calculated by taking the ratio of the difference between the initial and final weight to the weight of the initial starch portion used (Equation 5.4).

$$HC = \frac{W_i - W_f}{W_i} \times 100 \tag{5.4}$$

where

HC = Water or Oil holding capacity (%),

W_i = initial weight of *amadumbe* starch (g), and

W_f = final weight of *amadumbe* starch (g).

5.2.8 *Amadumbe* starch colour

The colour of starch was determined using the method used by Oyeyinka and Amonsou (2020). Standardisation was done using the Hunter Lab colour standards (ColorFlexEZ; Hunter

Associate Laboratories Inc, United States of America). The colour of the starch was measured by reading L*, a*, and b*. L*, a*, and b* refer to (degree of lightness), (redness to greenness), and (yellowness to blueness), respectively. To read the colour, starch was poured into a glass cup (04-7209-00 glass sample cup; Hunter Associate Laboratories Inc, United States of America) until it completely covered the bottom part of the cup.

5.2.9 Statistical analysis

Data analysis was performed using the GenStat 18.2.1 software, analysis of variance (ANOVA) was used to test for differences. The separation of means was determined using Duncan's multiple range test at the 5 % significant level. The relationship between the quality attributes was determined using linear regression analysis (Chisenga *et al.*, 2019).

5.3 Results and Discussion

This section will analyse and discuss the quality properties of *amadumbe* starch subjected to different storage environments.

5.3.1 Starch yield

Table 5.1 shows the impact of storage conditions and storage period on the yield of *amadumbe* starch. The starch yield ranged between 11.25 and 15.34 %. The range obtained in this study is comparable to the starch obtained by Falade and Okafor (2013) (10.03 – 18.61 %) and low compared to the range reported by authors such as Oyeyinka and Amonsou (2020) (24.00 – 32.00 %) and (Naidoo *et al.*, 2015) (35.00 – 36 .00 %). The variation in yield may be attributed to differences in the extraction method and differences in the genotype of *amadumbe* (Aprianita *et al.*, 2014). Singla *et al.* (2020) also reported that the extraction method also impacts the yield of *amadumbe* starch. The higher yield obtained by Oyeyinka and Amonsou (2020) and (Naidoo *et al.*, 2015) may be due to the authors using a centrifuge for 20 minutes. In the present study, the starch was separated by allowing the starch to settle for 48 hours.

Storage conditions had no significant impact ($p > 0.05$) on the yield of *amadumbe* starch. The starch yield ranged from 13.57 to 14.26 %, with High and Low-cold storages having the lowest and highest starch yield, respectively. Nourian *et al.* (2003) also reported that potato starch content decreased more rapidly at a lower temperature (4 °C) from 13.40 % to 8 % as compared to a higher temperature (20 °C). The reduction in starch content is due to the breaking down of starch into reducing sugars during cold storage (Sanchez *et al.*, 2021).

The storage period had a significant impact ($p < 0.001$) on the yield of *amadumbe* starch. The starch yield decreased from 15.34 to 12.51 % on days 0 and 70. Krochmal-Marczak *et al.* (2020) also reported that the starch content of sweet potatoes stored for six months was reduced by 20.42 %. The reduction in starch yield may be attributed to an increase in amylase during storage, which results in the breaking down of starch (Modi and Mare, 2016). The reduction is also due to cold-induced sweetening when starch is broken down into sugars (Sanchez *et al.*, 2021). Table 5.2 shows the correlation between the physicochemical properties of *amadumbe* starch. Starch yield had a positive correlation with swelling power ($r = 0.658$, $p < 0.001$), solubility ($r = 0.621$, $p < 0.001$), L* ($r = 0.417$, $p < 0.001$), and granular starch size ($r = 0.820$, $p < 0.001$) and a negative correlation with water holding capacity ($r = -0.451$, $p < 0.001$), oil holding capacity ($r = -0.561$, $p < 0.001$), a* ($r = -0.326$, $p < 0.05$) and b* ($r = -0.418$, $p < 0.001$).

Table 5.1 The yield (%) of starch from *amadumbe* subjected subjected to different storage conditions

	Storage conditions				
Storage period (days)	A	U	CBEC	HC	LC
0	15.34(0.53)^{f}	15.34(0.53)^{f}	15.34(0.53)^{f}	15.34(0.53)^{f}	15.34(0.53)^{f}
14	15.06(0.30)^{ef}	15.16(1.28)^{ef}	14.28(0.47)^{def}	14.36(1.48)^{ef}	14.52(0.27)^{ef}
28	14.75(1.80)^{ef}	14.56(0.13)^{ef}	14.11(0.11)$^{c-f}$	14.29(1.45)^{def}	13.69(0.48)$^{b-f}$
42	13.52(0.40)$^{b-f}$	13.43(1.28)$^{b-f}$	13.96(0.37)$^{b-f}$	14.02(1.12)$^{b-f}$	13.24(0.84)$^{b-e}$
56	13.29(1.70)$^{b-e}$	13.40(0.78)$^{b-f}$	13.70(1.23)$^{a-d}$	13.82(2.28)$^{b-f}$	12.38(0.24)$^{b-f}$
70	11.25(1.80)^{a}	12.13(0.75)^{ab}	13.19(0.23)$^{b-e}$	13.75(0.12)$^{b-f}$	12.26(0.28)^{abc}

	Storage conditions (A)	Storage period (B)	(A*B)
Level of significance	$p > 0.05$	$p < 0.001$	$p > 0.05$

All values are means of three values. Data contained in the parenthesis are the standard deviations. The means with different letters are significantly different at $p<0.05$ by LSD test. A = Ambient storage, U = Underground storage, EC = CoolBot® and evaporative cooler storage, HC = High-cold, and LC = low-cold storage.

Table 5.2 Correlation between physico-chemical properties of *amadumbe* starch subjected to different storage conditions

Parameter	SY (%)	S (%)	SP (g.g-1)	WHC (%)	OHC (%)	L*	a*	b*	GSS (µm)
SY (%)	1.000								
S (%)	0.621***	1.000							
SP (g.g-1)	0.658***	0.862***	1.000						
WHC (%)	-0.451***	-0.390***	-0.545***	1.000					
OHC (%)	-0.561***	-0.595***	-0.626***	0.654***	1.000				
L*	0.417***	0.709***	0.671***	-0.333**	-0.447***	1.000			
a*	-0.326**	-0.458***	-0.482***	0.413***	0.377***	-0.491***	1.000		
b*	-0.418***	-0.704***	-0.7600***	0.520***	0.621***	-0.559***	0.513***	1.000	
GSS (µm)	0.820***	0.886***	0.833***	-0.335**	-0.693***	0.865***	-0.779***	-0.725***	1.000

SY = Starch yield, SP = Swelling power, S = Solubility, WHC = water holding capacity, OHC = Oil holding capacity and GSS = Granular starch size. Level of significance $p > 0.05$*, $p < 0.05$**, $p < 0.001$***.

5.3.2 *Amadumbe* starch morphology

The morphology of *amadumbe* starch can be found in Figure 5.1a-f. The granules had predominately irregular and polygonal shapes with a smooth texture. This finding is consistent with the work of other authors, such as Naidoo *et al.* (2015) and Wang *et al.* (2020), that reported that *amadumbe* starch is polygonal and irregular in shape. Table 5.3 shows the change in *amadumbe* size during storage. The granular size ranged between 2.78 and 4.99 µm. This range is comparable to the range obtained by other authors such as Naidoo *et al.* (2015) (2.00 – 7.00 µm) and Oyeyinka and Amonsou (2020) (2.00 – 5.00 µm). Storage conditions had a significant impact ($p < 0 .001$) on the size of *amadumbe* starch. The granular size ranged between 3.89 to 4.83 µm, with Low and High-cold storage conditions having the smallest and highest sizes, respectively. The small size in Low-cold storage is due to the breaking down of starch into reducing sugars (Krochmal-Marczak *et al.*, 2020). Kaur *et al.* (2009) also reported that potatoes stored at 4°C showed a higher proportion of small size granules as compared to those stored at 20°C.

The storage period had a significant impact ($p < 0.05$) on the granule size of *amadumbe* starch. The particles decreased from 4.99 to 3.68 µm on days 0 and 70. Figure 5.1a illustrates the micrograph of *amadumbe* starch before storage. The particles appear tightly packed and have large granules. After 70 days, the starch in Ambient (Figure 5.1), Underground (Figure 5.1c), CoolBot® and Evaporative cooler (Figure 5.1d), and Low-cold (Figure 5.1f) storage conditions appear less packed and have a greater portion of small granular particles. The granules also appear more pitted and less smooth during storage. Modi and Mare (2016) reported that *amadumbe* showed erosion and indentation during storage. High-cold storage (Figure 5.1e) had granular morphology similar to the initial micrograph. The reduction in compaction and granular size during storage indicates degradation in the granules of the starch due to alpha-amylase (Modi and Mare, 2016). Granular starch size had a positive correlation with swelling power ($r = 0.833$, $p < 0.001$), solubility ($r = 0.886$, $p < 0.001$), and L* ($r = 0.865$, $p < 0.001$) and had a negative correlation with water holding capacity ($r = -0.335$, $p < 0.001$) and oil holding capacity ($r = -0.693$, $p < 0.001$).

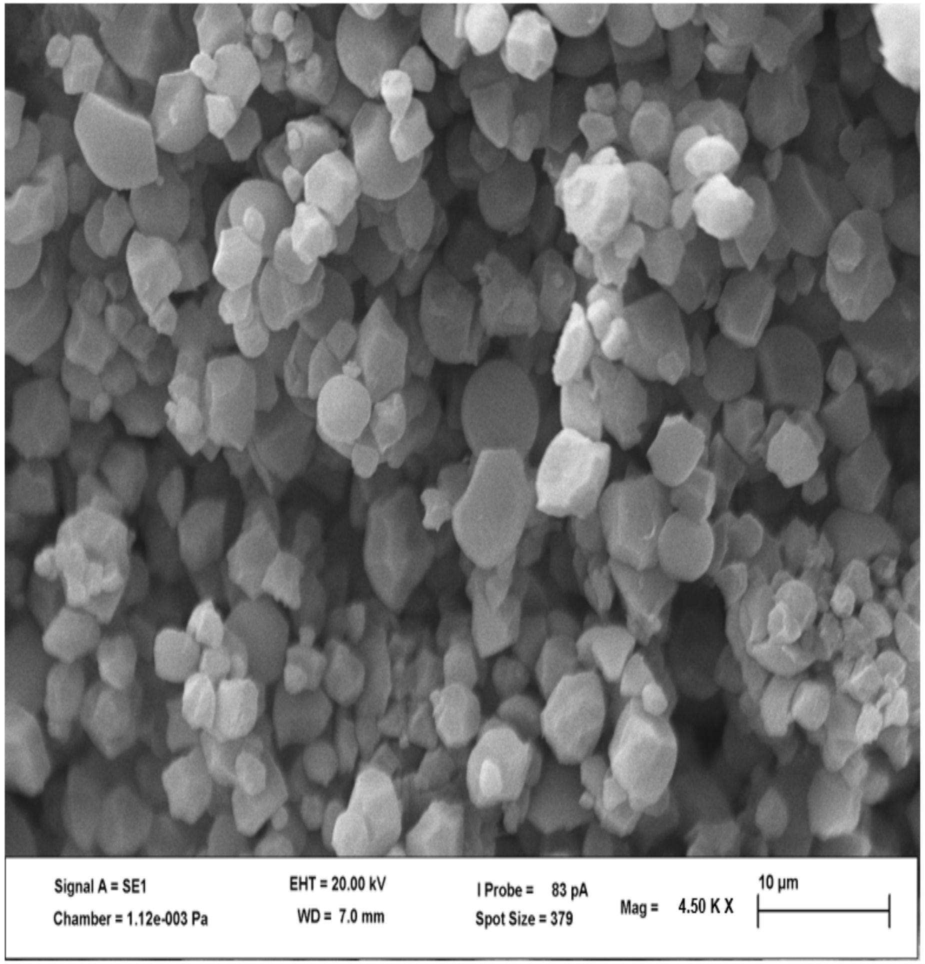
The reduction in granular size during storage is suitable when producing biodegradable packaging because small granules are recommended in making biodegradable packaging material (Mukurumbira *et al.*, 2017a). The small granular size of *amadumbe* starch is also suitable for producing foods such as infants formula, edible films, noodles because of improved digestibility (Kaushal *et al.*, 2015). High cold storage is the optimum storage condition for preserving the granular morphology of *amadumbe* starch because it resulted in the lowest degradation of starch.

Table 5.3 The granular size (µm) of starch from *amadumbe* subjected to different storage conditions

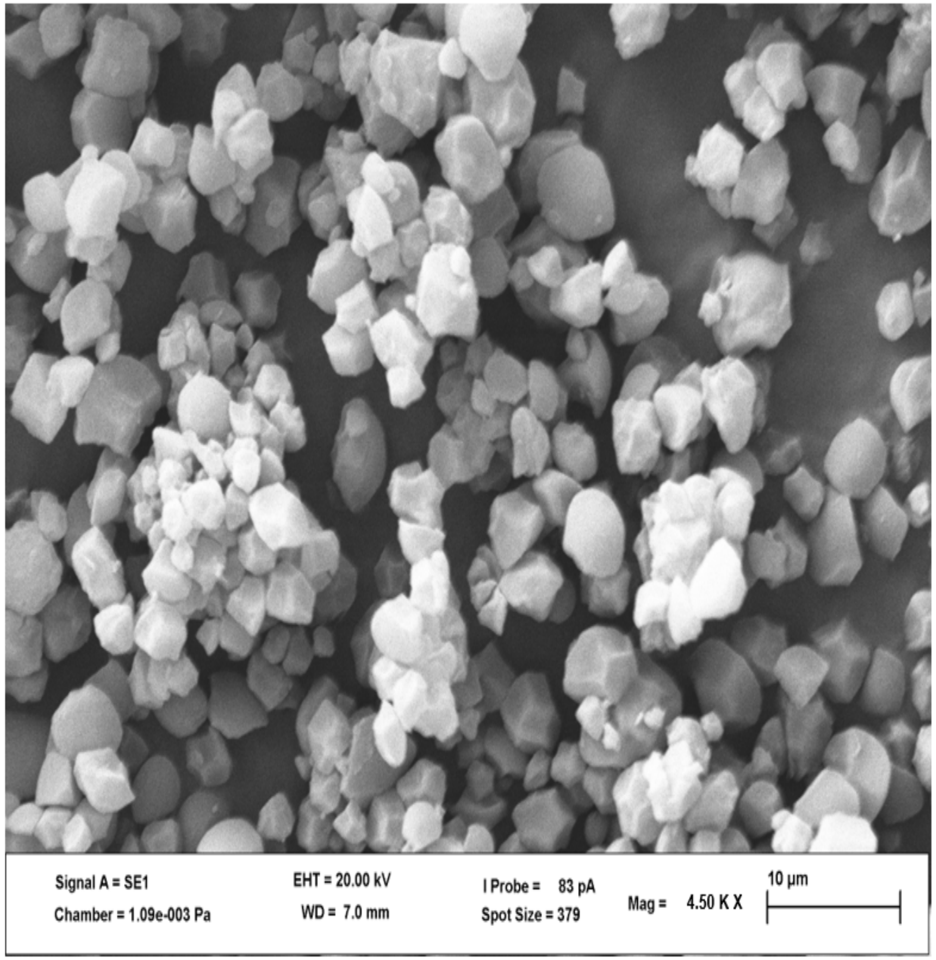
	Storage conditions				
Storage period (days)	A	U	CBEC	HC	LC
0	4.99(0.10)^{d}	4.99(0.10)^{d}	4.99(0.10)^{d}	4.99(0.10)^{d}	4.99(0.10)^{d}
70	3.10(0.52)^{ab}	3.62(0.24)^{b}	4.24(0.28)^{c}	4.68(0.71)^{cd}	2.78(0.29)^{a}

	Storage conditions (A)	Storage period (B)	(A*B)
Level of significance	$p < 0.001$	$p < 0.001$	$p < 0.001$

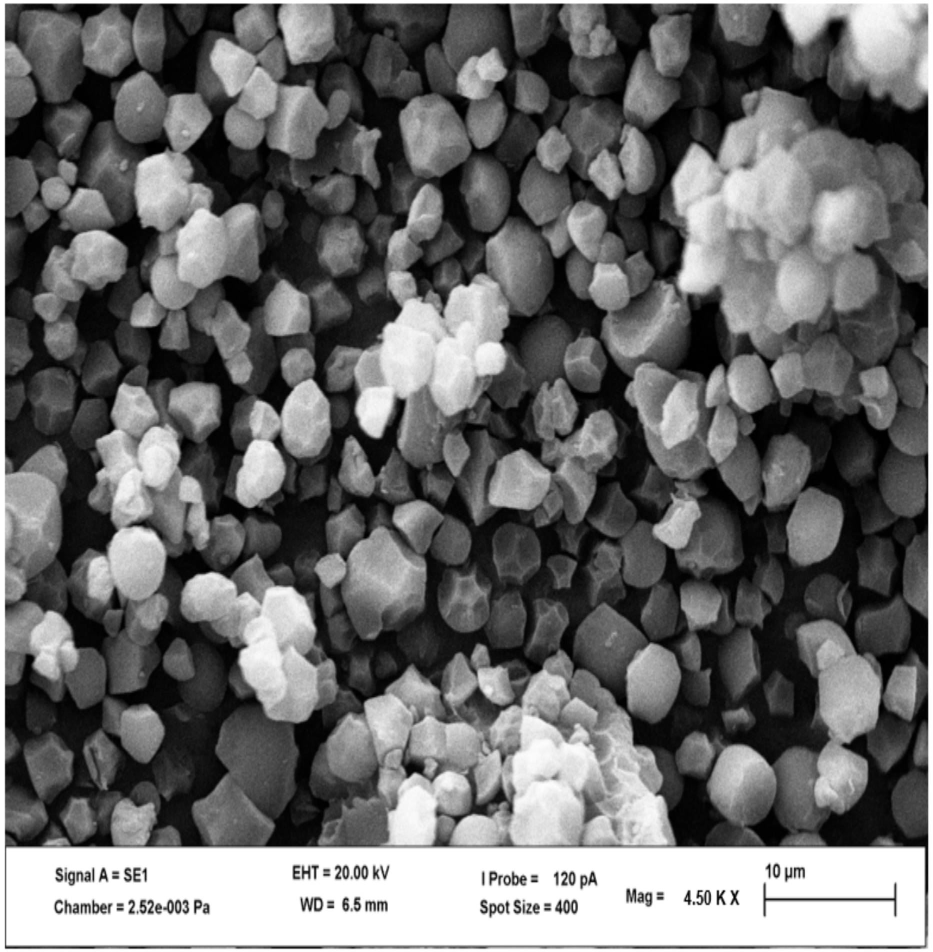
All values are means of three values. Data contained in the parenthesis are the standard deviations. The means with different letters are significantly different at $p<0.05$ by LSD test. A = Ambient storage, U = Underground storage, EC = CoolBot® and evaporative cooler storage, HC = High-cold, and LC = low-cold storage.


Signal A = SE1
Chamber = 1.12e-003 Pa
EHT = 20.00 kV
WD = 7.0 mm
I Probe = 83 pA
Spot Size = 379
Mag = 4.50 K X
10 µm

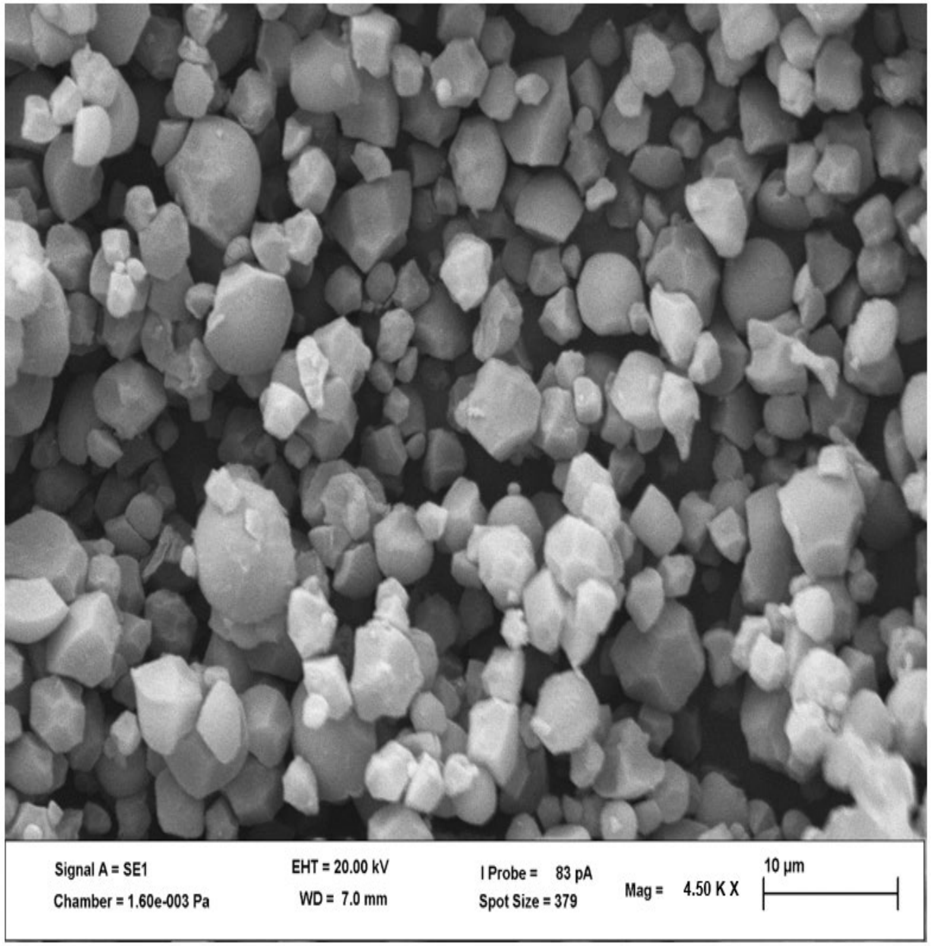
a)


Signal A = SE1
Chamber = 1.09e-003 Pa
EHT = 20.00 kV
WD = 7.0 mm
I Probe = 83 pA
Spot Size = 379
Mag = 4.50 K X
10 µm

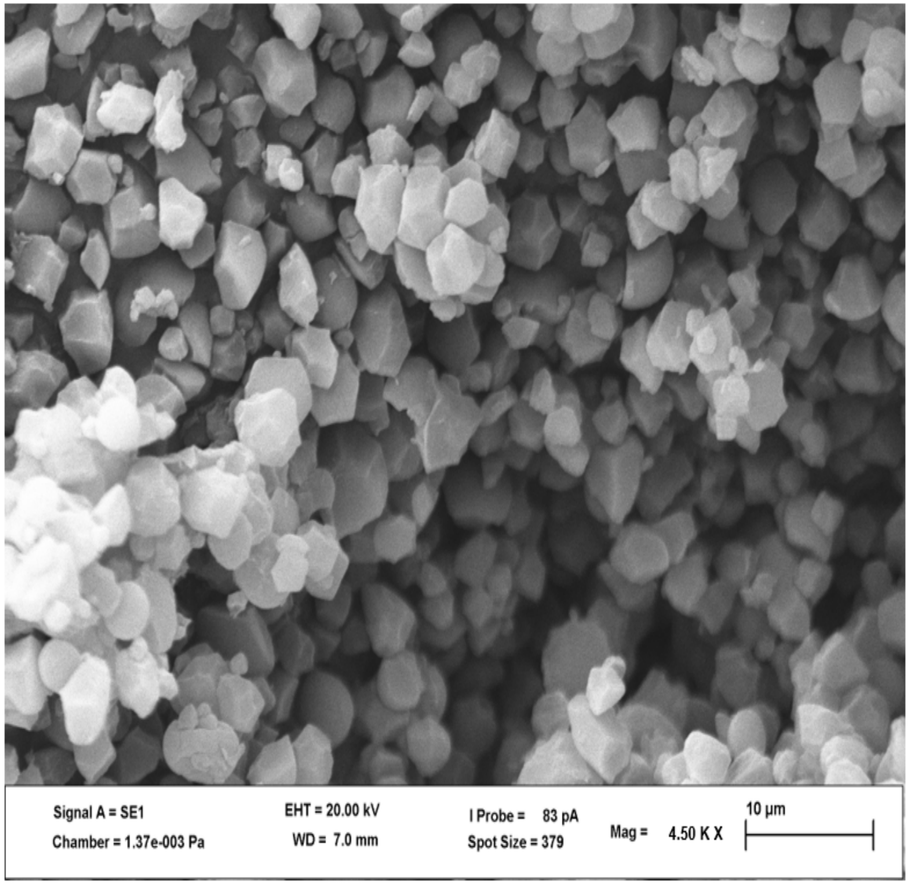
b)


Signal A = SE1
Chamber = 2.52e-003 Pa
EHT = 20.00 kV
WD = 6.5 mm
I Probe = 120 pA
Spot Size = 400
Mag = 4.50 K X
10 µm

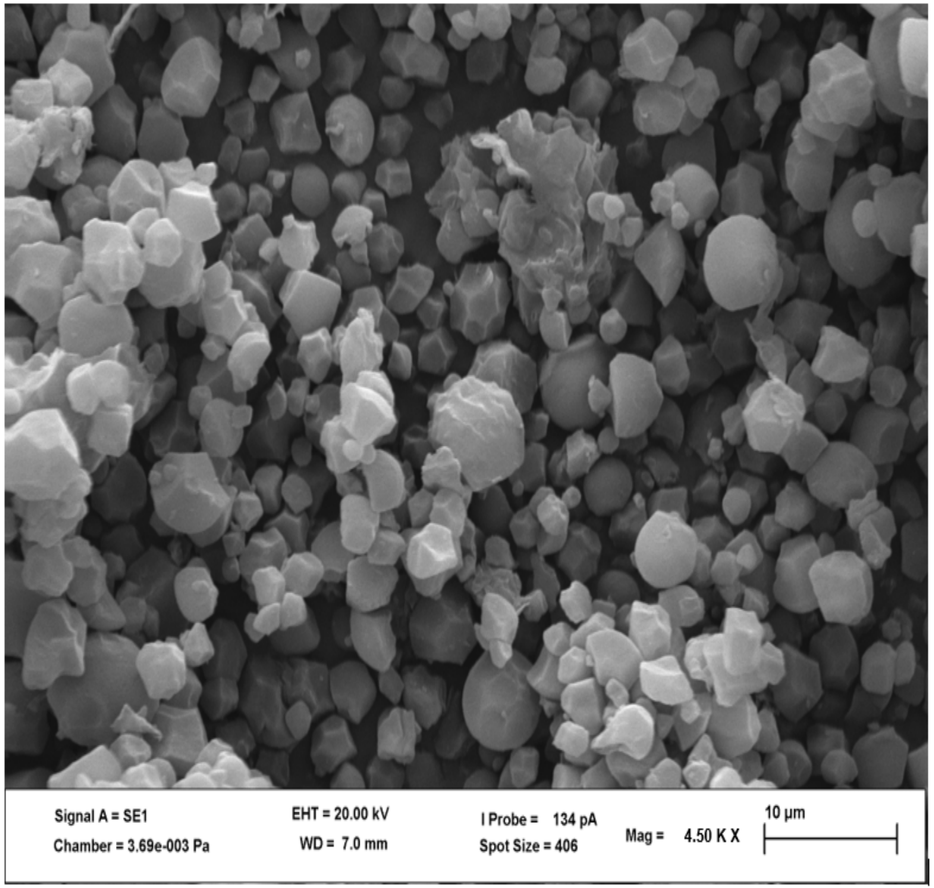
c)


Signal A = SE1
Chamber = 1.60e-003 Pa
EHT = 20.00 kV
WD = 7.0 mm
I Probe = 83 pA
Spot Size = 379
Mag = 4.50 K X
10 µm

d)



e)



f)

Figure 5.1 The effect of storage conditions on the morphology of *amadumbe* starch (a) Starch before storage, (b) Ambient storage, (c) Underground storage, (d) CoolBot® and Evaporative cooler storage, (e) High-cold storage (f) Low-cold storage after 70 days

5.3.3 *Amadumbe* starch swelling power and solubility

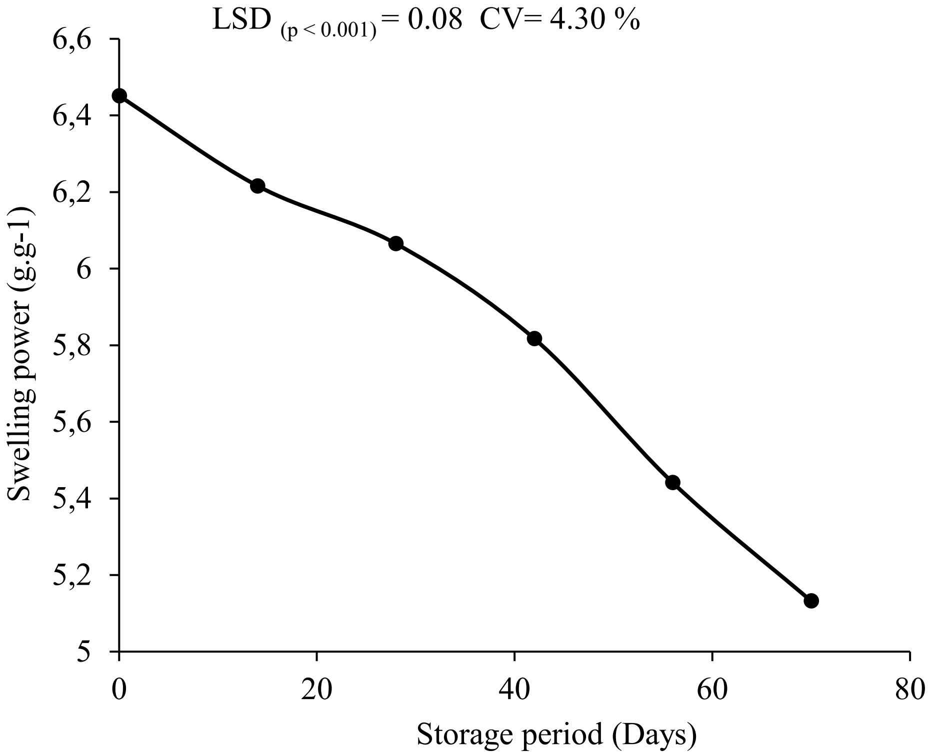
Figure 5.2a-c illustrates the effect of storage conditions and storage period on the swelling power of *amadumbe* starch. The swelling power ranged between 1.34 and 10.03 $g.g^{-1}$. The range obtained in this study is low compared to the swelling power obtained by other authors such as Alam and Hasnain (2009) (6.20 – 28.00 $g.g^{-1}$), Deka and Sit (2016) (10.57 – 13.25), and Nwokocha *et al.* (2009) (2.52 – 18.60 $g.g^{-1}$). The low swelling power may be due to non-starch components such as protein present in the starch, which reduces the swelling power (Chiranthika *et al.*, 2021).

Figure 5.2b illustrates the change in swelling power of *amadumbe* stored in different storage conditions. Storage conditions had a significant impact ($p < 0.001$) on the swelling power of *amadumbe* starch. The swelling power ranged between 5.70 to 6.15 $g.g^{-1}$, with Ambient and High-cold storage conditions having the lowest and highest swelling power, respectively. The high swelling power in High-cold storage may be attributed to the larger granular size because larger granules have an increased ability to swell. Falade and Okafor (2013) reported that *Xanthosomas spp* starch with larger granules than *amadumbe* starch had a higher swelling power. During extraction of *amadumbe* starch, other non-starch components such as protein, phosphorous, and lipids are not removed (Jane *et al.*, 1992; Naidoo *et al.*, 2015; Chisenga *et al.*, 2019a). These non-starch components such as phosphorus and lipids also influence the swelling power. Thus, a decrease in phosphorus will lead to a reduction in the swelling power. Sabiniano *et al.* (1994) reported that the phosphorous content of potatoes decreases during storage.

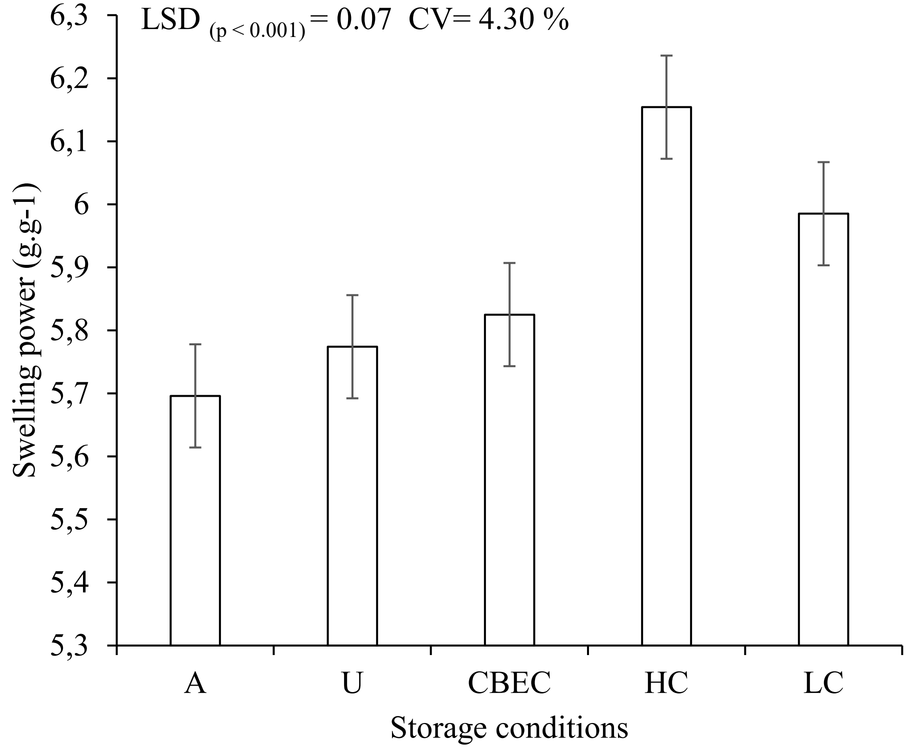
Figure 5.2a illustrates the change in swelling power of *amadumbe* starch as the storage period is increased. The figure illustrates that the swelling power of *amadumbe* starch decreased throughout the storage period. The storage period had a significant impact ($p < 0.001$) on the swelling power of *amadumbe* starch. The swelling power decreased from 6.45 to 5.13 $g.g^{-1}$ on days 0 and 70, respectively. The reduction in swelling power throughout the storage period may be attributed to increased lipids. Hoover and Ratnayake (2002) reported that the formation of amylose-lipid complexes inhibits starch swelling. Hu *et al.* (2017) also reported that surface protein and lipids inhibit starch swelling. Chisenga *et al.* (2019b) reported that a reduction in granular size reduces the swelling capacity of starch. Therefore, the reduction in starch yield and granular size during storage may have caused the reduction in the swelling power of *amadumbe* starch. The swelling power correlated positively with solubility ($r = 0.862$, $p < 0.001$), L* ($r = 0.671$, $p < 0.001$), and granular starch size ($r = 0.833$, $p < 0.001$) and correlated negatively with water holding capacity ($r = -0.545$, $p < 0.001$) and oil holding capacity ($r = -0.626$, $p < 0.001$). The negative correlation shows that water and oil holding capacities increase as swelling power decreases.

Figure 5.2c illustrates the change in swelling power of *amadumbe* starch due to temperature changes. The figure illustrates that the swelling power of *amadumbe* starch increased as a function of temperature. The temperature had a significant impact ($p < 0.001$) on the swelling power of *amadumbe* starch. The swelling power increased from 1.85 to 9.26 $g.g^{-1}$ at 50 and 90°C, respectively. The increase in swelling power as the temperature is increased is due to the breaking down of the hydrogen bonds formed between hydroxyl groups and starch, which then interacts with water (Sit *et al.*, 2014). Kayode *et al.* (2021), Chisenga *et al.* (2019b), and Oyeyinka and Amonsou (2020) also reported an increase in swelling power of potatoes, sweet potatoes, cassava, and *amadumbe*, respectively, as the temperature is increased.

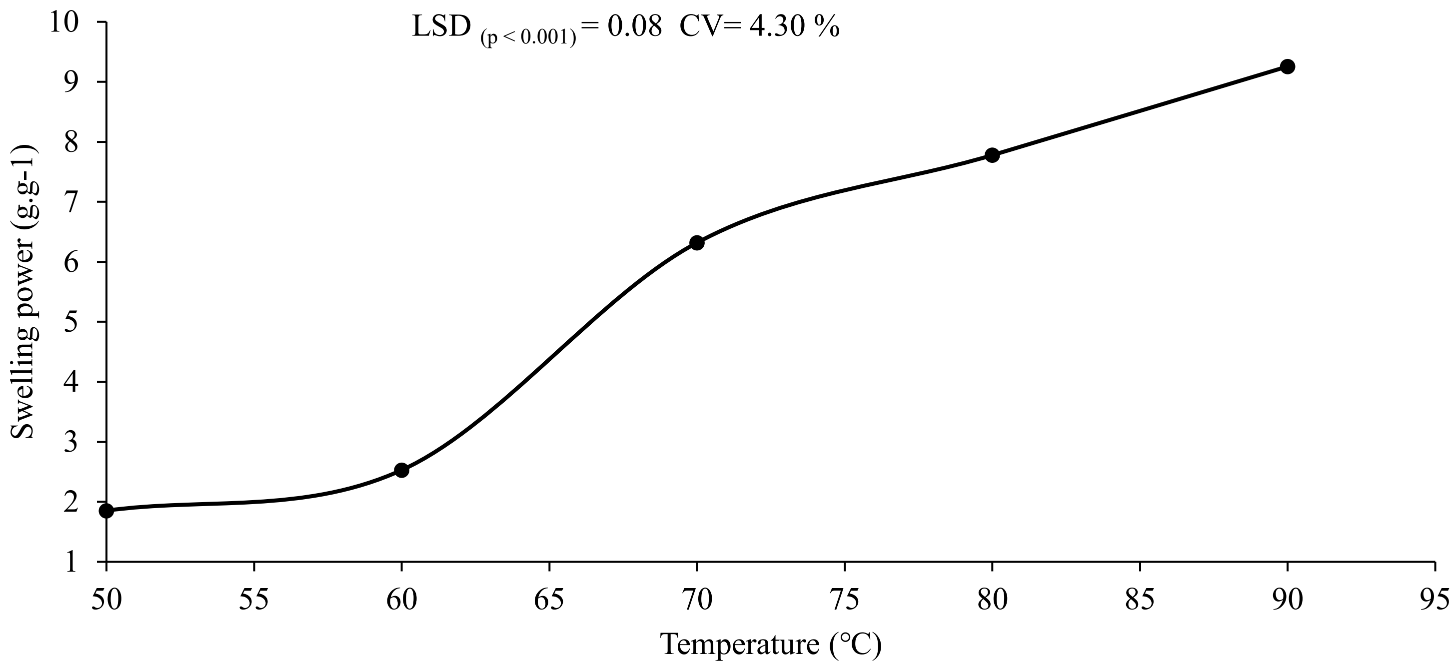
The interaction of storage conditions and the temperature had a significant impact ($p < 0.001$) on the swelling power of *amadumbe*. Low-cold storage had the highest swelling power increase of 408.96 % from 50 to 90 °C, while Ambient storage had the lowest swelling power increase of 386.10 %. The interaction of storage conditions and storage period had a significant impact ($p < 0.001$) on the swelling power of *amadumbe*. High-cold storage had the lowest decrease of *amadumbe* swelling power (12.31 %) while, Ambient storage had the highest reduction of 27.73 %, from day 0 to day 70. The interaction of storage period and the temperature had a significant impact ($p < 0.001$) on the swelling power of *amadumbe* starch. Day 0 had the Highest increase in swelling power of 456.39 %, while day 70 had the lowest increase of 352.52 %. The interaction of storage conditions, storage period and temperature, had a significant impact ($p < 0.001$) on the swelling power of *amadumbe*. Ambient storage conditions showed the lowest swelling power on day 70 at 50°C while, High-cold storage had the highest swelling power on day 0 at 90°C. Therefore, High cold storage conditions would be suitable for producing foods with high pasting viscosity (Buckman *et al.*, 2018).


LSD (p < 0.001) = 0.08 CV= 4.30 %
6,6
6,4
6,2
6
5,8
5,6
5,4
5,2
5
0
20
40
60
80
Swelling power (g.g-1)
Storage period (Days)

a)


LSD (p < 0.001) = 0.07 CV= 4.30 %
6,3
6,2
6,1
6
5,9
5,8
5,7
5,6
5,5
5,4
5,3
A
U
CBEC
HC
LC
Swelling power (g.g-1)
Storage conditions

b)



c)

Figure 5.2 The effect of storage period (a), storage conditions (b), and temperature (c) on the swelling power of *amadumbe* starch.
A = Ambient storage, U = Underground storage, EC = CoolBot® and evaporative cooler storage, HC = High-cold, and LC = low-cold storage.

Figure 5.3a-c illustrates the effect of storage conditions and storage period on the solubility of *amadumbe* starch. The solubility ranged between 0.56 to 11.32 %. The range obtained in this study is low compared to the solubility obtained by Alam and Hasnain (2009) (2.63 – 22.50), (Deepika *et al.*, 2013) (8.10 – 49.03 %) and (Nwokocha *et al.*, 2009) (1.12 – 18.50). Chisenga *et al.* (2019a) reported that the solubility of starch is influenced by the granular size, temperature, and other non-starch components.

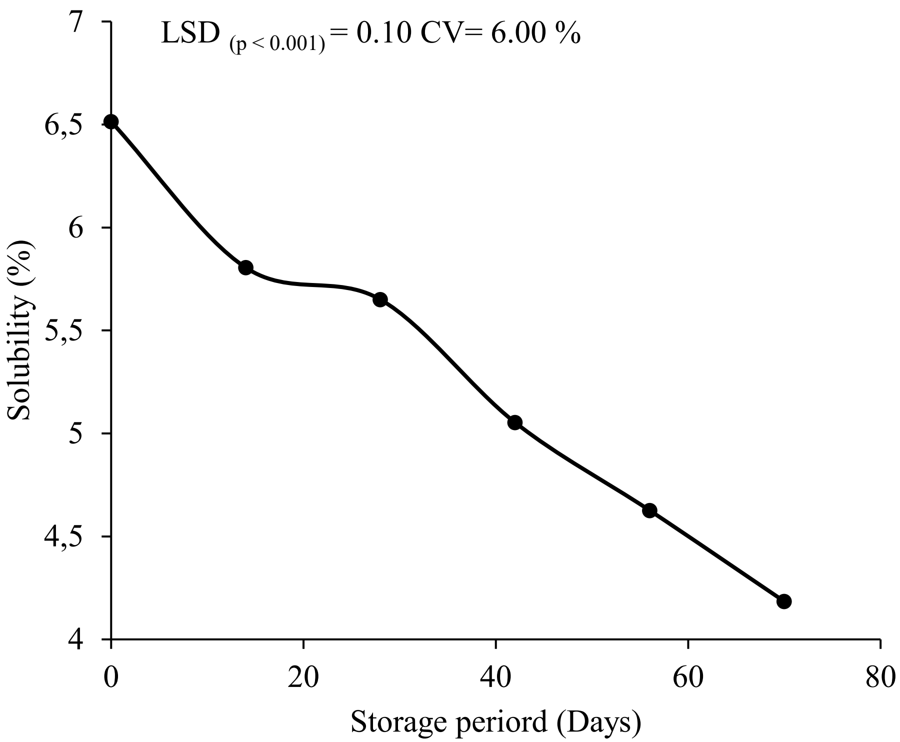
Figure 5.3b illustrates the change in solubility of *amadumbe* stored in different storage conditions. Storage conditions had a significant impact ($p < 0.001$) on the solubility of *amadumbe* starch. The solubility ranged between 4.51 and 5.98 %, with Ambient and High-cold storage conditions having the lowest and highest solubility, respectively. The high solubility in High-cold storage conditions may be attributed to the larger granular size because larger granules have increased solubility (Falade and Okafor, 2013). This study also found that solubility has a positive correlation with granular starch size ($r = 0.886$, $p < 0.001$) and L* ($r = 0.709$, $p < 0.001$). The positive correlation between granular starch size and solubility shows that as the particle size decreases, the solubility also decreases. Chisenga *et al.* (2019a) reported that large granules have a higher solubility due to having a higher volume because solubility has a strong positive correlation with swelling power. The study also found that solubility strongly correlates with swelling power ($r = 0.862$, $p < 0.001$). This present study also found that solubility positively correlates with granular starch size ($r = 0.820$, $p < 0.001$). In contrast, Naidoo *et al.* (2015) concluded that the difference in the granular size of cultivated and wild had no significant influence on the solubility of *amadumbe* starch.

Figure 5.3a illustrates the change in the solubility of *amadumbe* starch as the storage period is increased. The figure illustrates that the solubility of *amadumbe* decreased throughout the storage period. The storage period had a significant impact ($p < 0.001$) on the solubility of *amadumbe* starch. The solubility of *amadumbe* starch decreased from 6.51 to 4.18 % on days 0 and 70, respectively. The decrease in solubility during storage may be attributed to increased lipid content. Lipid-amylose complexes restrict swelling, which leads to a reduced loss of amylose through leaching, thus decreasing solubility (Alcázar-Alay and Meireles, 2015). The decrease may also be attributed to loss of granular arrangement due to starch degradation because of amylase activity (Nwokocha *et al.*, 2009). The solubility of *amadumbe* starch correlated negatively with water holding capacity ($r = -0.390$, $p < 0.001$) and oil holding capacity ($r = -0.595$, $p < 0.001$), a* ($r = -0.458$, $p < 0.001$) and b* ($r = -0.704$, $p < 0.001$).

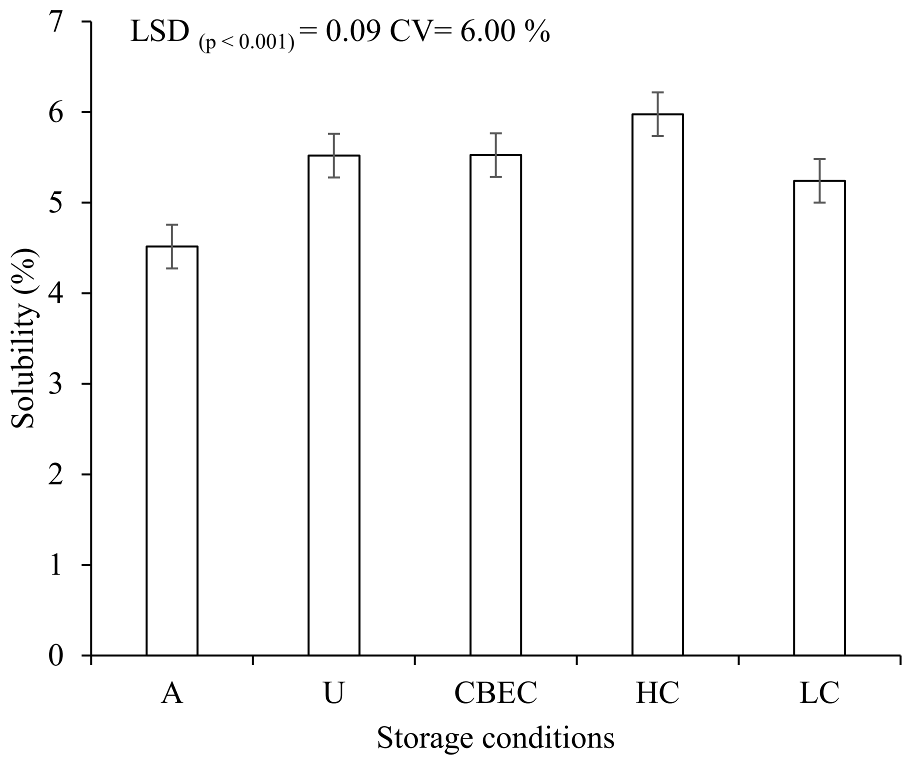
Figure 5.3c illustrates that the solubility of *amadumbe* increases as a function of temperature. The temperature had a significant impact ($p < 0.001$) on the solubility of *amadumbe* starch. The solubility of *amadumbe* starch increased from 1.74 to 8.37 % at 50 and 90°C, respectively. Chisenga *et al.* (2019a) reported that non-starch components are responsible for variations in the solubility of cassava starch. The increase in solubility may be due to increased soluble non-starch components such as sugars during storage (Verma *et al.*, 2018).

The interaction of storage conditions and the temperature had a significant impact ($p < 0.001$) on the solubility of *amadumbe* starch. High-cold storage had the highest solubility increase of 599.91 % from 50 to 90 °C while, Low-cold storage had the lowest solubility increase of 329.74 %. The interaction of storage conditions and storage period had a significant impact ($p < 0.001$) on the solubility of *amadumbe*. Ambient storage conditions had the highest reduction in solubility of 49.06 %, while High-cold storage had the lowest reduction of 20.99 % from day 0 to day 70. The interaction of storage period and the temperature had a significant impact ($p < 0.001$) on the solubility of *amadumbe*. Day 0 had the highest increase in solubility of 514.43 % from 50 to 90 °C, while day 70 had the lowest increase of 384.13 %. The interaction of storage conditions, storage period, and temperature had a significant impact ($p <0.001$) on the solubility of *amadumbe*. The highest solubility was found on day 0 at 90°C across all storage conditions, while the lowest was found in Ambient storage conditions on day 70 at 50°C.

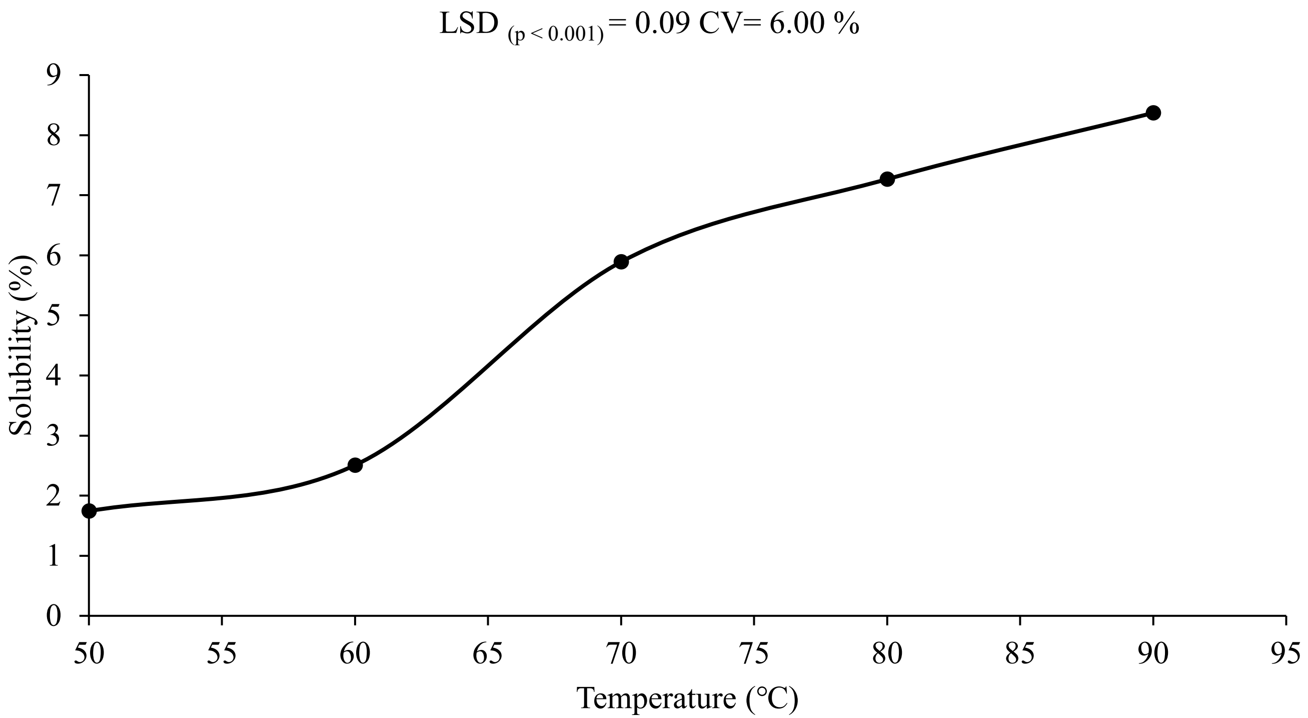
High cold storage is the best method for preserving *amadumbe* starch solubility, while ambient storage is the worst. The high solubility of High-cold storage will be suitable to produce food such as baked products because it has a higher ability to swell (Kaushal *et al.*, 2015)


LSD (p < 0.001) = 0.10 CV= 6.00 %
Solubility (%)
Storage periord (Days)
7
6,5
6
5,5
5
4,5
4
0
20
40
60
80

a)


LSD (p < 0.001) = 0.09 CV= 6.00 %
Solubility (%)
Storage conditions
7
6
5
4
3
2
1
0
A
U
CBEC
HC
LC

b)



c)

Figure 5.3 The effect of storage period (a), storage conditions (b), and temperature (c) on the solubility of *amadumbe* starch. A = Ambient storage, U = Underground storage, EC = CoolBot® and evaporative cooler storage, HC = High-cold, and LC = low-cold storage.

5.3.4 *Amadumbe* starch water and oil holding capacities

The change in the water holding capacity of *amadumbe* starch during storage can be found in Table 4.5. The water holding capacity ranged between 227.15 and 363.62 %. The range obtained in this study is high compared to the water holding capacity obtained by other authors such as Hoyos-Leyva *et al.* (2018) (140 – 150 %) and Njintang *et al.* (2008) (60 – 250 %). The high-water holding capacity may be due to the high protein content reported in this study. The water holding capacity of *amadumbe* starch is influenced by non-starch components such as mucilage and protein content (Raungrusmee and Anal, 2019; Chiranthika *et al.*, 2021).

Storage conditions had a significant impact ($p < 0.05$) on the water holding capacity of *amadumbe* starch. The water holding capacity ranged from 241. 62 to 277.01 %, with Ambient and High-cold storage conditions having the lowest and highest water holding capacity, respectively. The low water holding capacity in Ambient storage conditions may be attributed to the degradation of starch granules, which interns reduces the amylose content (Chisenga *et al.*, 2019a). Oyeyinka *et al.* (2020) found that the amylose content of refrigerated cassava reduced during storage due to amylase activity. Raungrusmee and Anal (2019) reported that a reduction in amylose decreases the water holding capacity of starch since amylose can effectively bind water molecules. The presence of higher amounts of other non-starch components in *amadumbe* starch, such as protein and mucilage may have resulted in the high water holding capacity in High-cold storage (Chiranthika *et al.*, 2021).

The storage period had a significant impact ($p < 0.001$) on the water holding capacity of *amadumbe* starch. The water holding capacity increased from 227.15 to 316.69 % on day 0 to day 70. The increase may be attributed to an increase in the portion of small granular particles during storage (Kaur *et al.*, 2009). Kayode *et al.* (2021) reported that small granular starch absorbs more water due to an increased surface area. This study also found a negative correlation between the water holding capacity and granular starch size ($r = -0.335$, $p < 0.05$) and L* ($r = -0.333$, $p < 0.001$) of *amadumbe* starch. The negative correlation between water holding capacity and granular starch size shows that water holding capacity increases as granular starch size decreases. Storage may have also caused the loosening of starch semi-crystalline, which increases the water holding capacity (Njintang *et al.*, 2008). The water holding capacity of *amadumbe* starch had a positive correlation with oil holding capacity ($r = 0.654$, $p < 0.001$), a* ($r = 0.413$, $p < 0.001$), and b* ($r = 0.520$, $p < 0.001$).

The interaction of storage conditions and storage period had a significant impact ($p < 0.05$) on the water holding capacity of *amadumbe* starch. High-cold storage had the highest water holding capacity, which increased by 60.08 % from day 0 to day 70 while, Ambient storage conditions had the lowest water holding capacity, which increased by 15.13 %. Therefore, High-cold storage is the best storage method in preserving the water holding capacity of *amadumbe* starch and would be suitable to produce food with high viscosity (Njintang *et al.*, 2008).

The change in the oil holding capacity of *amadumbe* starch during storage can be found in Table 4.5. The oil holding capacity ranged between 214.32 and 444.01 %. The range obtained in this study is alarmingly high compared to the oil holding capacity obtained by other authors such as Saxby *et al.* (2021) (120.00 – 315.50 %) and Njintang *et al.* (2008) (60.00 – 249. 00 %). The high oil holding capacity may be attributed to more non-starch components, such as protein that remains after starch extraction (Wongsagonsup *et al.*, 2021).

Storage conditions had a significant impact ($p < 0.001$) on the oil holding capacity of *amadumbe* starch. The oil holding capacity ranged from 337.82 to 369.15 %, with Ambient and High-cold storages having the lowest and highest water capacity, respectively. The High oil holding capacity in High-cold storage conditions may be attributed to the higher protein content present in the starch (Chiranthika *et al.*, 2021).

The storage period had a significant impact ($p < 0.001$) on the oil holding capacity of *amadumbe* starch. The oil holding capacity increased from 214.31 to 421.07. % on days 0 and 70, respectively. During storage, the reduction in oil holding capacity is due to starch degradation, resulting in reduced amylose content (Verma *et al.*, 2018). This study also found oil holding capacity had a negative correlation with the granular starch size ($r = -0.693$, $p < 0.002$) and L* ($r = -0.447$, $p < 0.001$) of *amadumbe* starch. The negative correlation shows that the oil holding capacity increases as granular starch size decreases. The increase may also be attributed to changes in the charges on the protein molecule during storage (Shad *et al.*, 2011).

The oil holding capacity of *amadumbe* starch had a positive correlation with a* (r = 0.377, p < 0.05) and b* (r = 0.621, p < 0.05).

The interaction of storage conditions and storage period had a significant impact (p < 0.001) on the oil holding capacity of *amadumbe* starch. High-cold storage had the highest oil holding capacity, which increased by 107.17 % from day 0 to day 70 while, Ambient storage had the lowest oil holding capacity, which increased by 79.43 %. Therefore High-cold storage is the best storage method in preserving the oil holding capacity of *amadumbe* starch and would be suitable for retaining flavours and enhancing the mouthfeel of food (Falade and Okafor, 2013).

5.3.5 *Amadumbe* starch colour

Table 4.6 shows the impact of storage conditions and storage period on the colour of *amadumbe* starch. The L* ranged from 92.18 to 95.34, the range obtained in this study is comparable to the L* values reported by other authors such as Oyeyinka and Amonsou (2020) (96.34 – 96.94), Deka and Sit (2016) (92.95), Njintang *et al.* (2008) (83.20 – 94.90), and Sit *et al.* (2014) (93.3 – 94.4). The difference in L* may be due to differences in the starch extraction methods, the genetic makeup, and the carotenoid pigment (Njintang *et al.*, 2008; Uchechukwu-Agua *et al.*, 2015).

Storage conditions had a significant impact (p < 0.001) on the L* of *amadumbe* starch. The L* ranged from 93.31 to 94.25, with Ambient and High-cold storages having the lowest and highest L*, respectively. Nourian *et al.* (2003) also reported a higher decrease in L* of potatoes stored at 20°C as compared to 4°C. This study also found a positive correlation between the L* and granular starch size (r = 0.865, p < 0.001) of *amadumbe* starch. The correlation shows that as starch size is reduced due to degradation, the L* is also reduced. The storage period also had a significant impact (p < 0.001) on the L* of *amadumbe* starch, the L* decreased from 94.65 to 92.89 on days 0 and 70, respectively. The colour change may be attributed to the Millard reaction between reducing sugars and proteins (Deka and Sit, 2016). Reducing sugars increase during storage and may react with protein to form brown substances. The L* had a negative correlation with a* (r = -0.492, p <0.001) and b* (r = -0.559, p <0.001) which shows that as a* and b* increases the L* reduces.

The a* of *amadumbe* starch ranged from 0.34 to 1.59, the range obtained in this study is comparable to the low a* values reported by other authors such as Deka and Sit (2016) (2.02), Oyeyinka and Amonsou (2020) (0.04 – 0.10), and Sit *et al.* (2014) (1.90 – 2.20). Storage conditions had a significant impact ($p < 0.001$) on the a* of *amadumbe* starch. The a* ranged between 0.75 to 0.93, with Underground and Low-cold storage conditions having the lowest and highest a*, respectively. The high a* in Low-cold storage still needs to be elucidated. However, it may be due to the formation of brown substances when reducing sugars react with the amino acid of protein (Nascimento and Canteri, 2018).

The storage period had a significant impact ($p < 0.05$) on the a* of *amadumbe* starch. The a* increased from 0.72 to 1.18 on days 0 and 70, respectively. The increase in a* values during storage may be attributed to oxidation (Uchechukwu-Agua *et al.*, 2015). The interaction of storage conditions and storage period had a significant impact ($p < 0.001$) on the a* of *amadumbe* starch. Ambient storage conditions had the highest increase in a* of 118.55 %, while Underground storage conditions had the lowest increase of 11.99 % from day 0 to day 70. The a* showed a positive correlation with b* ($r = 0.513$, $p <0.001$) and a negative correlation with granular starch size ($r = -0.779$, $p <0.001$).

The b* of *amadumbe* starch ranged from 3.10 to 4.62. The range obtained in this study is high compared to the b* reported by authors such as Deka and Sit (2016)(1.56) and Oyeyinka and Amonsou (2020) (0.89-1.14). Storage conditions had no significant impact ($p > 0.05$) on the b* of *amadumbe* starch, while the storage period had a significant impact ($p < 0.001$). The b* increased from 3.10 to 4.32 on days 0 and 70, respectively. The increase in b* found in this present study is contrary to the work reported by Uchechukwu-Agua *et al.* (2015), who reported that the b* of cassava decreased during storage and attributed the decrease to the degradation of yellow pigments. The b* had a negative correlation with granular starch size ($r = -0.725$, $p <0.001$). Boudries *et al.* (2009) reported that L* values higher than 90 are suitable for use in industry. Therefore the starch of *amadumbe* stored in all storage conditions would be good for mixing with other starches (Wang *et al.*, 2020).

Table 5.4 The water and oil holding capacities (%) of starch from *amadumbe* subjected to different storage conditions

Capacity	Storage period (days)	A	U	CBEC	HC	LC
Water holding	0	227.15(5.84)^{a}	227.15(5.84)^{a}	227.15(5.84)^{a}	227.15(5.84)^{a}	227.15(5.84)^{a}
	14	232.72(25.80)^{ab}	249.21(14.28)$^{a-d}$	245.28(7.08)$^{a-d}$	242.91(2.65)$^{a-d}$	235.86(7.56)^{abc}
	28	234.67(14.57)^{abc}	267.43(26.53)$^{a-e}$	266.86(47.29)$^{a-e}$	265.12(14.89)$^{a-e}$	266.43(4.38)$^{a-e}$
	42	236.30(2.58)^{abc}	277.56(20.52)^{cde}	282.99(1.46)^{de}	279.21(32.49)^{cde}	275.58(14.07)^{bcde}
	56	257.39(48.87)$^{a-e}$	276.03(18.73)$^{b-e}$	297.05(9.62)^{e}	284.06(9.76)^{de}	285.72(5.45)^{de}
	70	261.51(50.14)$^{a-e}$	278.78(13.80)^{cde}	337.02(30.88)^{f}	363.62(45.72)^{f}	342.50(20.13)^{f}
Oil holding	0	214.32(3.22)^{a}	214.32(3.22)^{a}	214.32(3.22)^{a}	214.32(3.22)^{a}	214.32(3.22)^{a}
	14	328.06(43.98)^{c}	352.90(18.70)$^{c-f}$	344.31(41.51)^{cd}	348.68(30.43)^{cde}	278.68(9.56)^{b}
	28	364.65(6.17)$^{d-g}$	355.85(6.15)$^{c-f}$	368.67(21.34)$^{d-h}$	387.12(7.72)$^{f-j}$	355.87(7.13)$^{c-f}$
	42	365.61(4.83)$^{d-g}$	357.92(19.16)$^{c-f}$	370.12(30.12)$^{d-h}$	404.38(29.55)$^{h-k}$	395.68(2.46)$^{g-i}$
	56	369.76(26.30)$^{d-h}$	379.88(14.20)$^{d-i}$	372.38(18.61)$^{d-h}$	416.28(14.87)^{jkl}	435.71(6.39)^{kl}
	70	384.55(9.25)$^{e-j}$	410.58(9.09)$^{i-l}$	430.45(32.67)^{kl}	444.01(6.19)^{l}	435.74(9.91)^{kl}

Capacity	Level of significance		
	Storage conditions (A)	Storage period (B)	A*B
Water holding	$p < 0.001$	$p < 0.001$	$p < 0.05$
Oil holding	$p < 0.001$	$p < 0.001$	$p < 0.001$

All values are means of three values. Data contained in the parenthesis are the standard deviations. The means with different letters are significantly different at $p<0.05$ by LSD test. A = Ambient storage, U = Underground storage, EC = CoolBot® and evaporative cooler storage, HC = High-cold, and LC = low-cold storage.

Table 5.5 The colour of starch from *amadumbe* subjected to different storage conditions

Colour parameters	Storage period (days)	A	U	CBEC	HC	LC
L*	0	94.65(0.37)$^{f\text{-}k}$	94.65(0.37)$^{f\text{-}k}$	94.65(0.37)$^{f\text{-}k}$	94.65(0.37)$^{f\text{-}k}$	94.65(0.37)$^{f\text{-}k}$
	14	92.68(1.09)^{abc}	94.82(0.20)^{ijk}	95.04(0.24)jk	95.34(1.09)^{k}	94.66(0.28)$^{f\text{-}k}$
	28	93.51(1.63)$^{a\text{-}i}$	94.74(0.51)$^{h\text{-}k}$	93.82(0.22)$^{c\text{-}j}$	94.59(0.21)$^{f\text{-}k}$	94.46(0.22)$^{e\text{-}k}$
	42	92.58(1.18)^{abc}	92.18(0.84)^{a}	93.69(0.59)$^{b\text{-}j}$	94.12(1.16)$^{d\text{-}k}$	93.77(0.45)$^{c\text{-}j}$
	56	93.21(0.58)$^{a\text{-}f}$	92.42(1.16)^{abc}	93.07(0.33)$^{a\text{-}e}$	93.22(0.39)$^{a\text{-}g}$	93.51(0.55)$^{a\text{-}i}$
	70	92.26(0.17)^{ab}	92.86(0.59)$^{a\text{-}d}$	93.28(1.06)$^{a\text{-}h}$	93.63(0.49)$^{a\text{-}j}$	92.42(1.39)^{abc}
a*	0	0.72(0.16)^{bcd}	0.72(0.16)^{bcd}	0.72(0.16)^{bcd}	0.72(0.16)^{bcd}	0.72(0.16)^{bcd}
	14	0.80(0.14)$^{b\text{-}e}$	0.75(0.11)$^{b\text{-}e}$	0.84(0.15)^{cde}	0.77(0.36)$^{b\text{-}e}$	0.83(0.41)^{cde}
	28	0.71(0.28)^{bcd}	0.45(0.19)^{ab}	0.64(0.12)^{abc}	0.34(0.09)^{a}	0.73(0.16)^{bcd}
	42	0.69(0.13)^{abcd}	0.97(0.19)$^{c\text{-}f}$	0.99(0.31)$^{c\text{-}f}$	0.92(0.21)$^{c\text{-}f}$	0.64(0.11)^{abc}
	56	0.94(0.10)$^{c\text{-}f}$	0.78(0.10)$^{b\text{-}e}$	1.05(0.06)^{def}	1.59(0.11)^{h}	1.26(0.07)^{fgh}
	70	1.57(0.11)^{h}	0.80(0.08)$^{b\text{-}e}$	1.12(0.24)^{efg}	0.97(0.19)$^{c\text{-}f}$	1.43(0.28)^{gh}
b*	0	3.10(0.16)^{a}	3.10(0.16)^{a}	3.10(0.16)^{a}	3.10(0.16)^{a}	3.10(0.16)^{a}
	14	3.35(0.69)^{abc}	3.55(0.24)$^{a\text{-}e}$	3.38(0.24)^{abc}	3.277(0.85)^{ab}	3.06(0.55)^{a}
	28	3.90(0.70)$^{b\text{-}f}$	3.61(0.46)$^{a\text{-}e}$	3.41(0.41)^{abc}	3.457(0.06)$^{a\text{-}d}$	3.54(0.17)$^{a\text{-}e}$
	42	4.02(0.13)$^{c\text{-}g}$	3.63(0.16)$^{a\text{-}e}$	3.83(0.30)$^{b\text{-}e}$	3.64(0.03)$^{a\text{-}e}$	3.66(0.04)$^{a\text{-}e}$
	56	4.06(0.21)$^{c\text{-}g}$	3.89(0.43)$^{b\text{-}f}$	4.05(0.41)$^{c\text{-}g}$	3.90(0.05)$^{b\text{-}f}$	3.73(0.23)$^{a\text{-}e}$
	70	4.54(0.48)^{fg}	4.22(0.12)^{efg}	4.62(0.27)^{g}	4.04(0.38)$^{c\text{-}g}$	4.15(0.01)$^{d\text{-}g}$

	Level of significance		
Colour parameter	Storage conditions (A)	Storage period (B)	A*B
L*	$p < 0.001$	$p < 0.001$	$p > 0.05$
a*	$p < 0.05$	$p < 0.001$	$p < 0.001$
b*	$p > 0.05$	$p < 0.001$	$p > 0.05$

All values are means of three values. Data contained in the parenthesis are the standard deviations. The means with different letters are significantly different at $p<0.05$ by LSD test. A = Ambient storage, U = Underground storage, EC = CoolBot® and evaporative cooler storage, HC = High-cold, and LC = low-cold storage.

5.4 Conclusion

This study investigated the effect of different storage conditions on the quality attributes of starch derived from stored *amadumbe* corms. The study revealed that the quality attributes of *amadumbe* starch are influenced by storage conditions, storage period, and the interaction of storage conditions and storage period. All studied parameters showed a significant correlation with each other. Starch derived from corms stored in Ambient storage conditions (17.30 – 23.59°C, 75.02 – 75.15 %) showed a massive loss in quality attributes while corms stored in High-cold storage conditions (9.26 – 11.54°C, 97.57 – 100.00 %), had minimal losses in quality attributes. High-cold storage conditions reduced the loss in starch yield, swelling power, solubility, and granular starch size and reduced the change in L* and b*. It also resulted in the highest increase in water and oil holding capacities.

The study revealed that High-cold storage resulted in the lowest reduction in starch yield (10.37 %), granular starch size (6.21 %), swelling power (12.31 %), solubility (20.99 %), L* (1.08 %). It also resulted in the highest increase in water holding capacity (60.02 %) and oil holding capacity (107.17 %). While Ambient storage resulted in the highest decrease in starch yield (10.37 %), granular starch size (6.21 %), swelling power (12.31 %), solubility (20.99 %), L* (1.08 %). It also resulted in the highest increase in water holding capacity (60.02 %) and oil holding capacity (107.17 %).

The starch morphology study revealed that the granules of *amadumbe* starch had predominantly irregular and polygonal shapes with a smooth texture. On day 0, the starches had large granular particles which are densely packed; however, after 70 days, Ambient, Underground, CoolBot® and evaporative, and Low-cold storage conditions showed a reduction in the granular size and appeared less densely packed. High-cold storage showed less decline in granular size and resulted in more densely packed granules than all studied storage conditions.

This study revealed that High-cold, followed by CoolBot® and evaporative cooler storages, were the best storage method in preserving the quality attributes of *amadumbe* starch. In contrast, Ambient storage conditions resulted in the worse ability to maintain *amadumbe* starch quality attributes. Therefore, storing amadumbe in ambient storage is not recommended as it results in massive losses in quality attributes of amadumbe corms, flours and starches.

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6. CONCLUSION AND RECOMMENDATIONS AND FUTURE RESEARCH OPPORTUNITIES

This chapter will draw the conclusion of this research, make recommendations, and identify future research opportunities.

6.1 Conclusion

The literature review in Chapter 2 revealed that *amadumbe* remains an underutilised crop in South Africa, and very little research is available on the post-harvest storage of the tuber. The tuber has health-related benefits due to its high resistant starch and fibre content. The high resistance starch reduces glucose absorption in the small intestine, which is ideal for diabetic people. While higher fibre content helps regulate the blood sugar levels of consumers. Currently, mechanical refrigeration, evaporative cooler, and underground storage pits are used to control or partially regulate temperature and relative humidity. However, there is limited information on how low-temperature storage and other storage technologies impact the quality of fresh *amadumbe* corms, flours, and starches. The review also determined that no work has reported the effect of CoolBot® and evaporative cooler storage on the quality of *amadumbe* corms, flours, and starches. It also showed that *amadumbe* is processed into flour and starch because of its high moisture content. The review also found that *amadumbe* can be used in various processing industries, such as producing chips, noodles, cookies, and paste. The possibility of using *amadumbe* in these processing industries is dependent on the quality parameters such as colour, texture, dry matter content, swelling power, water and oil holding capacities, solubility, and specific gravity. The review showed that the quality of *amadumbe* varies with the cultivar, geographical location, maturity stage, planting period, storage, and growing conditions. Therefore, the effect of storage conditions on the quality of South African *amadumbe* cultivars needs to be established.

The main purpose of this study was to determine the optimum storage conditions that result in reduced post-harvest losses of *amadumbe*. This was achieved by evaluating and analysing the effects of different storage methods such as Ambient (A), Underground pit (U), CoolBot® and evaporative cooler (CBEC), High-Cold (HC), and Low-cold (LC) on the quality properties of *amadumbe* corms, flours, and their starches. This research addresses the challenge of *amadumbe* being stored in environments that promote post-harvest losses. It also provides the environmental conditions that can be used to design innovative storage facilities that will have reduced post-harvest losses and low capital and operating costs.

The results showed that High-cold storage conditions (9.26 – 11.54°C, 97.57 – 100.00 %) followed by CoolBot® and evaporative cooler storage conditions (12.32 – 15.72°C, 64.75 – 92.76 %) are best storage methods and resulted in a minimal loss in the quality attributes of *amadumbe* corms, flours, and starches. While Ambient storage conditions (17.30 – 23.59°C, 75.02 – 75.15 %) resulted in a short shelf life and massive loss in quality attributes.

Chapter 3 focused on evaluating the effect of storage conditions on the physiological and mechanical properties of *amadumbe* corms. Storage conditions, storage period, and the interaction of these factors influenced the physiological and mechanical properties of *amadumbe* corms. The results revealed that Ambient storage conditions had a short shelf-life and massive quality changes. While High-cold storage followed by CoolBot® and evaporative cooler storage had slow quality changes. Ambient storage had the highest increase in physiological weight loss, hardness, toughness, specific gravity, and dry matter content. It also had the lowest decrease in shear force and cutting energy. While High-cold storage followed by CoolBot® and evaporative cooler storage (12.32 – 15.72°C, 64.75 – 92.76 %) seemed to have a slow quality change

Chapter 4 focused on determining the effect of storage conditions on the quality attributes of flour derived from stored *amadumbe* corms. The results showed that the physicochemical properties of *amadumbe* flour are influenced by storage conditions, storage period, and the interaction of these factors. Flour derived from corms stored in High-cold storage followed by CoolBot® and evaporative storage conditions were of better quality than all storage conditions. In contrast, Ambient storage was the worst storage and showed a massive loss in quality attributes. Flour derived from corms stored in High-cold storage were of better quality. It had minimal reductions in (moisture content, swelling power, solubility, and protein content), minimal increase in (a* and b*), and the highest increase in the (oil holding and water holding capacities). While Ambient storage conditions showed a massive loss in quality attributes. The microscopic morphologies of *amadumbe* flour were irregular and polygonal in shape. The flours exhibited larger densely packed granular particles connected by fibrous materials on day 0. After 70 days of storage, there was a reduction in the size and compactness of the granular particles. The change in flour morphology was less profound in High-cold storage.

Chapter 5 focused on determining the effect of different storage conditions on the quality attributes of starch derived from stored *amadumbe* corms. The results revealed that storage conditions, storage period, and the interaction of storage conditions and storage period influenced the quality attributes of *amadumbe* starch. Starch derived from corms stored in Ambient storage conditions showed a massive loss in quality attributes while corms stored in High-cold storage followed by CoolBot® and evaporative storage conditions had minimal losses in quality attributes. High-cold storage resulted in the lowest reduction in starch yield, granular starch size, swelling power, solubility, and L*. It also resulted in the highest increase in water holding capacity and oil holding capacity. While Ambient storage resulted in the highest decrease in starch yield, granular starch size, swelling power, solubility, and L*. The starch morphology study revealed that the granules of *amadumbe* starch are predominantly irregular and polygonal-shaped. The granules of starch were densely packed and large on day 0. However, after 70 days of storage, the granules become loosely packed and reduced in size. The loss in granular morphology was less profound in High-cold storage than in all storage conditions due to less degradation.

6.2 Recommendations

Based on the findings of this study, the following recommendations can be made:

1. CoolBot® and evaporative cooler is the second-best storage condition with high relative humidity. The storage chamber can be improved by lowering the temperature below 10°C and increasing the ventilation.
2. Packaging may be added as a treatment to reduce post-harvest losses.
3. Pre-treatment with chemicals such as sodium chloride, ethanol, and sodium hypochlorite may be added as a treatment to reduce microbial spoilage.
4. The tubers that are stored must not only be of similar weight but also similar sizes.

6.3 Future research opportunities

The following research opportunities can be explored in the future:

1. Studies on thermal and rheological properties of stored *amadumbe* flours and starches.
2. Studies can be done to quantify or characterize the quality of the end products (Baked products, crips, noodles, and paste) of stored *amadumbe* corms, flours, and starches.
3. The collected data can be used to model the quality kinetics of *amadumbe* corms, flours, starches as influenced by storage conditions.
4. The data collected can also be used to model the economic impact of the losses in quality attributes of stored *amadumbe*.