

**DETERMINATION OF YIELD PERFORMANCE AND REGENERATION
POTENTIAL OF UPLAND-GROWN ARROWROOT [*Colocasia Esculenta* (L.)
SCHOTT] IN KENYA**

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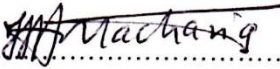
**A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor
of Philosophy in Agriculture of Kenya Methodist University**

SEPTEMBER 2025

DECLARATION AND RECOMMENDATION

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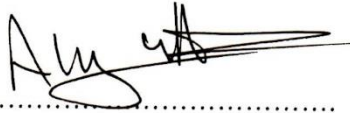
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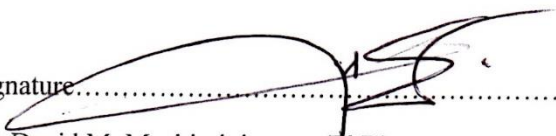
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DEDICATION

This thesis is dedicated to my parents, Esther Wanjiku and my late father, Samuel Macharia, who inspired my love for education despite the challenges they faced.

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ABSTRACT

Despite arrowroot's potential yield, its production in Kenya remains limited, primarily due to the small area available for cultivation and the basic planting techniques employed. The objectives were to determine the optimal planting depth and the most effective GA₃ dosage for inducing propagule production. Field and pot experiments were conducted in 2023 and repeated in the 2024 main cropping seasons at the Teaching and Research station, Egerton University, Nakuru County, to evaluate upland-grown arrowroot for varying planting depths on arrowroot tuber yield and yield components. A field experiment was laid out using a randomized complete block design with four replications. The factors included pit depths of 20 cm, 30 cm, 45 cm, and 60 cm. Data collected included shoot parameters, corm yield, and yield components. The planting depths significantly influenced the corm weight per plant: 60 cm (2.67 kg), 45 cm (2.02 kg), 30 cm (1.24 kg), and 20 cm (0.35 kg) yielded the heaviest corms per plant in fresh weight. The depth also affected shoot parameters significantly ($p \leq 0.05$). The same trend was maintained for corm yields per hectare: 60 cm (44.63 t ha⁻¹), 45 cm (38.43 t ha⁻¹), 30 cm (29.58 t ha⁻¹), and 20 cm (7.54 t ha⁻¹) were significantly different from each other ($p \leq 0.05$). A second pot experiment was conducted in a greenhouse involving two arrowroot cultivars, *Girigaca* and *Kienyeji*. The results show that the interaction between the cultivar and GA₃ was significantly different for the number of rhizomes, length, and number of nodes per rhizome ($p \leq 0.05$). However, the girth of the rhizome was not significantly affected ($p \leq 0.05$). Spraying gibberellic acid (GA₃) at 750, 500, 250, and 100 ppm significantly increased the number of rhizomes produced by *Girigaca*, with a dose of 750 ppm producing the highest number of rhizomes. The *Kienyeji* cultivar failed to produce rhizomes but developed suckers. The interaction between the *Girigaca* cultivar and spraying with distilled water (Control) produced suckers and no rhizomes. Furthermore, a study was conducted to determine the influence of GA₃ treatment on the mother plant on the sprouting capacity, plant height, and leaf area of the plantlets produced from rhizomes. The results showed that the interactions between GA₃ and the media significantly affected the number of sprouts ($p \leq 0.05$), but not the height and leaf area of the plantlets. The outcomes suggest that the rhizomes obtained from arrowroot treated with GA₃ influenced the sprouting of rhizome nodal cuttings. The river sand used for sprouting performed better than the sawdust in the initial growth phases, but the latter is a viable alternative. The study demonstrated that planting depth has a significant impact on the yield of upland arrowroot, with deeper pit depths yielding better results for corm weight and overall production. It is recommended that (1) farmers for upland arrowroot production adopt 30 cm wide and 30 to 60 cm deep moisture pits for enhanced yields, (2) gibberellic acid may be sprayed on potted arrowroot plants for rapid, large-scale rhizome production of suckers. But additional research is needed on cultivar maturity and plant density.

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LIST OF ABBREVIATIONS AND ACRONYMS

ABA	Absciscic acid
AEZs	Agro-Ecological Zones
BA	Benzyl Adenine
BAP	Benzyl Amino Purine
CGR	Crop Growth Rate
CW	Coconut water
DAP	Days After Planting
DAT	Days After Treatment
DW	Dry weight
FAO	Food and Agriculture Organization of the United Nations
FYM	Farm Yard Manure
GA ₃	Gibberellic Acid
IAA	Indole-3-acetic acid
LA	Leaf Area
LAI	Leaf Area Index
NSC	Non-Structural Carbohydrate
PGRs	Plant Growth Regulators
Ppm	parts per million
UN	United Nations
UNESCO	United Nations Educational, Scientific, and Cultural Organization

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Arrowroot [*Colocasia esculenta* (L.) Schott] is recognized as one of the most essential and beneficial root and tuber crops in the world Robbin (2004) as highlighted in a study by Mongi & Chove (2020). This adaptable crop is predominantly farmed and eaten in many regions of Africa, Oceania, and the Orient Tumuhimbise et al. (2009), reflecting its diverse culinary and nutritional applications (Gerrano et al., 2019). The West African region is the leading producer, with Nigeria alone accounting for over 25% of the world's total arrowroot production, according to FAO data from the United Nations for 2020 (Igbozulike, 2015; Oladimeji et al., 2022).

In many rural communities across Africa, arrowroot plays a crucial role in ensuring food security (Nanbol & Namo, 2019). It serves as a subsistence crop for small-scale farmers, generating income Tumuhimbise (2015), which highlights its importance in sustaining local economies and livelihoods (Otekunrin et al., 2021). Arrowroot (*Colocasia esculenta* (L.) Schott), commonly called “Nduma” in Kenya Serem et al. (2008) and taro in Uganda (Talwana et al., 2010) is mainly cultivated in the Eastern Africa region by smallholder farmers for subsistence in the wetlands, marshes, and river banks (Akwee et al., 2015). Arrowroot has been identified as an essential indigenous root crop with tremendous potential to provide food security, improve nutrition, and generate income for rural poor households (Talwana et al., 2009; Otekunrin et al., 2021).

The increasing social awareness of the utilization of indigenous food sources, which are healthy and safe, has led to an increased demand for arrowroot tubers (Mabhaudhi et al., 2013; Oduro et al., 2021). Arrowroot is preferred as a staple food because of its significantly higher energy

starch and protein than all the other central root and tuber crops Tshipamba et al. (2021) in addition to vitamins and mineral salts. It is particularly suitable for consumers with dietary health issues, such as diabetes and hypertension (Orji et al., 2014). It is also recommended for infants and the elderly because its starch grains are tiny and highly digestible than those of other root and tuber crops (Gerrano et al., 2019; Oladimeji et al., 2022).

Arrowroot has been traditionally cultivated by rural small-scale farmers in Kenya for a long time Muthoni and Shimelis (2023); however, its actual contribution to household food, nutrition, and income security is often underrated and overlooked (International Plant Genetic Resources Institute [IPGRI], 2002). Moreover, the country's extent of production and consumption is not fully documented (Akwee et al., 2015). This is because minimal research has been done (Tumuhimbise et al., 2009). Consequently, insufficient information exists regarding the arrowroot value chain Mehdi et al. (2024) particularly regarding the improvement of traditional cropping systems in comparison to integrated climate-smart technologies (Goenaga & Chardon, 1995).

A high demand for arrowroot tubers has not been fulfilled, partly due to low production and poor yields achieved by farmers (Akwee et al., 2015). In Kenya, arrowroot is primarily produced in the Western and Central provinces Uwamariya et al. (2021) where numerous cultivars are distributed across diverse agroecological zones (AEZs). These local cultivars have not been genetically and phenotypically characterized Matthews et al. (2021) and their growth attributes remain unknown to breeders and producers (International Plant Genetic Resource Institute [IPGRI], 2002). Therefore, deliberate studies on the genotypic and phenotypic characterization of existing local cultivars and landraces are likely to have a significant impact on arrowroot production and consumption (Mbouobda et al., 2013; Ogbonna et al., 2015).

Unlike other root and tuber crops, arrowroot has received little attention. It is mainly cultivated informally Bentley et al. (2018); Oladimeji et al. (2022), with no regard for good agronomic practices such as fertilizer application, plant spacing, and planting depth (Ogbonna et al., 2015). These practices have influenced the growth and yields of arrowroot in other regions (Tumuhimbise, 2015).

When arrowroot is grown under rainfed conditions, the subsequent crop after harvesting usually gets insufficient time to mature due to late planting (Ud-Deen, 2009). This is the leading cause of low tuber yield; therefore, innovative growing technologies Serem et al. (2008) that reduce shoot growth time and enhance early tuber formation are needed (Ngetich, et al., 2015). This is likely to increase the yield of late-planted crops, particularly in moisture-stress-prone areas and upland arrowroot crops grown under the current prevailing climate change (Seeda et al., 2021).

Therefore, plant growth regulators (PGRs) can hasten growth and development as reported in other crops (Lolael et al., 2013). The regulation of plant growth through various physiological and biochemical processes is well-documented (Swennen et al., 2014). Therefore, searching for adaptable production protocols to increase arrowroot production Si et al. (2018) will significantly reduce nutritional problems and food scarcity among the population, especially during drought (Bhuiyan et al., 2015).

Gibberellic acid (GA_3) is a plant hormone that regulates vital physiological growth processes in plants, such as root and shoot elongation (Chaudhary et al., 2019). However, its effectiveness depends on the application at the right concentration and time (Saini et al., 2021). Although gibberellic hormone has been associated with the promotion of various plant growth functions Shiwachi et al. (2003) the increase in the number of stolons and leaves may have an impact on sucker emergence and stem elongation, as well as on plant growth processes (Chauhan et al.,

2010). Saini (2021) in a study on the influence of GA₃ on Indian mustard Brassica and Szczepanek (2021) in a study on plant growth regulators for Red Fescue reported that yield was significantly increased.

Another experiment was conducted on the response of potatoes (*Solanum tuberosum* L.) to the application of GA₃, which increased total tuber yield but damaged some tubers (Chindi & Tsegaw, 2019). An earlier study by Swennen (2014) observed that, in addition to enhancing the productivity of plantain bananas, GA₃ application also stimulated sucker development without negatively affecting the mother plant.

Plant tissue culture technology and plant growth regulators Khangjarakpam et al. (2019) have been helpful for rapidly multiplying many vegetatively propagated crops (Hussain & Tyagi, 2006). Therefore, the best approach is to identify innovative technologies that generate sufficient propagation materials through research, which can be used to provide propagules in large quantities to support national food security (Wamalwa et al., 2022).

1.2 Statement of the Problem

Traditionally, arrowroot is cultivated in wetlands and on low-lying riverbanks. These areas are often the dumping grounds or waterways for contaminated wastewater, stormwater, and toxic industrial effluents. Arrowroot is known to trap and accumulate contaminants such as heavy metals or pesticides, which can lead to a multitude of harmful effects on human body tissues and organs. This has discouraged many potential consumers from purchasing arrowroot due to quality concerns and uncertainty about the source of the arrowroot, particularly those suspected of being grown under wetland conditions.

Consequently, cultivating arrowroot in upland areas under rain-fed conditions may ensure safe, healthy, and high-quality production. Moreover, the upland cultivation of arrowroot may mitigate against the contamination and bio-accumulation of heavy metals in arrowroot corms,

ultimately facilitating the conservation of the ever-diminishing wetlands and marshy ecology. Since arrowroot crops require a significant amount of water to produce high yields, growing upland arrowroot will necessitate the use of innovative climate-smart technologies for water harvesting and conservation, particularly in light of the current impacts of climate change. Growing upland arrowroot in round pits maximizes water harvesting and use efficiency, improves crop nutrition, and increases tuberization depth. This will significantly enhance overall tuber crop production (Gweyi-Onyango et al., 2021).

However, the area under arrowroot production in Africa, particularly in Kenya, is relatively small compared to world-leading countries. This is partly due to several limiting factors, including the unavailability of sufficient suitable land with agroecological requirements that match current production systems, as well as the uncertainties associated with climate change. Furthermore, neither inorganic nor organic fertilizers are applied under the present production systems. Therefore, soils are often deficient in essential nutrients necessary for high productivity.

Consequently, because of low yields, arrowroot is usually more costly than the other root and tuber crops. Therefore, it is less affordable to most consumers, despite its preference for other root and tuber crops, due to its nutritional and other health benefits.

To increase the area under arrowroot cultivation, growers face several challenges. To begin with, there is a severe shortage of propagation materials, such as headsets and suckers, to enable farmers to replant and expand their production.

Moreover, arrowroot is mainly grown in limited and protected swamps, marshes, and riparian lands. Additionally, arrowroot has a limited capacity to regenerate quickly, and accessing sufficient planting materials for commercial or large-scale production is challenging. This has adversely affected its propagation and ultimately increased productivity.

Tissue culture technology has the potential to overcome some of these challenges that limit arrowroot improvement and production. In addition, tissue culture technology is the only tool capable of producing large quantities of disease-free planting material on a large scale within a limited period and space, which is not season-dependent, unlike traditional propagation.

However, the multiplication of arrowroot in Kenya has generally been modest under the tissue culture approach. This is partly due to the high cost of production involved and the lack of sufficient information on specific in vitro micropropagation protocols Manju et al. (2017) for local arrowroot cultivars. Whereas that would have been the ideal technology to hasten and enhance arrowroot production in Kenya, the challenges are too significant to expand commercially. Therefore, it is necessary to investigate an alternative method that is effective in initiating the regeneration of arrowroot suckers, ensuring a continuous flow of planting materials through the value chain. This would ultimately encourage farmers and other stakeholders to emerge as permanent producers of arrowroot planting materials. However, research on macro-propagation in arrowroot cultivation is limited, and the available information is scarce (Dantas et al., 2021). Therefore, the outcomes of this study will encourage farmers to adopt the appropriate technologies to ensure increased arrowroot productivity.

1.3 Purpose of the Study

The primary goal is to enhance food security and income among smallholder farming communities in the Country.

1.4 Objectives

1.4.1 General objective

The study aimed to evaluate the yield performance and regeneration potential of upland-grown arrowroot [*Colocasia esculenta* (L.) Schott] in Kenya. This will be achieved by assessing

effective agronomic practices, utilizing moisture pits and plant growth regulators, to enhance food and nutrition security.

1.4.2 Specific objectives

- i. To evaluate the effect of using the moisture retention pit planting technique on the growth and yields of upland-grown arrowroot.
- ii. To determine the effects of different rates of gibberellic acid (GA₃) on the growth and regeneration of two different cultivars of arrowroots.
- iii. To evaluate the effect of the sprouting capacity of rhizome nodal cuttings generated from arrowroot induced by gibberellic acid (GA₃).

1.5 Hypotheses (Ho)

The following hypotheses were tested in this study:

- i. The moisture pit planting technique does not affect the growth and yield of upland-grown arrowroot.
- ii. The application of Gibberellic acid (GA₃) does not affect arrowroot growth and regeneration.
- iii. The gibberellic acid (GA₃) does not affect the sprouting of arrowroot rhizome nodal cuttings.

1.6 Justification of the Study

There is limited information available on upland-grown arrowroots; only a small amount of research has been conducted over the years to address the challenges that hinder production. Arrowroot is considered an indigenous and neglected tuber crop, despite its potential to provide livelihoods, food, and nutritional security, which has often been underestimated. Currently, the demand for arrowroot tubers is high, leading to market prices that exceed those of potatoes,

cassava, sweet potatoes, and yams. This is primarily due to consumers' increasing awareness of the benefits associated with consuming arrowroot. The average on-farm yields of arrowroot have remained low compared to the research output. It is imperative to urgently transform technologies that address these handicaps, as growers encounter several challenges beyond cultural production methods. To begin with, the land reserved for production is often prone to flooding, soil erosion, and landslides; therefore, it is unsuitable for cultivation. Additionally, the types of domesticated arrowroot cultivars available to farmers regenerate very slowly and have a limited capacity to produce propagules. This creates a severe shortage of planting materials for both small-scale and large-scale commercial production, negatively impacting national food security. Furthermore, arrowroot has always been cultivated in places where it faces challenges. For instance, much arrowroot is produced in these encroachment areas, which are often protected wetlands. The form and design of these endangered environments create a more serious challenge when cultivated for arrowroot production. The wetlands are water reservoirs due to their nature and location, which serve as the dumping sites for urban, industrial, and domestic waste, rendering the water and soil around them unsafe and posing a health risk. Therefore, cultivating arrowroot in these environments poses a significant risk to consumers. This has not endeared wider adoption of eating arrowroot due to the inherent fear of poisoning. Mongi & Chove (2020) studied the quality of arrowroot grown in wetlands around the Lake Victoria basin, revealing the containment of heavy metals, such as mercury, arsenic, lead, chromium, and copper. The concentration of these heavy metals in the soil and the arrowroot corms exceeded the maximum recommended levels set by the FAO/WHO (1995) and the EU (2004, 2006), rendering the arrowroot unsafe for human consumption. Njenga et al. (2020) surveyed urban and peri-urban farms in eastern Nairobi, measuring concentrations of Cadmium (Cd), Manganese (Mn), Lead (Pb), and Zinc (Zn) in soils, irrigation water, and arrowroots. Their findings revealed that Cd levels reached 2.5 mg/kg, which is 20 times the

allowable limit, while Mn was found at 71.1 mg/kg, 35 times the permissible limit. Additionally, both Pb and Zn were present at 0.29 mg/kg and 78.8 mg/kg, respectively, exceeding the allowable limits set by the WHO. Due to the aforementioned challenges in cultivating this critical tuber crop, there is an urgent need to develop climate-smart technologies that address the issue of low arrowroot yields by integrating current agronomic practices. Enabling the shift, expansion, and cultivation of upland arrowroot presents a dual advantage: securing high-quality corms and increasing the production area, since reliance on wetlands will no longer limit land availability. The real game changer, however, lies in innovations that accelerate the regeneration and multiplication of planting materials. Existing scientific approaches for rapid arrowroot propagation, such as tissue culture, remain costly and demand highly specialized expertise, factors that constrain accessibility for smallholder farmers. This study addresses these challenges by evaluating practical, farmer-friendly innovations. The research findings indicate that the moisture pit method significantly enhances the yield performance of upland-grown arrowroot. At the same time, the use of rhizome nodes as a propagation technique improves the availability and regeneration potential of planting materials. Together, these strategies offer a low-cost and scalable pathway toward strengthening food and nutrition security through sustainable arrowroot production (Pugalendhi et al., 2020).

To address the arrowroot yield gap and improve food security for vulnerable, poor rural households in Kenya Boakye-Achampong et al. (2017); Hamma et al. (2014), there is a need to shift from swamp to upland arrowroot production to increase acreage. Rain-fed arrowroot farming may be one of the most cost-effective ways to boost output among resource-constrained smallholder farmers, especially when combined with the identification of arrowroot cultivars suitable for a short crop cycle that fits into the double-cropping seasons common in many regions that grow arrowroot (Nwite et al., 2017). Although some researchers

have studied upland arrowroot growth and yield, they emphasized the discrepancies in the results. Due to this, the study aimed to investigate the moisture pit planting method as a suitable approach for producing arrowroot in rainfed environments and the application of plant growth regulators to induce the regeneration of propagules in Kenya's highlands (AEZ III).

1.7 Limitations of the Study

The research focused on selected local arrowroot cultivars sourced from farmers' fields, as the arrowroot cultivars grown in Kenya have not been genotypically characterized. In Kenya, a diverse array of arrowroot cultivars and landraces exists, highlighting the region's rich agricultural diversity. This study focuses on two particular types: Dasheen, known locally as Girigaca, and Eddoe, referred to as Kienyeji. These two cultivars have been selected due to their significant morphological and genetic differences, which provide a unique opportunity for comparative analysis. Additionally, the planting materials of the cultivars were readily available. Therefore, examining the cultivar distinctions, the study aimed to enhance our understanding of their growth characteristics, nutritional profiles, and potential uses in local culinary traditions. Unfortunately, specific vital data for this could not be collected due to unavailable instruments and equipment. Additionally, it was not feasible to replicate the experiments in various locations, ideally with warmer weather conditions and different types of soil, which would have provided a broader perspective on the study's findings.

CHAPTER TWO

LITERATURE REVIEW

2.1 Broad Description of Arrowroot

Arrowroot [*Colocasia esculenta* (L.) Schott] has many names depending on the Country or region where it is cultivated (Anonymous1 (2006-2024). For example, it is referred to as taro or cocoyam (West Africa), eddoe (Barbados), Arrowroot (Kenya), Kolkas (Egypt), Dalo (Fiji), Hako (Hawaii), Yu-tao (China), Mukhi Panikachu (Bangladesh), eddoe taro (Indonesia) or dasheen, and an array of local names (Laishram et al., 2019). Arrowroot is believed to have originated from India, as the primary centre of domestication, and then spread to East, Southeast, or Central Asia (Oladimeji et al., 2022). Other scholars claim New Guinea may have been the secondary centre of domestication Anonymous1 (2006-2024); Ivancic & Lebot (2000) or Indo-Malayan area Lakitan et al. (2022) therefore, there is no consensus on the centre of origin.

Arrowroot is a perennial, tropical herbaceous plant that is classified as Liliopsida (*class*), Arales (*order*), Araceae or aroids (*family*), with two genera - taro (*Colocasia esculenta*) and tannia (*Xanthosoma sagittifolium*) Fitriani et al. (2016) and Otekunrin et al. (2021) is a central subtropical and tropical root and tuber crop in utilization according to (Bogale, 2018). Arrowroot is primarily cultivated for its corms or tubers. To a lesser extent, leaves and stolons Si et al. (2018) are virtually the whole arrowroot plant that is edible by humans or animals (Tumuhimbise, 2016). The corm is processed into various products: flour, chips, syrup, and starch. The latter is particularly significant because of its physical and functional properties for industrial use (Igbozulika et al., 2015).

The dominant cultivated arrowroot genera are *Colocasia*, species *esculenta* (taro), and *Xanthosoma*, species *sagittifolium* (tenia) (Hill et al., 1939; Hunt et al., 2002). Other species of

arrowroot include *Alocasia* and *Cyrtosperma* (Fitriani et al., 2016). The largest Arrowroot-producing region in Africa is West Africa Legesse et al. (2021), while the rest of the areas have negligible production.

Arrowroot is a perennial plant that is grown annually; it is a Liliopsida plant that grows to approximately 2 m (Otekunrin et al., 2021). Its leaves are simple, broad, and roughly heart-shaped (Oladimeji et al., 2022). The size varies from medium to large, with a dark green, smooth surface and a light green underside. Sometimes the leaves have a purple or red tinge. The corms or tubers are round to globular in shape, and their size varies significantly (Anonymous, 2006-2024). They are also covered with brown skin and roots (Osundare et al., 2015). The flesh ranges from pinkish, purple, beige, or white. Arrowroot requires seven months in hot weather and slightly longer in cool weather (Ud-Deen, 2009). This crop is a central tropical root and tuber crop, usually grown as a source of carbohydrates (Iwuagwu et al., 2017). Arrowroot is also presently being grown for export in major producing regions for industrial applications Boakye et al.(2018), since its starch has multiple uses in the food industry (Otekunrin et al., 2021).

The primary purpose of growing arrowroot is to provide food as a root vegetable, where the corms are steamed, boiled, fried, baked, and stewed. In some countries, leaves, stems, and petioles are also eaten. The arrowroot corms are processed into flour and used to produce other high-value products, such as bread, cookies, baby food, and pasta (Igbozulike et al., 2015). Arrowroot is a customary staple root and tuber crop, frequently grown among small-scale rural farmers with inadequate access to resources and technological information. Previously, arrowroot was considered a crop for the impoverished Tajudeen et al. (2019), whose cultivation and consumption were primarily associated with rural poor communities. However, it is consumed across socioeconomic statuses (Akinfenwa, 2017). Arrowroots are higher in protein

than sweet potato, cassava, potato, and yams Tshipamba et al. (2021) and contain essential vitamins and mineral salts.

Despite the many benefits of consuming arrowroots, large-scale cultivation has remained insignificant compared to other root or tuber crops. This is due, in part, to low production, a problem associated with access to suitable land and scarcity of planting materials, as well as the level of technology required for scaling up (Tshipamba et al., 2021).

2.2 Arrowroot Taxonomy

Originating in Northeastern India and Asia Macharia et al. (2014) and likely spreading worldwide, the species reached Central and South America Rashmi et al. (2010), where it is believed to have been domesticated from its wild ancestors (Ahmed et al., 2020). The botanical variety referred to as *Colocasia esculenta* (Arrowroot) is cultivated throughout the tropics and some temperate climates, and is thought to have been introduced to Africa either from Asia via North Africa or Madagascar Sharv (1976) before spreading to the rest of the regions by slave traders. Many authors agree that the domestication of arrowroot may have occurred in multiple areas, as its wild precursors are widely distributed across the globe (Oladimeji et al., 2022). Arrowroot or true taro is among the few edible arum genera in the Araceae family (Tumuhimbise et al., 2009; Boampong et al., 2020).

Initially, it was classified into two species called *Colocasia esculenta* and *Colocasia antiquorum* Chauhan et al. (2010) which are extensively cultivated in the genus *Colocasia* (Boakye-Achampong et al., 2017). However, there exists confusion in distinguishing the types of arrowroot grown in East Africa, unlike the case in Nigeria, where the distinction of the species is clear, and the two edible aroids, Taro and Tannia, are well-categorized (Prativi et al., 2014). They are erect, herbaceous, monocotyledonous, and perennial root crops and belong to the *Araceae* family.

Arrowroot [*Colocasia esculenta* (L.)] is related to other common species, such as Xanthosoma and Caladium, which are grown as ornamentals and sometimes found on riverbanks as cover vegetation (Zulkhairi et al., 2020). Arrowroot is also known as taro or cocoyam, which is sometimes used interchangeably for taro or eddo in West Africa, mistakenly called “arrowroot in East Africa, and eddoe or dasheen in the Caribbean and Asia, and Mukhi Kachu in Bangladesh and India, where it exists in over 100 genera in more than 1,500 species (Mandal et al., 2013). However, not all family members are edible because many contain high levels of anti-nutrients in the corms and leaves (Maretta et al., 2020). These oxalate compounds cause itching and have adverse health effects, including the formation of kidney stones, which can lead to renal disorders (Uwamariya et al., 2021; Rashmi et al., 2018). However, the cultivated, improved cultivars have low amounts of calcium oxalate, which can be easily removed before consumption by soaking in water and thoroughly cooking or boiling (Uwamariya et al., 2021).

2.3 Morphology Characteristics

Morphologically, Arrowroot is differentiated according to its phenotypic characteristics of corm, leaf, and petiole appearance (Rashmi et al., 2018). Lebot (2010) and Zulkhairi (2022) have stated that the diversity of arrowroot according to the color of flesh, shape, and size of the corm, petiole length, and color, and stolon development is mainly determined by their Centre of origin Lloyd et al. (2021) therefore influenced by the genetic constitution of the cultivar. Generally, leaf color ranges from dark green on the upper side to pale green on the underside, with a diverse tinge of purple. The leaf petiole color ranges from purple to green or a mixture of both, while the corm flesh color ranges from pink to yellow to white, with or without fibers (Oladimeji et al., 2022).

2.4 Leaf

Arrowroot produces three to four leaves at a time, with the younger ones at the center and the older ones at the outer part of the stem. Depending on the cultivar and growing environmental conditions, the arrowroot plant produces 24-40 leaves in its lifetime Anonymous (2006-2024). The leaf sprouts from the rhizome underneath, creating a triangular-ovate, sub-rounded, and mucronate apex, with the tip of the basal lobes rounded or serrated and supported by a sheathing petiole at the base (Wulansari et al., 2021). The lamina is approximately forty centimeters long and twenty centimeters wide, depending on the type and availability of growth factors. The arrowroot leaf is normally arrowhead-shaped or elephant ear-like, with a dark green, smooth upper epidermis and light green lower epidermis, which has vascular vessels fanning from the midrib vessel where the petiole connects the blade with the leaf base. The leaves are covered with a waxy layer of small structures called papillae, which repel water, rendering the leaf hydrophobic. The leaves are held upwards by strong, erect petioles that grow to lengths of about two meters. Due to the presence of high anti-nutrient compounds, the leaves are not widely consumed in Kenya, despite being rich in protein, minerals, vitamins, and dietary fiber, and can be fed to livestock. Therefore, arrowroot (*Colocasia esculenta* L.) is the primary type cultivated in Kenya, purposely for the corms as a source of root carbohydrates. The consumption of leaves as a vegetable is not widely practiced, probably due to their anti-nutrient properties that are difficult to overcome. However, utilization of the leaf of arrowroot would positively complement the high carbohydrate content of the corm, which is the main staple food, since the leaves are rich in antioxidants, particularly Quercetin from the pigmentation of arrowroot vegetation (Muthoni & Shimellis, 2023).

2.5 Corm

Arrowroot is a tuber crop used mainly for human food. It belongs to the *Colocasia* or *Xanthosoma* genus, which typically forms cylindrical or spherical corms or tubers covered with brown skin and leaf scales or hairs, with pink, beige, or white flesh (Anonymous, 2006-2024). The leaves emerge from growing tissues at the tip of the tuber. The corms or tubers are usually short stems filled with food storage tissue (Osundare & Fajinmi, 2015). Sometimes, depending on the type or variety, arrowroot corms have lateral buds which produce cormels, suckers, or stolons, which are underground rhizomes (Rashmi et al., 2018). Arrowroot is often grown as a short annual, even though it is a perennial plant, and is harvested after one season, typically between seven and twelve months after planting. At maturity, depending on the growing conditions and the arrowroot cultivar, indicated by the beginning of shrinking, yellowing, and dying back of leaves, the “mother” plant produces young side-plantlets called suckers, which usually are separated from the parent and grown as new plants (El-Sayed et al., 2016).

2.6 Sucker

Arrowroot is propagated vegetatively using either headsets, also called tops, or large suckers, which are the preferred method; the use of stolons as planting material is less common than headsets and suckers. They usually have small shoots (Setyawan et al., 2021). For the successful cultivation of arrowroot, regardless of the planting material used, it must be sourced from a healthy crop (Akwée et al., 2015). The choice of a sucker as the predominant planting material for arrowroot is because of its abundance and availability (Diaguna et al., 2023). According to Bhende and Kurien (2015), all suckers can be used for propagation. Still, large ones are preferred because they contain an apical bud, exhibit rapid growth, and have a high rate of survival, ultimately producing high tuber yields (Gondim et al., 2018). The number of arrowroot plant suckers produced varies from none to a few or more (Blomme et al., 2000).

The cropping system, which involves planting and marketing corms for specific purposes, dictates the ultimate number of suckers needed in a plantation (Nwite et al., 2017). A good cultivar must maintain a balance between the quality of the corms produced and sufficient suckers for replanting and expanding arrowroot plantations (Yadav et al., 2011). However, where the standard practice is to propagate both headsets and suckers, a minimum number of suckers per plant will suffice (Otekunrin et al., 2021). Alternatively, where farmers can only plant suckers due to the unavailability of headsets, losses occur.

The life cycle of arrowroot consists of three growth stages: establishment, vegetative, and maturity (Ud-Deen, 2009). The suckers generated in each of these stages will have different characteristics, such as size and point of attachment, which influence the corm growth and quality of the sucker as planting material (Ndion et al., 2003). The suckers produced during the vegetative growth stage are attached more deeply to the corm, have broader bases compared to those formed during the maturity growth stage, which are attached shallowly, have narrower bases, and are easier to remove for subsequent crop planting. This is the reason they are preferred (Lakitan et al., 2022).

Consequently, sucker prolific cultivars are sometimes selected when arrowroot is grown using the farmers' practice of minimum resource input, targeting the production of small arrowroot corms (Tumuhimbise et al., 2009). However, in only a very few arrowroot production systems is a high sucker number a desirable character. For instance, when arrowroot is grown in fields prone to flooding during the rainy seasons, producing small-sized corms is acceptable to farmers and consumers. In such a scenario, the corms from the sucker contribute to the overall marketable yield (Sunitha et al., 2013).

2.7 Anti-nutritive properties of Arrowroot

Recent studies on identifying potential crops to mitigate hunger and micronutrient deficiency Gregory et al. (2017) have proposed arrowroot (*Colocasia esculenta* L.) as a candidate due to its status as a nutrient-rich superfood. Moreover, arrowroot contains a high amount of anthocyanin compounds that possess antidiabetic, anticancer, antimicrobial, and anti-hypertensive properties, thereby reducing the risk of heart disease (Maretta et al., 2020). Furthermore, arrowroot contains other compounds such as polyphenols and antioxidants, which combat cancer growth and oxidative stress. Arrowroot tubers' high fiber and resistant starch protect against colon cancer and inflammatory diseases (Kaushal et al., 2015). However, the widespread consumption of arrowroot has been prevented by the presence of antinutrient substances such as; oxalate, phytate, and tannin Rashmi et al. (2018) and Modi et al. (2007) that cause a toxic reaction when any part of the arrowroot plant; leaf, petiole or corm is consumed raw Uwamariya et al. (2021), arrowroot like all members of Araceae family are thus, considered toxic Buntha et al. (2008) since there is a possibility of bioaccumulation of heavy metals in arrowroot corms due the association of anti-nutrients and soil trace elements that influence the level of toxicity (Idowu-Adebayo et al., 2015; Uwamariya et al., 2021).

2.8 Arrowroot Production in Kenya

Arrowroot production is insignificant compared to other countries in Africa Akwee et al., 2015), despite its potential to improve farmers' food security status and income Serem et al. (2008), as well as its cultivation under a traditional system for centuries (Muthoni & Shimelis, 2023). The lack of recognition of arrowroot as a necessary root and tuber crop may be attributed to its unique agroecological requirements. The significant regions cultivating Arrowroot include Nyanza, Western, Central, and Eastern Provinces (Njuguna et al., 2023). Studies have shown that farmers have the knowledge and skills to grow crops (Tumuhimbise, 2015).

However, suitable land scarcity, lack of improved cultivars, and a source of propagation materials have hampered the growth and expansion of Arrowroot production (Macharia et al., 2014).

2.9 Production of Arrowroot Worldwide

There are various types and species of arrowroot cultivated worldwide; the two most widespread include the old-taro (*Colocasia esculenta*), primarily grown in East Africa, and tannia (*Xanthosoma sagittifolium*), mainly grown in West Africa (Norman et al., 2022). The arrowroot crop is an excellent source of dietary fiber and carbohydrates, with high protein levels, vitamins, and minerals (Maretta et al., 2020). It also has multiple industrial applications, as it provides ingredients for the development of various products. The crop can grow under diverse climatic regimes from equatorial tropics to temperate zones (Ndon et al., 2003). In many regions, the demand and consumption of arrowroot tubers have increased because of the prevalence of traditional foods (Igbozulike, 2015). In Ghana, for instance, the current output of arrowroot exceeds demand, which exacerbates the deficits of cereal grains (Tajudeen et al., 2019). Arrowroot is produced and used in both human food and animal feed (Setyawan et al., 2021) and is currently being considered for industrial applications due to its starch and non-starch polysaccharide properties (Igbozulika, 2015; Laishram et al., 2019).

One of the significant challenges of mainstreaming arrowroot production into national food production systems in many countries, especially in Africa, is the perishability of the harvested corms, which have a short shelf life (Diaguna et al., 2023). Consequently, severe post-harvest losses result from the damage caused by lifting and gathering, which is exacerbated by the lack of appropriate storage facilities (Nuani et al., 2022). The storage of arrowroots requires a cool, dry, and well-ventilated environment with very low temperatures (Seedat et al., 2021).

However, many traditional methods are used for short-term storage; otherwise, severe losses occur.

Since arrowroot production is primarily located in rural areas and undertaken by resource-poor farmers, the production remains low due to various factors, including land shortages for expansion. This is because the current arrowroot production systems are restricted to wetlands, which are also protected natural resources. Therefore, to fully realize the potential of Arrowroot as a contributor to food security and industrial applications, appropriate technologies must be developed to mitigate existing constraints (Owusu-Darko et al., 2014; Fitriani et al., 2016).

2.10 Arrowroot Regeneration Techniques

The local arrowroot cultivars are conventionally propagated using headsets, and to a lesser extent, suckers are also planted (Akwee et al., 2015). However, there are serious challenges in obtaining enough supply of either of the planting materials because arrowroot cultivars are both slow and poor in regeneration (Bhuiyan et al., 2015). Therefore, seeking a quick and prolific technique to produce propagules is inevitable. A more suitable tool, such as plant tissue culture, should be adopted to increase the availability of arrowroot planting materials rapidly. This will ensure a continuous supply of high-quality and sufficient propagules, thereby reducing the constraints on planting material availability (Deo et al., 2009; Tamimi & Othman, 2020). In contrast, the conventional propagation or natural production of suckers and headsets is not feasible for large-scale production (Bogale, 2018). However, this technology has serious challenges due to a lack of skills among adopting farmers and other propagators. The cost of equipment and chemicals needed is also prohibitive (Ubalua et al., 2016).

Consequently, a more practical technique for the rapid multiplication of arrowroot, such as macropropagation, has been widely utilized in banana multiplication (Opata et al., 2020). Like bananas, arrowroot is mainly produced through vegetative propagation. Therefore, if

contamination is minimized, it may be possible to apply similar macropropagation techniques to rapidly multiply the relatively healthy arrowroot plantlets. It can also be launched locally by an individual or an organization with few training requirements. Macropropagation is probably a more appropriate technique for regenerating planting materials because it is simple and cost-effective in producing large numbers of arrowroot seedlings (Tshipamba et al., 2021).

2.11 Current Arrowroot Regeneration Techniques

The traditional methods of propagating arrowroot, which involve the use of headsets and sucker shoots from the parent plant Tumuhimbise et al. (2016) reflect the deep-rooted knowledge of agriculture. However, these methods face significant obstacles as arrowroot cultivars are notably slow to regenerate Wulansari et al. (2012) and demonstrate a poor propagation rate, which complicates the search for a reliable supply of planting materials. This challenge requires the development of a faster and more efficient technique to produce a large quantity of propagules.

Researchers have explored advanced conventional multiplication techniques to increase planting materials by manipulating corms and cormels; however, the results have yet to meet expectations (Opata et al., 2020). The potential of tissue culture and *in vitro* techniques presents an alternative (Acedo et al., 2018). However, the high costs and need for technical expertise have limited their widespread adoption (Sagoe et al., 2018).

The genuine opportunity lies in developing practical tools and methodologies for the swift proliferation of arrowroot planting materials that can be readily embraced by the farming community (Njuguna et al., 2023). This would ensure that farmers have access to high-quality and healthy propagules. This is crucial as we face the demands of large-scale agricultural operations, which require a steady supply of planting materials (Manju et al., 2017).

Conventional methods, however, struggle to sustain the volume needed for extensive cultivation.

Recognizing the challenges in implementing modern propagation technologies, particularly the lack of technical skills and the financial burdens associated with advanced methods, the emergent macropropagation methodology arises as a possibility for the rapid multiplication of arrowroot, proving effective in banana production (Tumuhirwe et al., 1993). Since arrowroot primarily propagates through vegetative methods, adapting macropropagation techniques could enhance the proliferation of arrowroot plantlets, nurturing healthier plants and reducing contamination risks (Tshipamba et al., 2019).

This approach is accessible, requiring only minimal training for individuals or organizations eager to adopt it. The macropropagation technique offers a simple and cost-effective solution for generating large quantities of arrowroot plantlets (Weerainghe et al., 2003). It positions growers to meet the rising demand for planting materials while championing sustainability and efficiency in the cultivation of arrowroot.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Experiment 1: Effect of Moisture Pit Planting Technique on Growth and Yield of Upland-grown Arrowroot

Introduction

The traditional practices of growing arrowroot are based on wetland, swamp, and riverbank environments characterized by constantly moist soils, poor root aeration, and small, shallow planting holes. The propagation in the ongoing farm is intertwined with harvesting, making agronomic practices such as applying organic or inorganic fertilizer impossible. Additionally, recycling planting materials in the same planting holes without disinfection can lead to the buildup of diseases and soil-borne pests. Growing arrowroot in the upland environment will require modifying the planting holes by making them broader and deeper to capture water, exposing the growing shoot to light, and incorporating organic manure, fertilizer, biochar, and mulch into the hole to ensure moist conditions in the root region. The study aimed to determine the effect of planting depth on the growth and yield of upland-grown arrowroot.

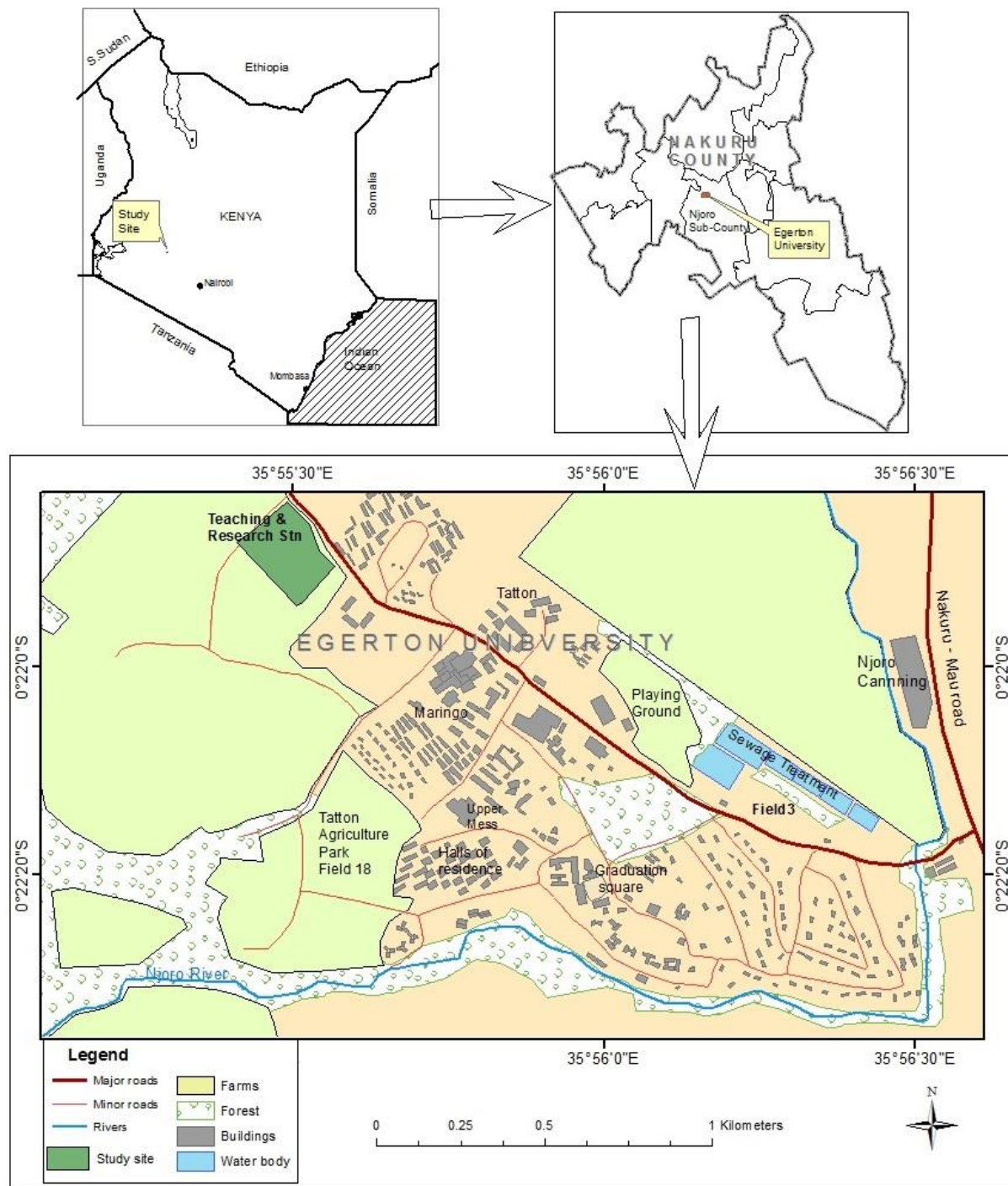
3.1.1 Description of the Study Area

The field experiment was conducted for two seasons (2023 and 2024) at the Agronomy Teaching and Research field Station, Egerton University, Njoro Campus, 22 km West of Nakuru City, located at 0°22'11.0"S, 35°55'58.0"E (Latitude: -0.369734; Longitude: 35.932779), and approximately 2,267 meters above sea level (Figure 3.1). The soils are free-drained and red-brown. They are categorized as *mollic phaeozems* in Agro-ecological zone III (AZE) of Kenya FAO (2014) and Jaetzold et al. (2006), with annual rainfall between 950 and 1,500 mm. They are distributed in bi-peaked seasons, with one peak commonly from March to

August and the second from September to November. The yearly average temperature ranges from 8°C to 23°C (FAO-UNESCO, 1994; Jaetzold et al., 2010).

Figure 3.1

Map of the Study Area



3.1.2 Experimental design, treatments, and field layout

This study employed a factorial experiment in a randomized complete block design (RCBD) as shown below, where the main factor was moisture pit depth with four levels (20 cm, 30 cm, 45 cm, and 60 cm), and the secondary factor was season with two levels (Clewer & Scarisbrick, 2001). The following number of days after planting (DAP) was taken to sample and record data for the growth parameters: 60, 120, 180, and 240. The experimental plots measured 3 m x 4 m (12 m²) with four replications. The arrowroot plants were spaced at 0.5 m intra-row and 1.0 m inter-row distances. The treatments involved planting arrowroot headsets into moisture pits with a diameter of 15 cm and 30 cm for the control and test, respectively.. The moisture pit depths tested were 20 cm (T1) control, i.e., farmers' practice. The study treatments were 30 cm (T2), 45 cm (T3), and 60 cm (T4). The headsets had a basal diameter of between 3 and 5 cm, with 2 cm of the corm remaining attached to the headset, along with a 30 cm stem comprising trimmed leaf petioles used for propagation. The moisture retention pits were dug using a machete and a hole-digger, separating the topsoil from the subsoil. The topsoil was reintroduced to the pit after being mixed with organic compost manure, organic fertilizer, and rice straw biochar during the subsequent pit refilling process (Dantas et al., 2021).

The prepared propagation materials (headsets) were planted at the depth of the moisture retention pit. This was done gradually using topsoil mixed with organic compost manure and biochar at rates of 10 and 5 tons per hectare, respectively. A commercial organic fertilizer (Evergrow Organic Fertilizer, manufactured by Farm Star, Kenya) was added to each pit at a rate of 500 kg per hectare. The mixture was filled back into the moisture retention pit at the base of the headsett to a height of about 10 cm and firm. The rest of the pit was mulched with chopped dry maize stovers at 10 t/ha (Njuguna et al., 2023; Bekeko, 2013). The re-filling procedure was repeated until the moisture retention pit was filled, and the shoot emerged above

ground. Care was taken while refilling the pits to ensure the headset was not covered with soil or mulch (Figure 3.2). The field was maintained weed-free through hand-weeding three times.

Field layout and randomization

Rep 1	1 T3	2 T2	3 T1	13 T4
Rep 2	4 T1	5 T3	6 T2	14 T4
Rep 3	7 T4	8 T3	9 T2	15 T1
Rep 4	10 T3	11 T1	12 T4	16 T2

The layout has four pit depth treatments ($T_1 = 20$ cm, $T_2 = 30$ cm, $T_3 = 45$ cm, and $T_4 = 60$ cm) and four replications.

Linear experimental model

$Y_{ijk} = \mu + D_i + S_j + B_k + DS_{ij} + \epsilon_{ijk}$, where;

Y_{ijk} = response, μ = mean,

D_i = Effect due to pit depth, S_j = Effect of seasons,

B_k = Effect due to blocking, DS_{ij} Interaction of pit depth and season,

ϵ_{ijk} = Random error

Figure 3.2

Upland-grown arrowroot planted in moisture pits



A: Moisture pit planting



B: Experimental field layout



D: Harvested corm and cormels



C: Mother plant with suckers

Figure 3.3

Harvested arrowroot corms, cormels, and headsett

A: Cormel, corm, sucker and headsett



B: Harvested corms



D: corm



C: Upland (L) and wetland (R)

3.1.3 Data collection

Growth Parameters

The growth parameters were evaluated at 60, 120, 180, and 240 days after planting (DAP) for two cropping seasons. These included: height, length, and width of the leaf and the number of leaves, stem girth, distance between mother plant and sucker, and number of suckers per plant. The number of leaves produced was counted cumulatively, from the oldest to the newly fully opened leaves. The height of the plant was measured from the base of the plant at ground level to the sharp end of the tallest leaf stalk using a tape measure. The number of suckers was counted cumulatively until the time of harvesting. The horizontal distance between the mother plant and the suckers was measured using a tape measure for all the suckers after emergence. The leaf area was established by measuring the length and width of three fully opened leaves per plant (tagged) in each sample. The final data were collected at 240 days after planting (DAP), and harvesting was done immediately by digging out a sample of six plants per treatment (Figure 3.3). The arrowroot leaf area was derived from the non-descriptive method (Biradar et al., 1978); Hisiu-Ying et al., 2004; Stoppani et al., 2003; which was calculated using the equation outlined by Agueguia (1993) as follows:

$LA = 0.75 \times L \times B$, where LA is the leaf area, 0.75 is the leaf area coefficient, L is the length from the petiole-attaching point to the leaf apex, and B is the widest leaf width passing through the petiole-attaching point and perpendicular to the leaf apex.

Similarly, Leaf area index (LAI) was determined by the equation expressed by Watson (1947):

$$LAI = [\text{Total leaf area (cm}^2\text{)} / \text{ground cover of the plant (cm}^2\text{)}]$$

Yield parameters

After harvesting six plants sampled from each treatment, corms and cormels were cut off to separate them from the tops. The length of the corm was measured from the posterior end to where the exterior leaf stalk is attached to the anterior of the corm. The corm diameter and girth were estimated at the cut-end and the widest part of the corm, respectively, using a Digital Vernier Caliper 150 mm (6 inches) Stainless Steel (Sunrom Electronics/Technologies, Ahmedabad, Gujarat 382445 India). The fresh weight of corms and cormels was measured using a digital balance (Model WEBW-3131-2). The corm and cormel yield per plant and total corm yield per 3 m² subplot were weighed (Figure 3.3), and the estimated corm yield (tons per hectare) was determined as per Equation:

$$\text{Corm yield (t /ha)} = [10,000 \text{ m}^2 \times \text{WC} / 3 \text{ m}^2] / 1,000$$

Where WC = weight of corm (kg) from a 3 m² harvested subplot

The data were collected from six randomly selected plants, tagged in each plot, and recorded at 60, 120, 180, and 240 days after planting (DAP).

3.1.4 Statistical analysis

The data obtained in this study were first subjected to normality tests before analysis. After satisfying the normality assumptions, the data were analyzed using SAS Software version 9.4. Analysis of variance (ANOVA) was performed to test the experimental hypotheses. Means were then separated using Tukey's HSD method, and Pearson's correlation coefficient was calculated to assess the strength of the relationship between response variables at a 95% confidence level.

3.2 Experiment 2: Effect of Gibberellic Acid (GA₃) on Growth and Regeneration of Select Arrowroot Cultivars

Introduction

Arrowroot is propagated through vegetative means using planting materials called a headsett, sucker, and stolon. The headsett is made from the mother plant by trimming leaf stalks with a small piece of corm or cormel. At the same time, the mother plant may produce suckers and stolons as secondary plants. The reported research indicates that the arrowroot plant has a very low multiplication ratio Asante et al. (2022), therefore, bulking sufficient planting material for scaling up production is a challenge. The greenhouse experiment aimed to evaluate the influence of foliar application of gibberellic acid (GA₃) on the growth and regeneration of selected local arrowroot cultivars, as well as the viability of the subsequent propagules produced.

3.2.1 Description of the study area

The experiment was conducted at Egerton University, Department of Crops, Horticulture and Soils, Teaching and Research Field Station. The site is located at 0°22'11.0"S, 35°55'58.0"E at an altitude of 2,267 m above sea level. The soils in this area are well-drained and exhibit a red-brown hue. They are classified as mollic phaeozems within Kenya's Agro-climatic Zone III (AZE) FAO (2014), receiving annual rainfall between 950 and 1,500 mm. This rainfall follows a bi-peak season distribution, with the first peak season from March to August and the second peak season from September to November. The average yearly temperature ranges from 8°C to 23°C (FAO-UNESCO, 1994; Jaetzold et al., 2010).

3.2.2 Design, treatment, and greenhouse layout

The experiment was carried out using a randomized Complete Block Design (RCBD) arranged in a split-plot design with four replications. The main plots consisted of cultivars, and the

subplot GA₃ treatments were applied at four different concentrations: 100 ppm, 250 ppm, 500 ppm, and 750 ppm, with distilled water serving as the control (0 ppm). A commercial grade gibberellic acid (GA₃) *a.i.*, traded as WOPRO 4 % (Charles Gerard Limited, Kenya), was the plant growth regulator (PGR) used in this study for growth, corm yield, and propagation material regeneration. There were five concentration levels of gibberellic acid (GA₃) treatments: 0 (control), 100 ppm (100 mg/l), 250 ppm (250 mg/l), 500 ppm (500 mg/l), and 750 ppm (750 mg/l), and two arrowroot cultivars were selected; *Girigaca* (ex-Murang'a), Dasheen type, and *Kienyeji* (ex-Nyeri), Eddoe type. The diluted gibberellic acid (GA₃) was sprayed using a fine mist pump at the initial growth stage, 60 days after planting. The potted plants were maintained in the greenhouse for 120 days and then transferred to the shade (50% lighting) until maturity, 240 DAP.

Greenhouse layout and randomization

Replicate 1	Girigaca	T4	T1	T5	T2	T3
	Kienyeji	T3	T4	T2	T1	T5
Replicate 2	Kienyeji	T2	T3	T1	T4	T5
	Girigaca	T5	T1	T4	T3	T2
Replicate 3	Girigaca	T1	T4	T3	T5	T2
	Kienyeji	T4	T5	T1	T2	T3
Replicate 4	Kienyeji	T3	T2	T5	T1	T4
	Girigaca	T2	T5	T4	T3	T1

T1 = 0 (dist.water), T2 = 100 ppm, T3 = 250 ppm, T4 = 500 ppm and T5 = 750 ppm.

Row = Main plot (Cultivar); Cell = Sub plot (GA₃ dose)

Linear model

$$Y_{ijk} = \mu + R_i + C_j + (R \times C)_{ij} + G_k + (C \times G)_{jk} + \varepsilon_{ijk}$$

Where:

μ = overall mean

R_i = effect of replicate

C_j = effect of cultivar - Main-plot factor

$(R \times C)_{ij}$ = overall-plot error term

G_k = GA₃ level effect - subplot factor

$(C \times G)_{jk}$ = cultivar $\times$ GA₃ interaction

ε_{ijk} = subplot error term

3.2.3 Greenhouse crop management

The potted plants were grown in black high-density polyethylene (HDPE) measuring 30 cm by 30 cm. The potting mixture consisted of topsoil, pumice, and P-fortified compost manure in a 2:1:1 ratio. The rice-husk biochar and commercial organic fertilizer (Evergrow Organic Fertilizer, Manufactured and distributed by Farm Star Brand, Kenya) were added at 150 g and 100 g, respectively. The two local arrowroot cultivars planted were *Girigaca* (ex-Murang'a), Dasheen type, and *Kienyeji* (ex-Nyeri), Eddoe type. The planting materials consisted of headsets of uniform height, 30 cm, and a 3 to 5-cm bottom diameter, ensuring experimental uniformity in potted plants (Figure 4.18). The plants were watered regularly at intervals of 7 days using watering cans.

3.2.4 Growth parameters measurements

The growth measurement methods described by Hunt et al. (2002) were employed to evaluate plant growth, corm yield, and yield components at the primary maturity stages. After establishment, five potted arrowroot plants were randomly tagged for data measurements in every treatment and replication. The sampling periods were 60, 120, 180, and 240 days after treatment with GA₃ (days after treatment, DAT). The plant samples were separated into leaves,

petioles, roots, rhizomes, corms, cormels, and suckers for measuring plant height (cm), number of leaves, stem girth, leaf length, and width. The following corm traits were measured: diameter, length, girth, and weight. The rhizome and sucker counts, as indicated by the arrowroot plants, were determined for each treatment in each sampling cycle (Figure 4.20). Furthermore, the number of nodes per rhizome for each plant was also counted. The arrowroot shoot (leaves and petioles) was evaluated for damage due to the effect of GA₃ treatment; it was visually determined using a 1-5 rating, where 1 = standard terminal leaf and petiole growth, 2 = slight terminal leaf deformed and retained, 3 = terminal leaf folded, scorched, and retained, 4 = severe terminal leaf damage and broken petiole, 5 = shoot decapitation or dead. The root and corm samples were oven-dried at a temperature of 65 °C using a Dry type bacteriological incubator with gravity convection, manufactured by Blue M Electric Company, Blue Island, Illinois, U.S.A. (STABIL-THERM). This process was performed after harvesting.

3.2.5 Statistical analysis

The data obtained were subjected to a normality test and a homogeneity test to assess cleanliness before analysis using SAS Software version 9.4. Analysis of variance (ANOVA) was conducted to test the study hypothesis at a 95% confidence level. *Post-hoc* analysis was done using Tukey's method. The analysis examined treatment effects and comparisons by evaluating the Pearson correlation among different dependent variables.

3.3 Experiment 3: Evaluation of Sprouting Capacity of Gibberellic Acid (GA₃) Induced Rhizomes

Introduction

Arrowroot is usually vegetatively propagated by the use of headsets or suckers. These planting materials are insufficiently available to establish a large area of land. This study involved the Arrowroot rhizomes generated by a local cultivar (Girigaca) after treatment with different doses of gibberellic acid (GA₃) in the greenhouse. This experiment aimed to investigate the capacity of rhizome nodal cuttings to sprout and develop into new plantlets that could be used for propagation. The procedure was formulated to establish a protocol for a new propagation technique.

3.3.1 Experimental design and treatment

The experiment was conducted at Egerton University, Department of Crops, Horticulture and Soils, Teaching and Research Field Station. To provide favorable conditions for rooting and growth, high temperature and humidity were provided by building wooden rooting chambers, which were covered with a 1000-gauge transparent polyethylene sheet (Manufactured by Grekkon Ltd, Nairobi, Kenya). A shade was later installed above the chambers, featuring a 50% sun-safe black agro-shade net, to protect the tender, sprouting plantlets from strong sunshine.

The size of each rooting chamber was 1.2 meters (width) x 3 meters (length) x 1 meter (height). The rooting chambers were covered with transparent polyethylene sheets to maintain high temperature and humidity (Figure 4.21). The experiment was conducted in a Completely Randomized Design (CRD) with three replications. Only one of the two arrowroot cultivars, Girigaca (Ex-Murang'a), the Dasheen type, was tested in this experiment, because the second

cultivar, *Kienyeji* (ex-Nyeri), Eddoe type, failed to produce rhizomes after treatment with foliar-applied gibberellic acid during the previous greenhouse experiment.

The two factors studied in the experiment were the sprouting of nodal cuttings obtained from rhizomes and the type of rooting media. The one arrowroot cultivar (Girigaca) grown earlier in the greenhouse experiment provided the rhizomes for sprouting (Figure 4.20). One hundred plastic bags, each measuring 15 cm by 22 cm, were filled with either fresh sawdust or river sand for each treatment. The arrowroot rhizomes were sourced from GA₃-treated potted arrowroot mother plants (a separate greenhouse experiment 2), which were sampled randomly and prepared for sowing as follows: The sampled rhizomes were washed with clean running water, taking care not to break or damage the axillary bud at the node (Plate 5.2). Then, sorted according to the four levels of GA₃ treatments: T₁ (100 ppm), T₂ (250 ppm), T₃ (500 ppm), and T₄ (750 ppm) from the source arrowroot potted plants. The apical meristems were removed using a sterile surgical blade, and 100 pieces of 2-node rhizome cuttings with axillary buds per treatment were selected for sowing. The rhizome nodal cuttings were treated by dipping them in a fungicide solution (Ridomil Gold[®], Active ingredient 4% Mefenoxam and 64% Mancozeb) at a rate of 25 g per 20 L of water before planting to prevent rotting. The nodal cuttings were planted at a uniform depth of 5 cm in the rooting media in the polybags before being moved to the rooting chambers. The rooting chamber was made using wooden poles, covered with a transparent polythene sheet, and placed under a 50% black shade net. The sprouting experiment was conducted over a period of four months. Watering was performed at regular 7-day intervals to ensure the survival of the sprouts and maintain high relative humidity in the rooting chambers (Figure 4.21). The data measurements were done bi-weekly. For the sprout counts, the criterion applied was based on the visible shoot protrusions in the rooting media.

The data was recorded periodically on the number of days to start sprouting, the number of sprouts, petiole length, shoot diameter, root length, leaf area, and survival rate after sowing into

the media in polythene bags. The growth rate of the new plantlets in polythene bags was assessed as a measure of seedling vigor using petiole length, leaf area, and root length (Figure 4.19).

3.3.2 Data measurements

The data was gathered on the following factors: days to the emergence of suckers from the sprouting media (Sawdust and River sand); the frequency of seedlings; the vigor of the seedling according to the petiole length and shoot diameter, number of sprouted seedlings, and the length of the roots per seedling (Figure 4.22). The study spanned 12 weeks, during which rhizome nodal cuttings were sown into media in polythene bags and placed in sprouting chambers.

3.3.3 Statistical analysis

The data obtained was tested for normality and homogeneity before analysis using SAS Software version 9.4. An analysis of variance (ANOVA) was carried out to test the study hypothesis at a 95% confidence level. *Post-hoc* analysis was done using Tukey's method. Pearson's correlation of dependent variables was also carried out.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. Experiment 1: Effect of Moisture Pit Planting Technique on Growth and Yield of Upland-grown Arrowroot

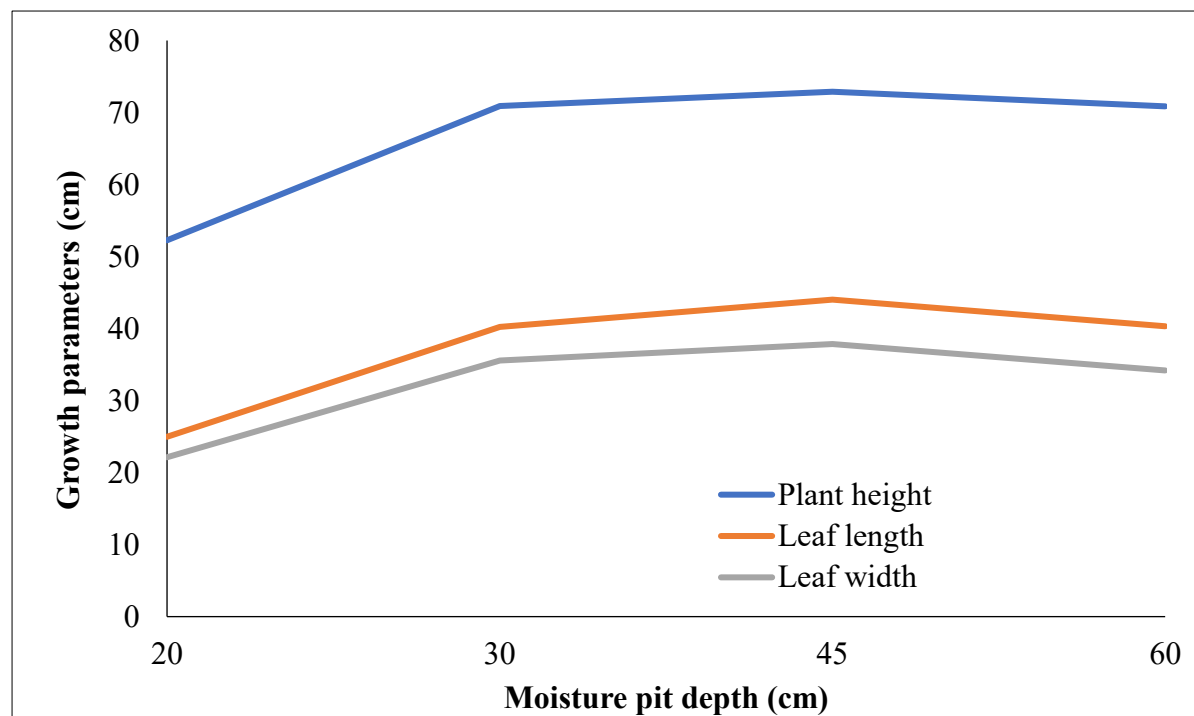
4.1.1 Growth parameters

Plant height, Leaf length, leaf width, and leaf area index

The data for plant height, leaf length and width, leaf area, and leaf area index were collected from six plants in the middle two rows of each experimental plot, within a sampling area of 3 m × 3 m. The effect of moisture retention pit depth on the plant height and leaf area for the two growing seasons (2023 and 2024) is shown in Figure 4.1.

Figure 4.1

Effect of moisture pit depth on the leaf length, leaf width, and plant height



There was a difference in plant height, leaf length, and leaf width in arrowroot planted at 30, 45, and 60 cm pit depths compared to the shallowest, 20 cm, as shown in Figure 4.1. The data recorded for plant height was also compared for the two seasons, as shown in Figure 4.2. This indicates that arrowroots planted in the second season produced taller plants for pit depths of 30 and 45 cm compared to those planted in the first season. The effect of pit depth on leaf area for the two growing seasons is shown in Figure 4.3, and it shows that arrowroots grown in the second season recorded a higher mean leaf area when planted at 20 and 45 cm pit depths than in the first season. During the first season, arrowroots planted in a 60 cm pit depth recorded the tallest plant height and largest leaf area compared to 45 cm and 30 cm, while 20 cm pit depth recorded the lowest. Both the plant height and leaf area increased considerably over time, irrespective of the pit depth in the two seasons. Remarkably, the inconsistency observed may be attributed to the higher rainfall received during the second cropping season.

Figure 4.2

Effect of moisture pit depth on the plant height for the two seasons

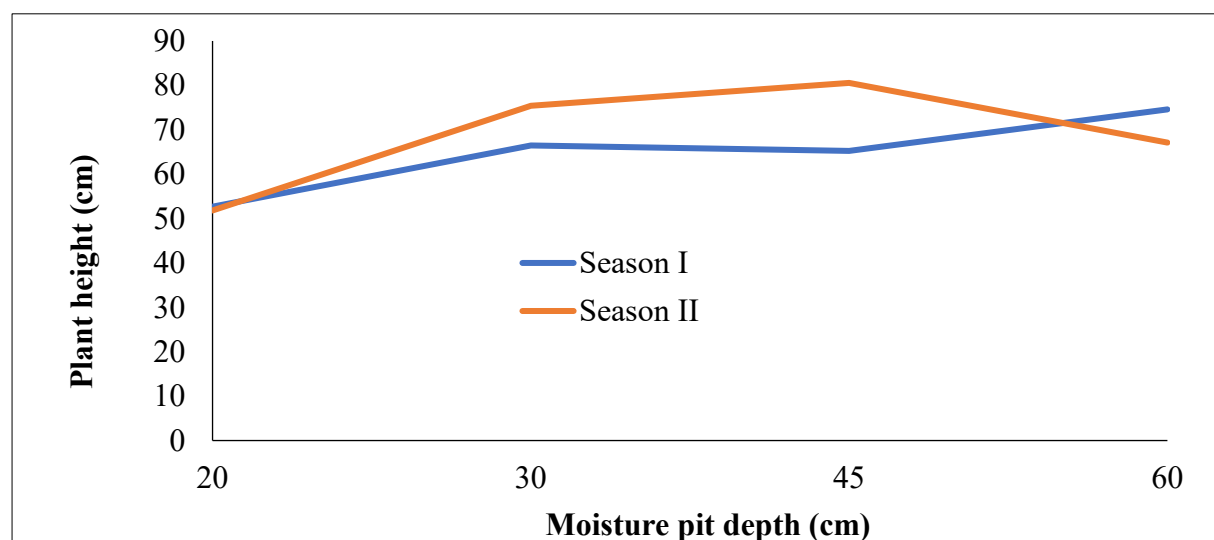


Figure 4.3

Effect of moisture pit depth on the leaf area for the two seasons

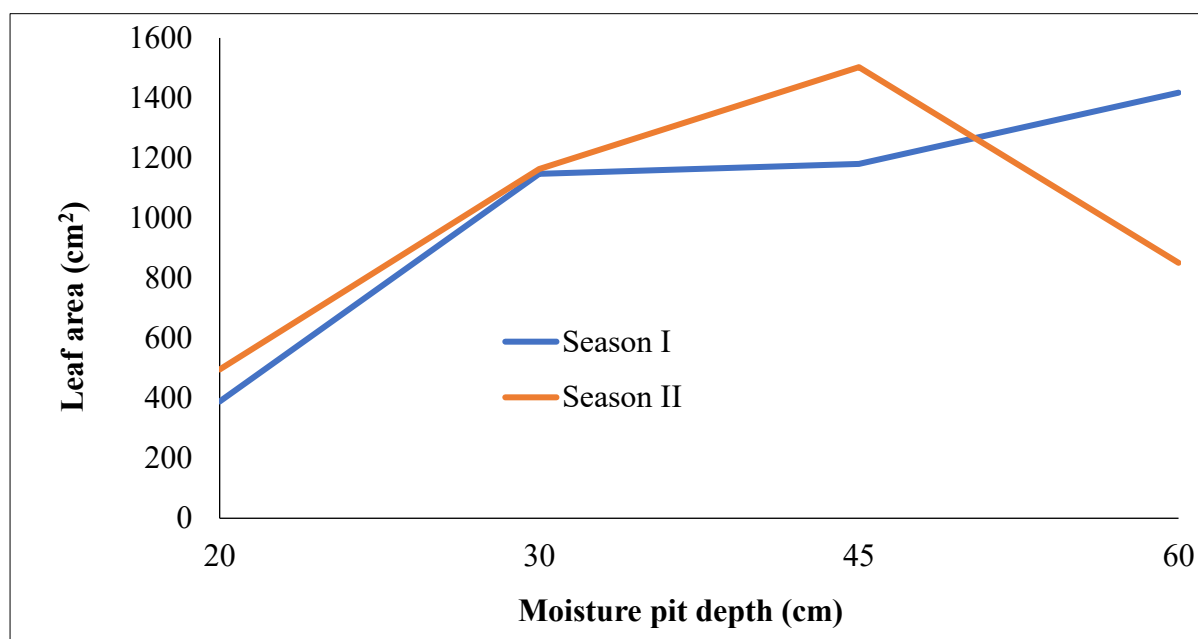
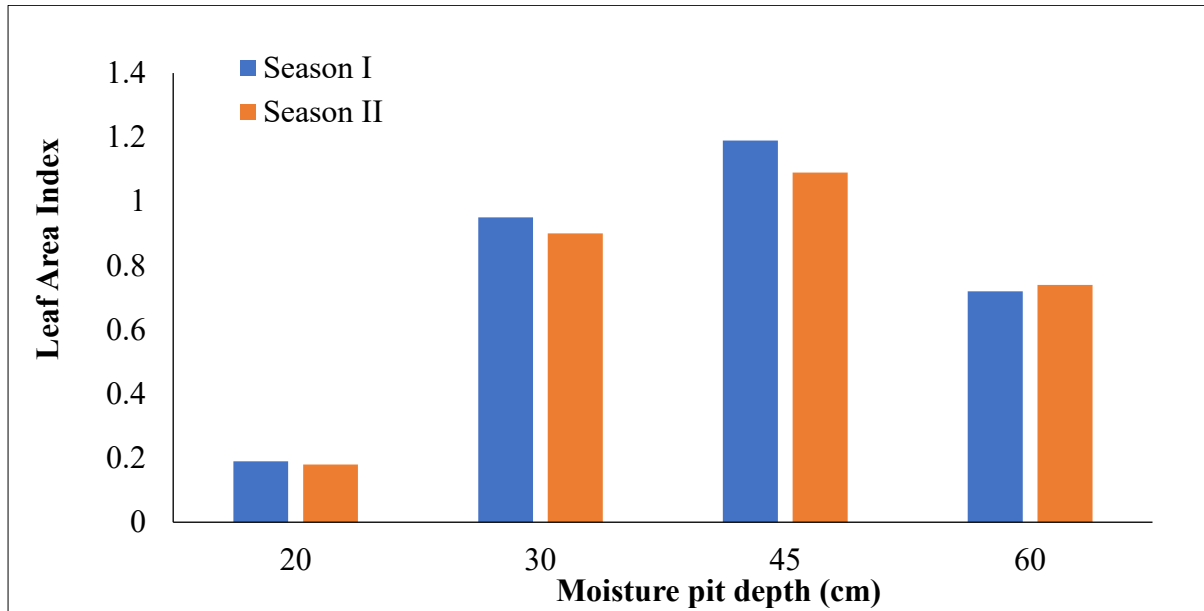


Figure 4.4 shows the effect of pit depth on the leaf area index for the two growing seasons, 2023 and 2024. There seems to be no differences between the two seasons in the leaf area index of arrowroot plants grown at the same pit depth. However, in the first season, arrowroots grown in pit depths of 45 cm recorded the highest mean leaf area index, followed by those in 30 cm and 60 cm depths, respectively. Those in 20 cm pit depths had the least. The same trend was observed in the second season, with pit depths of 45 cm recording the highest, followed by 30 cm and 60 cm in that order. Noticeably, the 20 cm pit depth posted the lowest LAI. There were no differences within the same pit depth across the two seasons in the leaf area index for all the pit depths. Remarkably, arrowroot planted at 45 cm pit depth produced the highest mean leaf area index, followed by 30 and 60 cm, respectively, while those at 20 cm depth recorded the lowest (Figure 4.4).

Figure 4.4

Effect of moisture pit depth on the leaf area index for the two seasons



To determine if the treatments produced significant effects, an ANOVA was conducted, and the results are summarized in Appendix 1. The analysis revealed that pit depth had a significant impact on plant height, leaf length and width, as well as on leaf area and leaf area index. For means comparison, Turkey's test was used, and the results are given in Table 4.1.

Table 4.1*Effect of moisture pit depth on Plant height and leaf Area across cropping seasons (2023-2024)*

Pit depth (cm)	Time (days)	Plant height (cm)		Leaf area (cm ²)	
		Season I	Season II	Season I	Season II
20	60	37.73±1.58 ^h	36.25±3.07 ^g	313.07±32.43 ^g	313.07±34.55 ^d
	120	45.00±2.28 ^{gh}	48.63±2.84 ^{efg}	418.67±24.76 ^{fg}	384.77±31.78 ^d
	180	60.50±2.60 ^{def}	60.20±3.39 ^{def}	417.19±28.8 ^{fg}	394.88±26.52 ^d
	240	67.50±1.32 ^{cde}	62.25±2.99 ^{de}	407.00±51.87 ^{fg}	889.83±470.26 ^{cd}
30	60	48.37±6.73 ^{fgh}	42.31±1.06 ^g	566.50±118.07 ^{efg}	295.49±28.72 ^d
	120	61.98±2.91 ^{def}	61.22±2.72 ^{def}	897.88±87.95 ^{def}	868.86±33.35 ^{cd}
	180	71.65±2.23 ^{bcd}	85.58±1.53 ^c	1389.86±134.33 ^{bcd}	1675.54±183.57 ^{ab}
	240	83.77±4.14 ^{ab}	112.45±3.63 ^{ab}	1733.51±105.01 ^{ab}	1812.14±115.87 ^{ab}
45	60	42.62±0.89 ^{gh}	46.37±1.35 ^{fg}	521.85±146.62 ^{efg}	438.78±81.14 ^d
	120	61.93±2.71 ^{def}	71.23±2.28 ^d	1012.60±104.89 ^{de}	1358.90±39.19 ^{bc}
	180	71.56±2.57 ^{bcd}	84.40±1.88 ^c	1362.38±110.00 ^{bcd}	1898.57±34.32 ^{ab}
	240	84.80±2.79 ^{ab}	120.25±2.95 ^a	1826.30±91.25 ^{ab}	2314.35±103.73 ^a
60	60	54.97±2.23 ^{efg}	41.06±1.32 ^g	668.92±67.30 ^{efg}	237.46±18.39 ^d
	120	67.23±2.08 ^{de}	57.06±1.63 ^{efg}	1230.81±84.49 ^{cd}	511.31±47.75 ^d
	180	81.02±5.29 ^{bc}	65.75±1.36 ^{de}	1665.86±37.45 ^{abc}	877.42±83.04 ^{cd}
	240	95.17±6.99 ^a	104.46±3.22 ^b	2105.04±157.11 ^a	1776.32±96.91 ^{ab}

Means followed by the same letter along the column are not significantly different at a $p \leq 0.05$ probability level.

The plant height was measured at various growth stages during the two growing seasons of 2023 and 2024. The initial measurement was indicated by the emergence of the shoot above the ground surface, and the final height was recorded at harvest time (240 days after planting, DAP). Throughout both seasons, a Significant increase in plant height was observed

(Table 4.1) as the growth period progressed Tumuhimbise et al. (2009), a trend that was consistent regardless of the depth of the pits, which is in agreement with findings of Lewu et al. (2017).

The data collected from season one (Table 4.1) revealed that a pit depth of 60 cm resulted in the highest mean plant height, measuring 95.17 cm. This was followed by pit depths of 45 cm, which grew to a mean height of 84.80 cm; 30 cm, with a mean height of 83.77 cm; and finally, 20 cm, resulting in the lowest mean height of 67.50 cm at harvest (240 days after planting, DAP).

In the second season, a similar pattern was evident, with greater plant heights recorded for pit depths of 45 centimeters (120.25 cm), 30 cm (112.45 cm), and 60 cm (104.46 cm) in comparison to the significantly lower height of 36.25 cm for the 20 cm pits. These findings suggest that deeper moisture retention pits have a positive impact on plant height, supporting the observations made earlier by Ndon et al. (2003) and a similar study conducted by Talwana (2010) that confirmed the findings. It is worth noting that this trend may be attributed to the larger volume of soil associated with deeper pits, combined with the use of internal mulching practices that may have enhanced water harvesting and retention, resulting in taller plants. Bekeko (2013) reported that a study evaluating the effect of maize stover mulch found increased yields due to enhanced soil moisture reserves. This view is also in agreement with the research findings of Syafiuddin et al. (2023). While it is widely acknowledged that the genetics of a cultivar and cultural practices significantly influence plant height, the relationship between planting depth and height remains inconclusive. Some researchers, Orji et al. (2014), have reported in their works that the type of seedbed does not affect plant height, while another study conducted by Tumuhimbise (2015) investigating the effects of plant spacing and planting depth on growth and development of arrowroot reported contradictory findings, indicating that planting depth did not influence plant height. According to Legesse & Bekele (2021), the height

of the arrowroot plant exhibits a wide variation due to genetic disparity and environmental responses.

In contrast, findings of Syafiuddin et al. (2023) demonstrated that the application of plastic mulch had a positive effect on the height of arrowroot plants. Conversely, Njuguna et al. (2023) reported that irrigation had no significant impact on the height of arrowroot plants. In contrast, Lewu et al. (2017) observed that the height of arrowroot plants increased to an optimum level before declining as they approached physiological maturity. However, this study reports a consistent increase in plant height, influenced by pit depth, from planting to maturity, with no signs of decline. This may explain the extra-tall and thick stem girth observed and recorded in the study, probably due to the influence of abundant loosened soil, extra space for root exploitation, and moisture availability in the root zones. It is worth acknowledging that, while this study was done in upland conditions, the studies mentioned were conducted in wetlands.

The number of leaves per plant in this study increased with time up to maturity, with no decline observed, which is in line with the results of earlier studies conducted by (Talwana et al., 2010). This had been contradicted before by a report from Ndion et al. (2003) who stated that the number of leaves in arrowroot increased with age to an optimum, after which it declined as the plants matured. In contrast, moisture retention pits that are deeper yielded a greater quantity of leaves compared to those that are shallower, and this increase proved to be lasting over time. This observation corroborates the results of Lakitan et al. (2021) who proposed that both agronomic practices and ecological conditions play a crucial role in determining the number of leaves produced by plants, which is associated with high moisture retention, as argued in a study by (Syafiuddin et al., 2023). A higher number of leaves in arrowroot is critical, as more leaves enhance photosynthetic capacity, leading to improved dry matter.

The study examined the effects of moisture retention pit depths of 20 cm, 30 cm, 45 cm, and 60 cm on the leaf length and width of arrowroots, revealing significant differences in leaf dimensions at shallower depths compared to those at deeper pits. Specifically, the leaf length and width at the 20 cm depth were evidently smaller compared to those in deeper pits, indicating that shallower pits do not support optimal growth conditions for upland arrowroot. The enhancement in leaf length and width was attributed to improved photosynthetic efficiency, a crucial factor for plant growth and development. The mature plants exhibited larger leaves, which facilitated better light absorption, thereby directly promoting overall growth and vigour. Although the results showed no significant differences in leaf length and width among the plants in the deeper pits, this may suggest that once the depth reaches a certain threshold, the benefits to the plant become uniform.

The findings emphasize that deeper pits create more favorable conditions for cultivating arrowroots, particularly in drier environments where water conservation is vital. Unlike arrowroots grown in swampy areas, which thrive in consistently moist and flooded soils, those cultivated in upland conditions depend heavily on sporadic seasonal rainfall. The strategic implementation of moisture retention pits not only improves water harvesting but also promotes moisture conservation, thereby enhancing the performance of upland-grown arrowroots. This method is significant for sustaining crop yields in regions where water scarcity is a pressing concern (Tumuhimbise, 2015).

As the depth of the moisture retention pits increased, there was a corresponding increase in leaf area of the plants over time, until it optimized. The study's findings confirm those reported by Lewu et al. (2017) since the leaf area is derived from the leaf size, it is evident that the deeper pits may have established a canopy earlier due to a steady supply of moisture compared to the shallow pits. This study's results conflict with Ndon et al. (2010) who report that leaf area in arrowroot, develops slowly, peaking at the middle growth stage and declining towards

maturity. Earlier studies contradict these findings, which may be attributed to the differences in cropping systems employed, specifically between wetland and upland systems (Talwana et al., 2010).

The leaf area index reported in this study was lower than 2.0, which is typically achieved in closely spaced arrowroot crops (Talwana et al., 2010). This study adopted a wider spacing to accommodate the large planting pits. The results indicated insignificant interaction between pit depth and seasonal fluctuations, suggesting that the observed rise in leaf area index (LAI) could be attributed to the increased rainfall recorded in 2024 compared to 2023 (see Appendix 12 for rainfall data). Precisely, the highest mean LAI of 1.14 was recorded for 45 cm pit depths, whereas the lowest values of 0.19 were measured for the shallow pit depths of 20 cm. This variation indicates that deeper moisture retention pits were more conducive to optimal arrowroot growth. LAI is closely correlated to yield; therefore, the higher LAI values recorded for deeper pits suggested corresponding higher yields (Gondim et al., 2018). LAI is a parameter used to estimate crop yields, as it is associated with dry matter assimilation.

Number of suckers, mother plant-sucker distance, stem girth, and number of leaves per plant.

Figure 4.5 illustrates the impact of pit depth on following growth parameters, including the number of suckers per plant, the distance between the mother plant and the suckers, stem girth, and the number of leaves per plant. There was a clear difference between the numbers of suckers produced by plants in pits with varying depths during the two cropping seasons. The pit depths of 30 cm, 45 cm, and 60 cm produced significantly higher numbers of suckers compared to the control, which was 20 cm deep, and had the lowest number of suckers in both seasons. In the second season, depths of 45 and 60 cm resulted in a higher number of suckers. The trend in the production of suckers per plant, based on pit depth, was identified as follows, from the deepest to the shallowest pit: 60 cm > 45 cm > 30 cm > 20 cm.

Figure 4.5

Effect of moisture pit depth and season on the number of sucker per plant

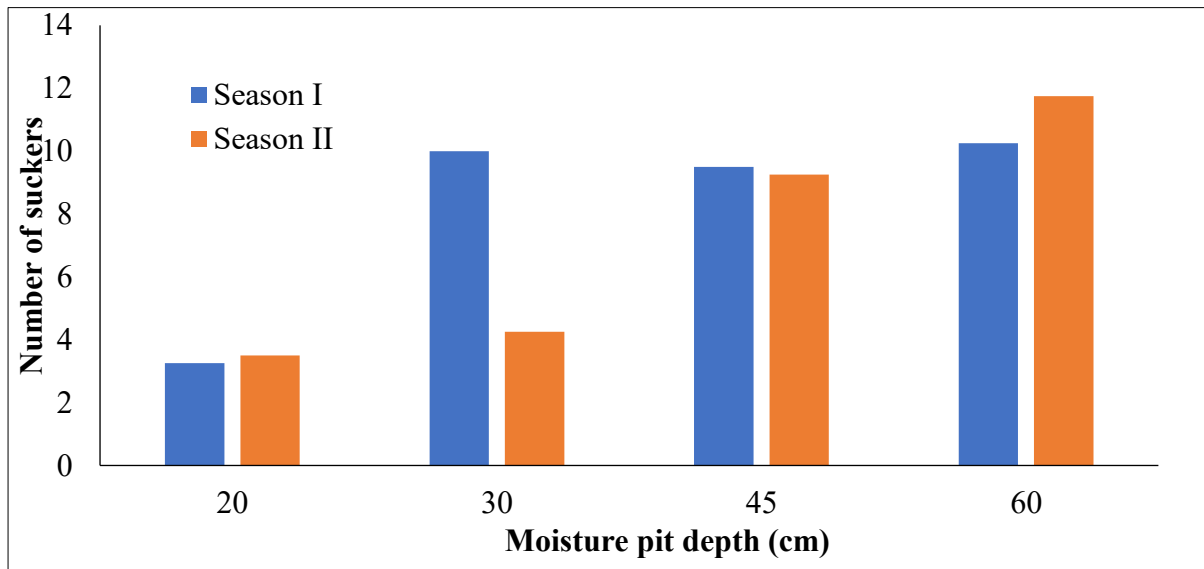
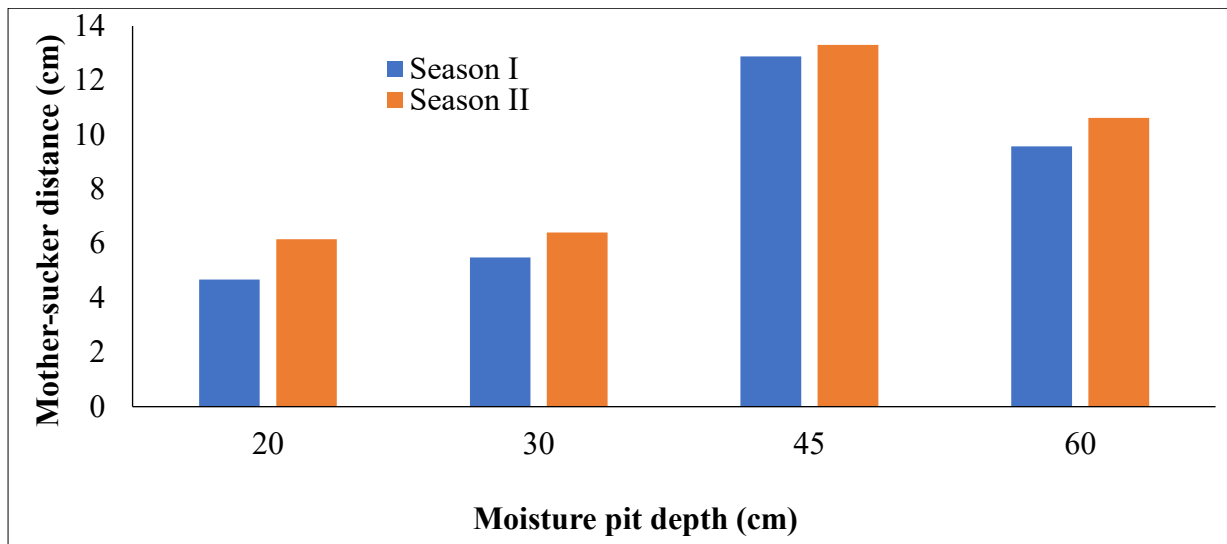


Figure 4.6 shows the effect of pit depth on the distance between the arrowroot mother plant and the daughter suckers. As observed from the illustrations, the 45 cm deep pits had the longest distance, followed by the 60 cm deep pits. The shallow pits, with pit depths of 20 and 30 cm, had the exact distance between the mother plant and the suckers. The same trend was sustained during the two cropping seasons.

Figure 4.6

Effect of moisture pit depth and season on the distance between the mother plant and the sucker



The data presented in Figure 4.7 shows the effects of pit depth on stem girth. The results indicate inconsistency in the growth of stems planted in the different pit depths across the two cropping seasons. However, it was observed that pit depths of 30, 45, and 60 cm had thicker stems compared to the control, which was a 20 cm pit depth.

Figure 4.7

Effect of moisture pit depth and season on the stem girth

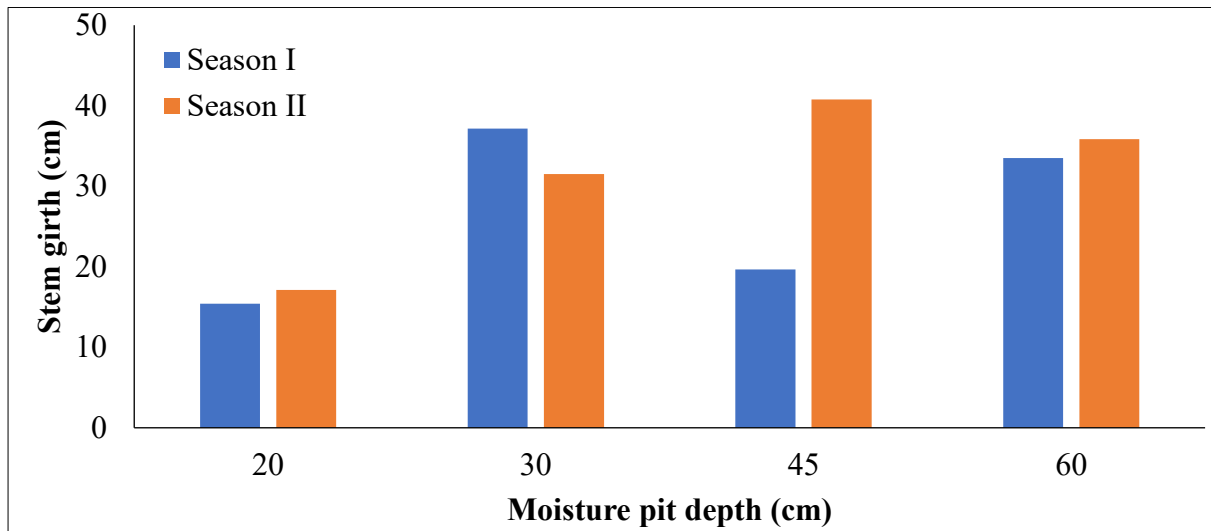
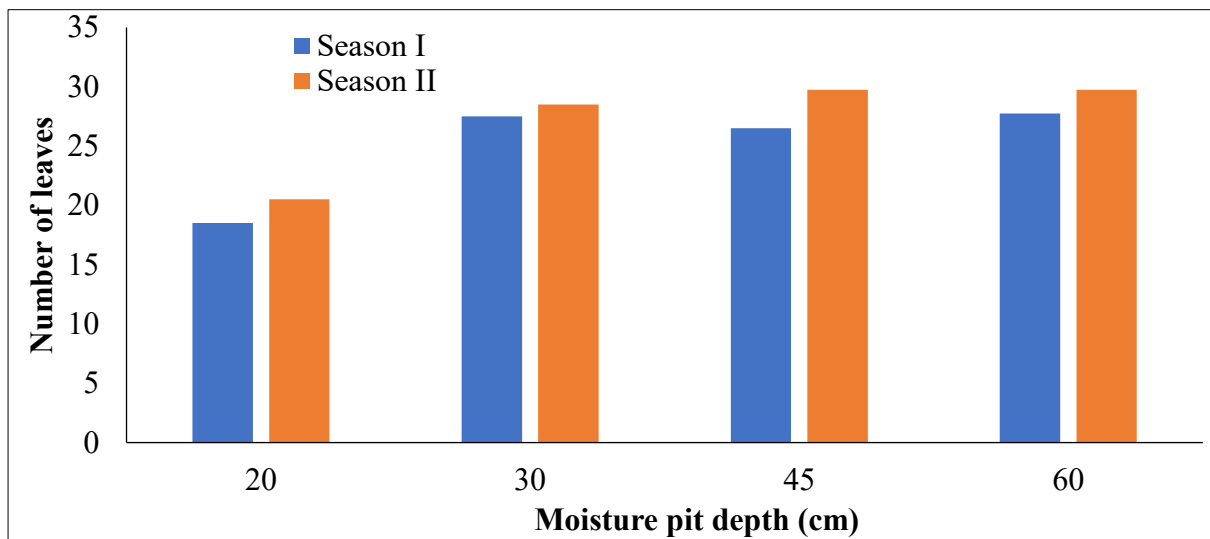


Figure 4.8 shows the effect of pit depth on the number of leaves per plant. Except for the shallow pit depth of 20 cm, all the other pit depths of 30, 45, and 60 cm produced higher numbers of leaves per plant, which were fairly uniform compared to the control (20 cm), which was slightly lower. However, there were no variations in the number of leaves per plant produced at the same pit depths over the span of two cropping seasons.

Figure 4.8

Effect of moisture pit depth and season on the number of leaves per plant



To determine if the treatments produced significant effects, an ANOVA was conducted, and the results are summarized in Appendix 2. The analysis revealed that pit depth had a significant impact on the number of suckers per plant, the distance between the mother plant and suckers, stem girth, and the number of leaves per plant. For means comparison, Turkey's test was used, and the results are summarized in Table 4.2.

Table 4.2*Effects of moisture pit depth, season, and on the arrowroot growth parameters*

Pit depth (cm)	Season	Mother/ sucker dist. (cm)	Sucker numbers	Stem girth (cm)	No. of leaves
20	I	4.67±0.70 ^c	3.25±0.48 ^c	15.40±1.70 ^c	18.50±0.65 ^b
	II	6.16±0.96 ^{bc}	3.50±0.29 ^c	17.13±0.58 ^{bc}	20.50±0.65 ^b
30	I	5.49±0.16 ^c	10.00±1.08 ^a	37.15±1.65 ^{ab}	27.50±1.04 ^a
	II	6.40±0.65 ^{bc}	4.25±0.48 ^{bc}	31.50±0.38 ^{abc}	28.50±1.32 ^a
45	I	12.88±1.17 ^a	9.50±1.04 ^a	19.65±8.12 ^{bc}	26.50±0.65 ^a
	II	13.31±0.54 ^a	9.25±1.38 ^{ab}	40.78±2.44 ^a	29.75±0.75 ^a
60	I	9.57±0.28 ^{ab}	10.25±0.25 ^a	33.50±1.44 ^{abc}	27.75±1.38 ^a
	II	10.62±1.06 ^a	11.75±1.89 ^a	35.85±1.28 ^{ab}	29.75±1.11 ^a

Means followed by the same letter along the column are not significantly different at a $p \leq 0.05$ probability level.

Important observations were made during the study, for instance, most of the sucker emerged during the intermediate growth stage, particularly between 60 and 120 days after planting (DAP). The analysis of the data revealed that deeper pits, at depths of 30 cm, 45 cm, and 60 cm, produced a significant number of suckers, with means ranging from 7.13 to 11.0, respectively. In contrast, the shallow control, 20 cm-deep pits produced significantly fewer suckers, averaging 3.38, which were located closer to the mother plant, making their removal more difficult. A clear trend was observed in how the pit depth influenced sucker generation, with the hierarchy of effectiveness being: 60 cm > 45 cm > 30 cm > 20 cm, indicating a decreasing sequence of values from the deepest to the shallowest pits. These findings align with Legesse & Bekele's (2021) research, which reported that the number of suckers produced by arrowroot ranged between 3 and 8. The report was not conclusive, because recent researchers have stated that so many suckers are unexceptional. Several studies have shown that many arrowroot genotypes have a very low multiplication rate (Tshipamba et al., 2021). It

is believed that the activation of sucker growth from the mother plant is determined by both endogenous and exogenous influences, of which the mechanisms of initiation and development are poorly understood Guo et al. (2020) therefore, they require further investigation.

Diverging from these results, the swamp cropping system involves planting in shallow holes, roughly 15 cm deep and 10 cm wide (Lewu et al., 2017). This method eliminates the necessity for deeper pits, as the growing conditions are generally moist, sometimes even submerged in water. The natural growth habit of arrowroot is such that it typically produces only a limited number of suckers, and sometimes none, depending on the particular cultivar and the existing weather conditions (Sagoe et al., 2018). Moreover, research by Bhende & Kurien (2015) on banana sucker production emphasizes that the depth at which the propagules are planted plays a crucial role in ensuring that sufficient nutrients are available at the feeding zone of the mother plant. This nutrient availability is essential for enhancing sucker production.

One of the challenges in managing suckers is their proximity to the mother plant, making them difficult to separate without causing damage. Therefore, any agronomic practice that increases the distance between the mother plant and suckers may considerably improve upland arrowroot production by facilitating the availability of planting materials. The scarcity of suckers is likely one of the reasons for the low uptake of suckers as a primary propagation material and the generally poor yields of arrowroot in swamp arrowroot and upland production systems (Legesse & Bekele, 2021).

The agronomic significance of achieving an optimal spacing is two-fold. First, suckers positioned further from the mother plant can be removed more quickly, minimizing the risk of damage to either the developing corm or the sucker itself. Second, the timely removal of suckers reduces competition for nutrients and resources, thus enhancing the quantity and quality of the corms produced by the mother plant. This process can also lower the prevalence

of undesired cormels, hence improving overall yield. As highlighted by Lakitan et al. (2021), removing suckers does not hinder the growth of the arrowroot mother plant. A robust positive correlation exists between the number of suckers and the number of leaves per plant, suggesting that proper management of suckers can lead to enhanced plant health and productivity.

The more significant impact of this practice in upland arrowroot production is the availability of a high number of suckers for propagation by “safe harvesting” while the crop is still growing. The common practice in wetland cropping systems is either to remove suckers from growing plants or secure them at the maturity of the arrowroot. This may not be recommended for upland production, which relies on seasonal rainfall for production. However, further research should be conducted to investigate the direct effect of eliminating all suckers on the growth and development of the mother plant's corm yield (Lakitan et al., 2021). This observation was momentous for enabling “early sucker harvesting” as the corms mature; therefore, the longer the distance from the mother plant, the easier and safer the removal without damaging either the sucker or the developing mother corm. These results are crucial in addressing the challenges of accessing sufficient propagation material, particularly for large-scale production, where large quantities are required. Therefore, establishing an upland arrowroot crop at a depth of 30 cm to 60 cm will contribute to high arrowroot yields and the availability of more suckers for propagation at the same time.

Even though no correlation was observed between the distance between the mother plant and the suckers and corm yield per plant, and the stem girth in the study, it may be inferred that suckers may be removed from the mother plant without compromising either the shoot growth or corm yield of the ensuing arrowroot crop (Lakitan et al., 2021). In a similar study by Lakitan et al. (2022), it was hypothesized that if all the suckers were eliminated, the mother plant's growth would actually improve. The number of suckers produced by arrowroots is influenced by both genetic and environmental factors, particularly plant nutrition (Bambang et al., 2021;

Legesse & Bekele, 2021). Therefore, the moisture retention pits used in the study seemed to have provided the best conditions for upland arrowroot growth and the generation of a higher number of suckers.

Interestingly, unlike other reported studies, the number of leaves per plant in this study did not exhibit an increase followed by a decrease as plants matured (Ndion et al., 2003). In contrast, deeper moisture retention pits (30, 45, and 60 cm) produced a significantly higher number of leaves compared to the shallower pit (20 cm), and this increase was maintained until maturity. This observation concurs with that made by (Legesse & Bekele, 2021). This observation corroborates the results of Lakitan et al. (2021) who proposed that both agronomic practices and ecological conditions play a crucial role in determining the number of leaves produced, thereby increasing photosynthetic capacity, which in turn enhances arrowroot yields. This view was earlier reported by (Talwana et al., 2010).

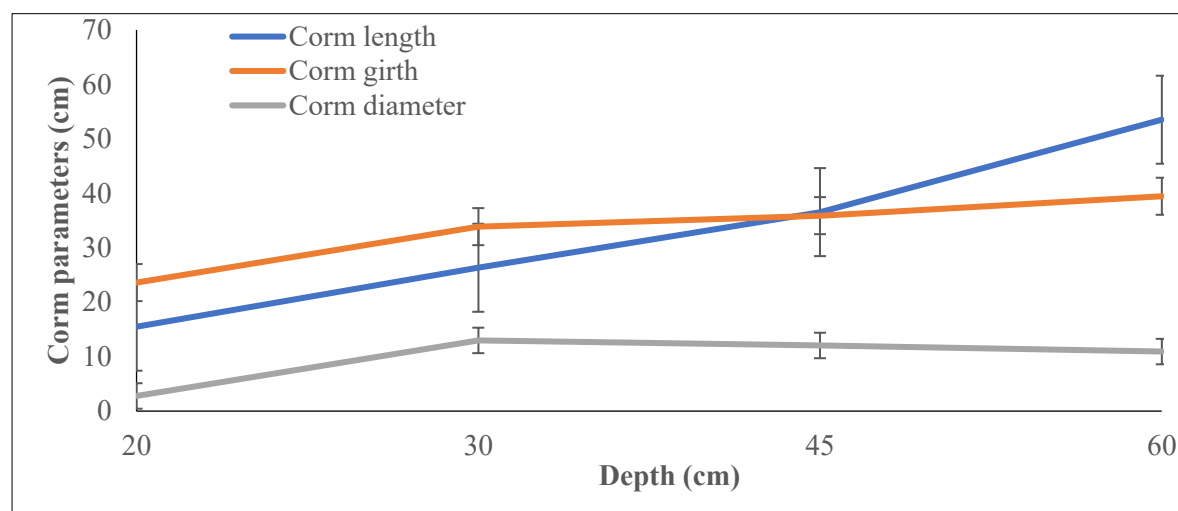
4.1.2 Arrowroot yield and yield components

Corm length, girth, diameter, corm weight, and yield

The ultimate yield of arrowroot depends on several yield components, including the corm length, girth, and diameter, as well as the weight of the corm. Figure 4.9 illustrates the impact of pit depth on these crucial parameters, specifically the outcome of pit depth on corm length. It was observed that as the pit depth increased from 20 cm to 60 cm, the corm length increased considerably for all depths, with the 60 cm pit depth recording the highest corm length, followed by 45, 30, and 20 cm, respectively. The corm girth also increased with an increase in pit depth. For instance, the responses from pit depths of 30, 45, and 60 cm were the same, but appreciably different from the control (20 cm); similar trends were observed for the corm diameter, even though the variation was minimal.

Figure 4.9

Effect of moisture pit depth on the corm length, girth, and diameter



To determine if the treatments produced significant effects, an ANOVA was conducted, and the results are summarized in Appendix 3. The results showed that pit depth had a considerable impact on corm length, corm girth, corm diameter, corm and cormel weight per plant, and for means comparison, Turkey's test was used, and the results are summarized in Table 4.3

Table 4.3

Effect of season on the arrowroot corm weight and yield components

Season	Corm length (cm)	Corm girth (cm)	Corm diameter (cm)	Corm wt./plant (kg)	Cormel wt./plant (kg)
Season I	31.79±3.50 ^a	32.75±1.49 ^a	10.32±1.77 ^a	1.43±0.21 ^b	0.93±0.13 ^b
Season II	34.15±4.06 ^a	33.65±1.67 ^a	9.04±0.96 ^a	1.71±0.25 ^a	1.18±0.19 ^a

Means followed by the same letter along the column are not significantly different at a $p \leq 0.05$ probability level.

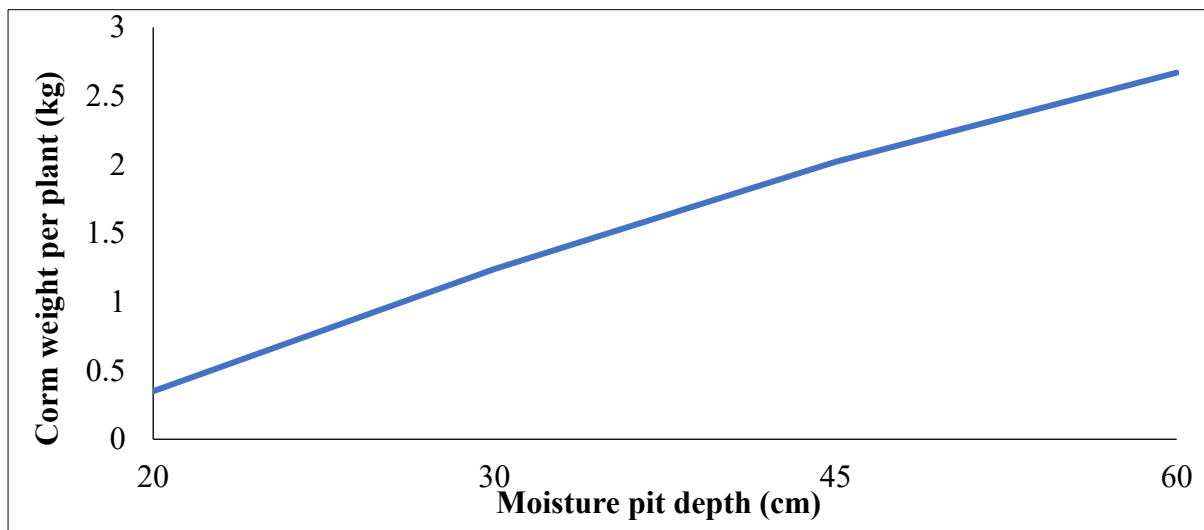
The results reveal that the season has a significant effect on the weight of both corms and cormels per plant. The weight recorded during the second season (2024) was highly significant

($p < 0.001$). The corm and cormel weights were higher during the second season (2024) than those observed in the first season (2023). Although the corm length, girth and diameter were not significantly affected by the season, the measures made were large and corms and cormel heavier compared to swamp arrowroot. Further analysis revealed a significant impact on the weight of both corms and cormels produced per plant across the two growing seasons, as detailed in Table 4.3. In particular, the 2024 growing season demonstrated a remarkable increase in corm weight, with an average of 1.71 kg per plant, surpassing the 2023 average of 1.43 kg. This increase suggests that an improvement in growing conditions may be due to enhanced rainfall received in 2024 (Appendix 12).

Figure 4.10 shows the effect of pit depth on the arrowroot corm weight. It was observed that different pit depths had an impact on the corm weights, evidently. The 60 cm pit depth produced the heaviest corms, followed by 45 cm and 30 cm, respectively, while the 20 cm pit depth produced the lightest corms. Notably, the corm weights per plant obtained in pit depths of 30, 45, and 60 cm are significantly higher compared to those in pit depth 20 cm.

Figure 4.10

Effect of moisture pit depth on the arrowroot corm weight per plant



To determine if the treatments produced significant effects, an ANOVA was conducted, and the results are summarized in Appendix 4. The analysis showed that pit depth had a substantial impact on corm weight per plant. For means comparison, Turkey's test was used, and the results are summarized in Table 4.4.

Figure 4.11

Effects of moisture pit depth on yield components

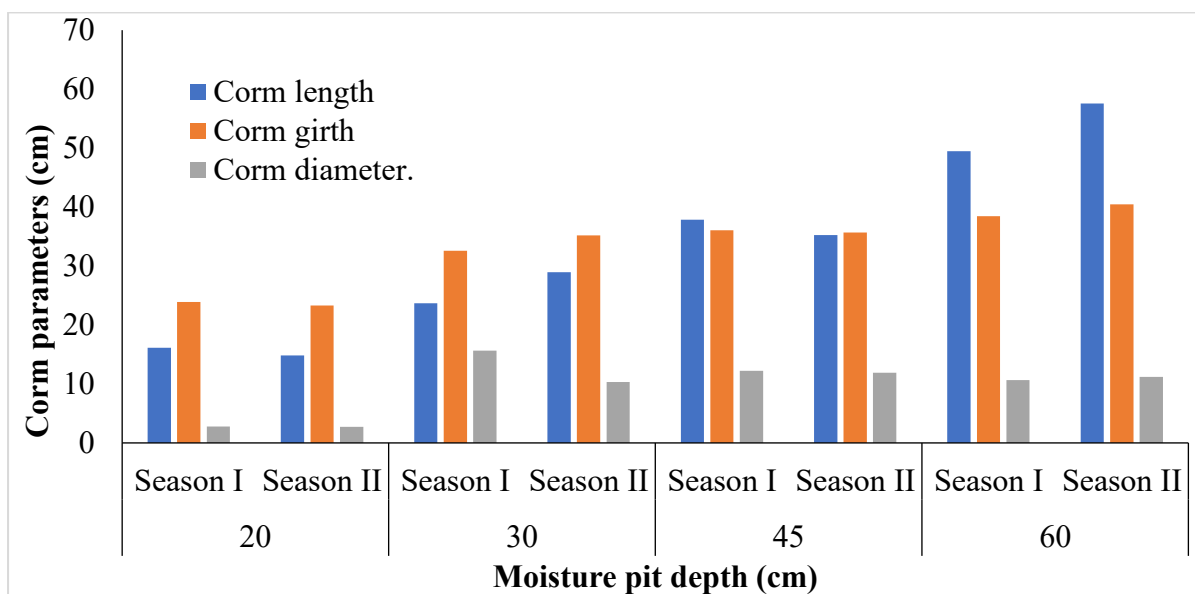


Figure 4.12

Effects of moisture pit depth on corm and cormel weights per plant

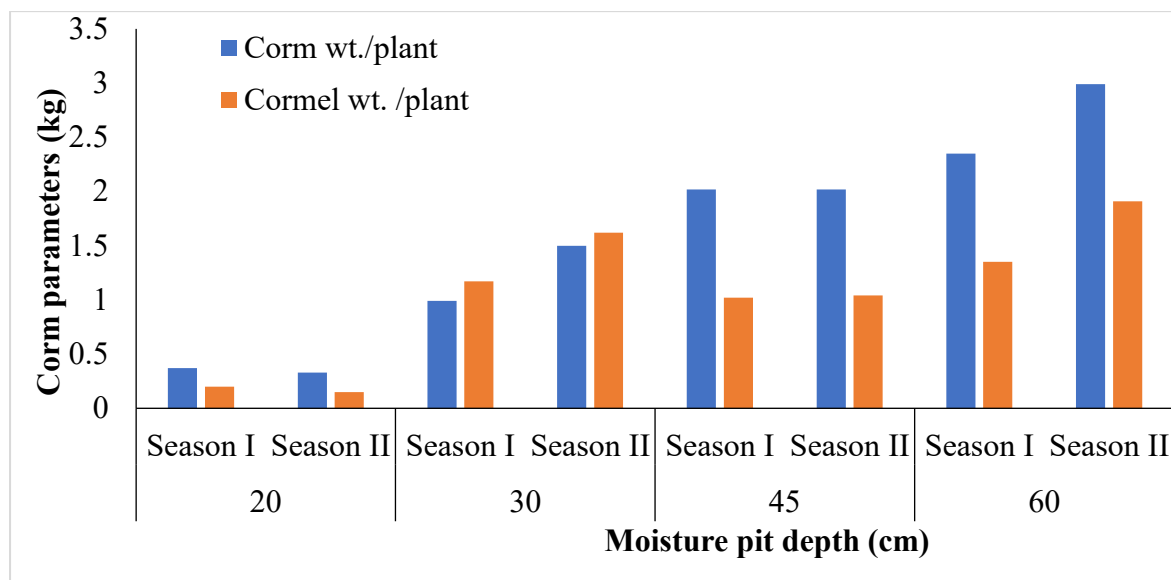


Table 4.4

Effects of moisture pit depth on the arrowroot yield components (2023 and 2024)

Pit depth (cm)	Season	Corm length (cm)	Corm girth (cm)	Corm diameter. (cm)	Corm wt./plant (kg)	Cormel wt. /plant (kg)
20	I	16.15±0.46 ^d	23.90±0.10 ^d	2.80±0.22 ^b	0.37±0.02 ^c	0.20±0.02 ^d
	II	14.85±0.54 ^d	23.30±0.47 ^d	2.75±0.13 ^b	0.33±0.01 ^e	0.15±0.03 ^d
30	I	23.69±1.75 ^{cd}	32.57±0.98 ^c	15.65±5.72 ^a	0.99±0.05 ^{de}	1.17±0.10 ^{bc}
	II	28.95±0.37 ^{bc}	35.17±0.42 ^{bc}	10.31±0.55 ^{ab}	1.50±0.07 ^{cd}	1.62±0.19 ^{ab}
45	I	37.83±0.31 ^b	36.08±1.13 ^{abc}	12.21±0.23 ^{ab}	2.02±0.18 ^{bc}	1.02±0.16 ^c
	II	35.25±1.50 ^b	35.70±1.20 ^{bc}	11.90±0.34 ^{ab}	2.02±0.01 ^{bc}	1.04±0.07 ^c
60	I	49.48±4.73 ^a	38.46±1.09 ^{ab}	10.64±0.19 ^{ab}	2.35±0.19 ^{ab}	1.35±0.15 ^{bc}
	II	57.55±3.27 ^a	40.45±0.86 ^a	11.22±0.20 ^{ab}	2.99±0.15 ^a	1.91±0.21 ^a

Means with the same letter along the column are not significantly different from each other as per Tukey's test at $p \leq 0.05$

Table 4.4 shows the effects of pit depth on corm components: corm length, girth, and diameter, for two seasons. The results highlighted some critical findings, for example, increasing the pit depth from 20 cm to 60 cm resulted in a substantial increase in corm length. However, while

corm girth and diameter were inconsistent, the only significant difference occurred between the shallowest pit depth of 20 cm and the deeper pits, which had insignificant differences ($p \leq 0.05$). Additionally, essential interactions between pit depth and seasonal conditions were observed, further emphasizing the complexity of these relationships, as outlined in Table 4.4. Outstandingly, arrowroots planted in 60 cm deep pits during the second season exhibited superior growth, achieving the highest measurements for corm length, girth, fresh corm weight, and cormel weight per plant. In contrast, corms cultivated at a 20 cm pit depth consistently recorded the lowest values for all measured parameters across both seasons, underscoring the impact of moisture retention and pit depth on the overall growth and development of the upland arrowroots. The results emphasize the importance of refining planting methods to enhance arrowroot yields. The cumulative results strongly suggest that cultivating arrowroots in deeper pits tends to improve yields, highlighting the importance of optimizing planting depth to maximize soil moisture reserve. The effects of moisture retention pit depth on yield components: corm length, corm girth, corm diameter, corm weight, and cormel weight per plant, are indicated in Table 4.4. Deeper pits had a positive influence on all yield components, particularly for the deepest pit (60 cm in depth). For example, at 45 and 60 cm depth, the corm length, girth, and corm weight were significantly higher than shallower pits (20 cm and 30 cm). Igbokwe et al. (2006) demonstrated that deeper planting resulted in longer corms than shallow planting. This suggests that deep planting of arrowroots creates favorable conditions by improving root development space and conserving moisture, which agrees with studies indicating that deeper planting promotes larger corm dimensions due to enhanced access to nutrients and moisture in deeper soil layers (Eze & Okorji, 2003). The basis of deep planting of arrowroot is that, unlike other root and tuber crops, arrowroot grows upwards from the bottom of the planting hole. The corm size is highly dependent on the depth at which the propagule is placed. Therefore, the planting depth becomes a critical factor in determining the

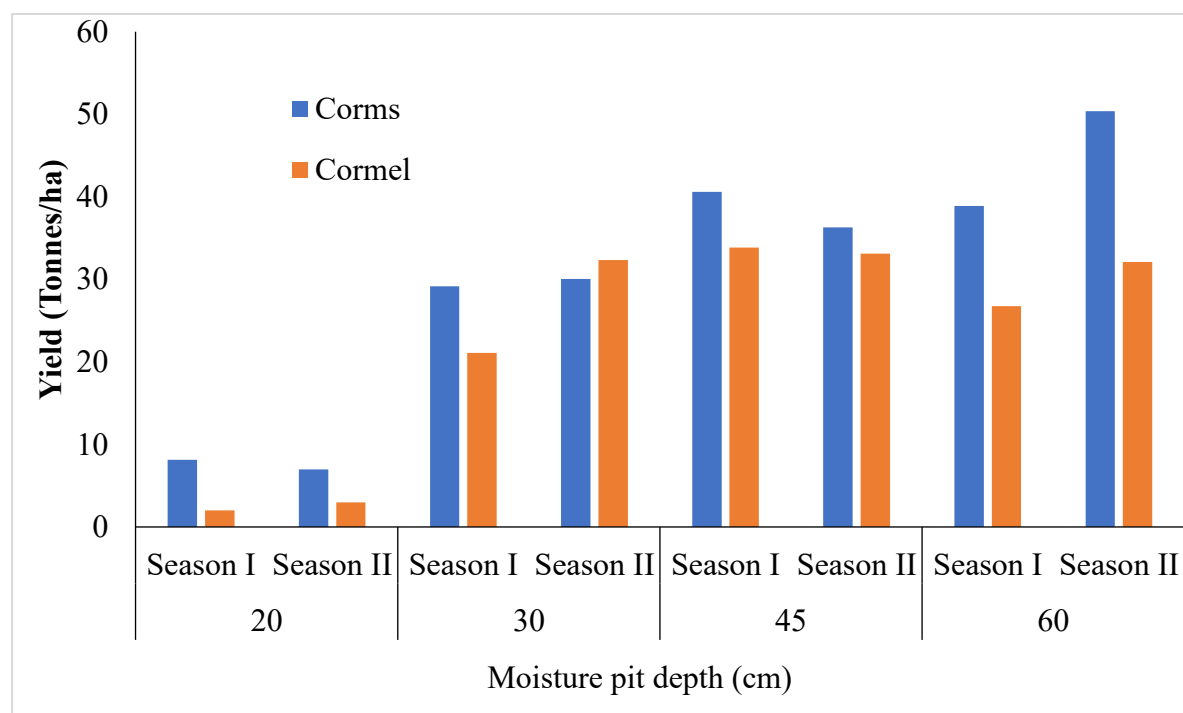
morphology of the corm. For instance, Tumuhimbise (2015) conducted a study to evaluate the effect of planting depth on corm yield, which revealed that corms of deeper-planted arrowroot in upland conditions had significantly larger girths than those planted in shallow pits. The loosened soil in the pits promotes lateral corm expansion, which increases corm length, diameter, and girth, as highlighted in a study by Njuguna et al. (2023) investigating arrowroot growth and yield under variable watering regimes. The interaction effects between seasons and the pit depth influence on the yield components were observed, determining corm yield (Tumuhimbise, 2015). Season two generally showed higher yields, as evidenced by increased corm weights per plant at 60 cm, which was 2.99 kg in season two compared with 2.35 kg in season one. The arrowroot corm weights and yields reported in this study were very high compared to those of a similar research on upland conducted in Uganda by Talwana et al. (2010), for instance, desirable corm specification is 0.9 to 1.8 kg in weight Talwana et al. (2010), the current study recommends planting upland arrowroots in pit depths of 30, 45 and 60 cm, which produced corms weighing on average, 0.99 to 2.99 We posted This can be attributed mainly to the heavier rainfall in second season.

The statistical analysis, with a significant difference at $p < 0.05$, reveals that variations in moisture depth and seasonal conditions have a substantial contribution to yield. For instance, the corm girth at 60 cm depth during season two was considerably higher (40.45 cm) than at 20 cm depth in season one (23.90 cm). The results of this study suggest that adopting moisture pit planting, combined with favorable seasons, optimizes arrowroot corm yield (Figure 4.11). Eventually, farmers adopting these conditions will achieve better yields.

Figure 4.12 shows the effect of pit depth on the arrowroot corm and cormel yield for the two cropping seasons. The highest corm yield was attained at a pit depth of 60 cm, followed by 45 cm, 30 cm, and 20 cm, respectively. The corm yield varied across all pit depths. The cormels are smaller corms produced by suckers growing in the same pit with the mother plant; therefore,

their weight contributes to the total yield. For marketability, they are grouped separately. The cormel yield for the three deeper pits, at 60, 45, and 30 cm, was higher than that of the control (20 cm), but the corm weights were consistent among the deeper pits and across the seasons. The total arrowroot yield per hectare, as shown in Figure 4.13, recorded 60 cm pit depth as the highest, followed by 45 cm, 30 cm, and 20 cm, the lowest.

Figure 4.13
Effect of moisture pit depth on the corm and cormel yields



To determine if the treatments produced significant effects, an ANOVA was conducted, and the results are summarized in Appendix 4. The analysis revealed that pit depth had a substantial impact on corm and cormel yields per hectare. For means comparison, Turkey's test was used, and the results are summarized in Table 4.5.

Table 4.5

Effect of moisture pit depth on arrowroot corm and cormel yield for two seasons (2023 and 2024)

Pit (cm)	Corm yield (kg/ha)		Cormel yield (kg/ha)		Total yield (kg/ha)	
	Season I	Season II	Season I	Season II	Season I	Season II
20	8,116.67± 653.41 ^d	6,958.33±3 59.37 ^d	2,000.00±3 60.04 ^d	2,966.67± 477.84 ^b	10,116.67 ±468.55 ^d	9,925.00± 436.61 ^d
30	29,141.67 ±254.79 ^c	30,027.50± 736.48 ^c	21,066.67± 349.76 ^c	32,322.50 ±792.80 ^a	50,208.33 ±256.67 ^c	62,350.00 ±513.14 ^c
45	40,579.17 ±613.58 ^a	36,281.67± 432.04 ^b	33,825.00± 395.94 ^a	33,105.00 ±785.79 ^a	74,404.17 ±897.15 ^a	69,386.67 ±798.95 ^b
60	38,875.00 ±293.12 ^b	50,383.33± 273.11 ^a	26,766.67± 302.86 ^b	32,094.17 ±821.34 ^a	65,641.67 ±574.26 ^b	82,477.50 ±693.55 ^a

Means followed by the same letter within a column are not significantly different at a $p \leq 0.05$ probability level.

The observations recorded in the first season, detailed in Table 4.5, reveal significant increases in corm yields associated with varying planting depths. The most substantial corn yield was achieved at a pit depth of 45 cm, where yields reached an impressive 40.58 tons per hectare in the first season. The lowest corm and cormel yields were recorded from the shallowest pit depths in the first season. Correspondingly, the highest cormels yield was also observed at the same Pit depth (45 cm), amounting to 33.83 tons per hectare. This trend shifted during the second season, when the optimal moisture pit depth for corm yield was found to be 60 cm, resulting in an outstanding yield of 50.38 tons per hectare. Meanwhile, the peak cormel yield was recorded at a shallower depth of 30 cm, with a yield of 32.32 tons per hectare for the second season. The shallowest pit depth from the 2023 growing season yielded 8.117 tons per hectare of corms, slightly declining to 6,958 tons per hectare in 2024. This performance highlights a significant disparity, as the yields from the deepest pits were four to five times

greater than those from the shallow pits at the time of harvest, as shown in Table 4.5. This growth indicates a trend toward greater productivity in the latter season, possibly linked to favorable environmental factors, particularly the higher rainfall amount received in 2024 (Appendix 12). However, it is worth noting that no significant differences were observed in corm length, girth, or diameter between the two seasons (Table 4.3). This lack of difference suggests that, while the overall weight of the corms and cormels increased, their physical dimensions remained consistent, indicating an improvement in biomass rather than morphological changes.

Table 4.6 presents the detailed results of the correlation coefficients analysis performed on the data obtained in the study, which revealed insightful relationships between yield and yield components, as well as growth parameters affected by the moisture pit planting depth. This analysis spanned two consecutive growing seasons, providing a comprehensive understanding of how these parameters interact with each other. Notably, a strong positive and significant correlation was identified between corm and growth parameters, indicating that improvements in one set of parameters often lead to improvements in the other. This finding underscores the interconnected nature of plant growth; for instance, as factors contributing to corm enhancement become more favorable, those associated with shoot development also improve.

Table 4.6

Coefficients of correlation among arrowroot yield and growth parameters across moisture pit depths in two seasons

	Corm length	Corm girth	Corm diameter	Corm weight	Sucker distance	Suckers number	Corm yield	Stem girth	Number of leaves
Corm length	1.000	0.868**	0.432*	0.936***	0.578***	0.679***	0.692***	0.462**	0.702***
Corm girth		1.000	0.558***	0.943***	0.579***	0.731***	0.829***	0.592***	0.812***
Corm diameter			1.000	0.461**	0.327 ^{ns}	0.523***	0.568***	0.534***	0.614***
Corm weight				1.000	0.675***	0.711***	0.765***	0.507***	0.741***
Sucker distance					1.000	0.491**	0.347 ^{ns}	0.297 ^{ns}	0.501**
Suckers number						1.000	0.575***	0.577***	0.503***
Cormel weight							1.000	0.601***	0.755***
Stem girth								1.000	0.636***
Number of leaves									1.000

ns= Not significant at $p \leq 0.05$; ***= Significant at $p < 0.001$; **= significant at $p < 0.01$; *=Significant at $p \leq 0.05$

The effect of planting depth on the growth and development of arrowroot has been widely studied (Lewu et al., 2017; Oladimeji et al., 2022). Nevertheless, scant information exists on the size of the planting hole and the procedure for headset or sucker placement, as well as refilling the hole after planting until establishment, especially under upland conditions, which require further investigation. Therefore, the present work focused on planting pits designed for rainwater harvesting and conservation to support the propagation of sown arrowroot material, enabling growth and development in the upland environment, where water is scarce, compared to traditional wetlands. Previous studies have suggested that deeper moisture retention pits (30 to 60 cm in depth) enhanced shoot and corm parameters compared to shallower pits (20 cm in depth). These findings align with those reported by Tumuhimbise (2015), who assessed the effects of plant spacing and depth. However, the depths applied were shallower than those used in the current study. Moreover, according to Opata et al. (2020), the deeper pits provide sufficient soil coverage to maintain moisture and nutrient availability, supporting the development of adventitious buds and roots while protecting them from desiccation. Onwueme (1999) researched planting depths of upland taro (*Colocasia esculenta*) and reported that deeper planting resulted in higher yields.

Additionally, shallower depths result in significantly reduced yields due to poor root penetration and loss of surface moisture. According to Norman et al. (2020), shallow planting in upland environments generally results in poor plant establishment and smaller corms due to inadequate soil moisture and increased plant stress. Low rainwater harvesting had a significant impact on growth parameters, such as plant height, leaf area, stem girth, and sucker initiation. It was confirmed that broader and deeper moisture retention pits lead to the yield of large, heavier corms, resulting in improved yields.

The moisture retention pit planting technique tested in this study significantly influenced the growth of arrowroots in the uplands and the attainment of high corm yields. The deepest pit

(60 cm) produced the highest corm yield (44.63 t ha⁻¹), followed by 45 cm (38.43 t ha⁻¹) and 30 cm (29.59 t ha⁻¹), with the shallowest pit, 20 cm, yielding the lowest (7.54 t ha⁻¹), an average of both seasons. These results align with the findings of Ubalua et al. (2016), which suggest that arrowroot corm yields can surpass 38 tons per hectare in field conditions under optimal growing conditions (Rahmawati et al., 2012).

According to Goenaga & Chardon (1995), arrowroot can yield up to 73 tons per hectare under intensive management. Additionally, a record yield of 37.5-75 tons per hectare has been documented under irrigation and heavy fertilization in Hawaii (Anonymous, 2006-2024). This trend agrees with the strong positive correlations obtained between corm and shoot parameters that enhance growth and development in this study. This output was significantly larger than that of other local and regional studies reported earlier. For example, Legesse and Bekele (2021) evaluated improved taro cultivars in two-year experiments, yielding 22.34 and 8.36 tons per hectare, respectively, as the highest and lowest corm yields. Similarly, Njuguna et al. (2023) reported the highest corm yield of 18.26 tons per hectare for long and 7.76 tons for short rains in Kenya. Ubalua et al. (2016) examined the potential of sustainable taro production in Nigeria, reporting yields of up to 38 tonnes per hectare.

However, a synthetic mulching study on Japanese arrowroot production reported a corm yield of 32 tonnes per hectare (Syafiuddin et al., 2023). Contrary to results, Tumuhimbise (2015) reported reduced corm yields; for instance, arrowroot planted at depths of 15 and 30 cm produced 11.61 and 15.19 tons per hectare, respectively. Njuguna et al. (2023) reported a corm yield of 20.84 tons per hectare in recent research investigating the effect of irrigating upland arrowroot in Embu, Kenya. Most studies reported have primarily focused on the yield potential of improved and local cultivars of arrowroot (Diaguna et al., 2023).

The studies compared were primarily conducted in wetland or lowland conditions. In contrast, the present research was conducted in an upland environment that relied solely on rainfall for

two consecutive growing seasons (2023 and 2024), alongside substantial applications of organic manure, fertilizers, and soil amendments, including biochar. This difference accounts for the variations observed in growth and yield measurements compared to previously reported results for wetland and upland-grown arrowroots (Goenaga, 1996).

Furthermore, the cultivar used in this research was the Dasheen-type arrowroot, which is typically cultivated in wetland areas and is known for its large central corm. Consequently, the moisture retention pits were designed to accommodate larger arrowroot suckers and organic amendments, thereby facilitating internal mulching. This differs from the smaller and shallower planting holes previously utilized by earlier researchers. For instance, Orji et al. (2014) recommended deep taro planting depths of 10-12 cm, with shallower depths at 5 cm, while Onwueme (1999) suggested that depths of 10-15 cm provided higher yields. According to Tumuhimise (2015), deep planting in upland taro (greater than 15 cm) can lead to lower yields. Tumuhimise (2015) investigated the impact of planting depth on taro corm yield under upland conditions, concluding that a depth of 30 cm resulted in a greater yield of corms compared to a depth of 15 cm.

In contrast, the present study found that the most profound planting depth of 60 cm yielded the highest corm production. It is essential to note that earlier studies have focused on wetland production systems, which consistently maintain a water supply throughout the growing period. In contrast, upland arrowroot production relies on intermittent rainfall, necessitating larger planting pits for effective water harvesting and conservation.

Previous findings by Talwana et al. (2010) highlighted the performance differences between Uganda's wetland and upland taro production systems, considering factors such as plant population and seedbed type. Their research confirmed that taro can be successfully cultivated under upland conditions. Although the previous research outcome supports the current

findings, it is essential to note that a different planting method was employed: moisture retention pits instead of traditional seedbeds. Further research is recommended to identify a suitable cultivar that enhances water and nutrient use efficiency, thereby improving productivity. This study recommends planting upland arrowroot at depths between 30 and 60 cm to achieve optimal production. Such an approach increases the yield of corms and cormels while enhancing their quality and characteristics, promoting adequate moisture conservation to support plant growth. Ultimately, the selection of planting depth should be tailored to specific site factors, including soil conditions, climate, and available resources.

4.2 Experiment 2: Effect of Gibberellic Acid on Growth and Regeneration of Arrowroot Cultivars

4.2.1 Effect of GA₃ concentration on rhizomes, nodes, and sucker of arrowroot

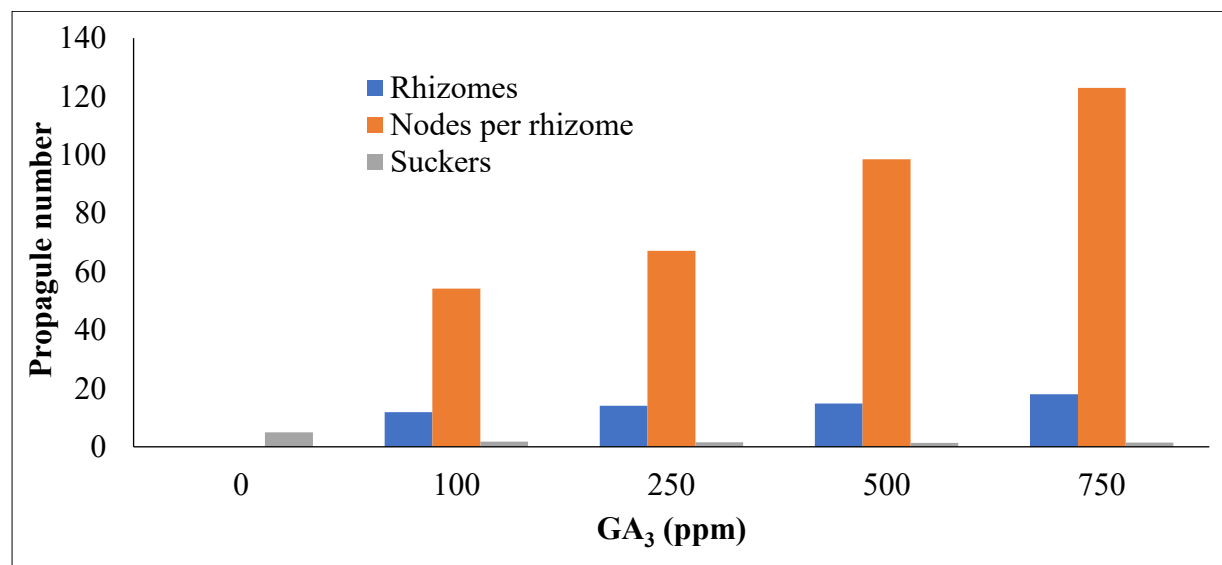
Figure 4.13 illustrates the response of various arrowroot cultivars to increasing concentrations of Gibberellic acid (GA₃), ranging from 0 to 750 ppm. It focuses on key parameters such as the number of rhizomes per plant, the number of nodes per rhizome, and the count of suckers produced by potted plants (see Plate 3.3). The data indicate a significant increase in the number of rhizomes per plant as the GA₃ concentration rises, from an initial count of zero for the control to an impressive high number of rhizomes per plant at the 750-ppm concentration, as presented in Figure 4.13. This response shows a clear dose-dependent trend, highlighting the positive effect of GA₃ on rhizome proliferation.

Additionally, the number of nodes per rhizome consistently increased with higher GA₃ concentrations. This trend suggests that elevated levels of GA₃ stimulate the activation of more axillary buds, thus enhancing overall rhizome development. This is as expected since the formation of a node is positively correlated. In contrast, sucker production displayed a more complex relationship with GA₃ concentration. The data indicate a decrease in sucker count, dropping from a high of 100 ppm to a low of 500 ppm, followed by a slight increase at 750

ppm. This inverse correlation implies that GA₃ may redirect the plant's growth energy from producing aerial suckers to prioritizing underground rhizome expansion (Guo et al., 2020). There was a slight decrease in the number of suckers at the highest concentration, which could reflect hormonal imbalances caused by excessive GA₃, potentially leading to partial reactivation of sucker growth, as discussed by Zhang et al. (2021). These findings support the hypothesis that high concentrations of GA₃ favor rhizome growth over the development of aerial structures, such as leaves, petioles, or stems, and suckers, aligning with the conclusions of Kumar et al. (2020).

Figure 4.14

Effect of GA₃ on the number of rhizomes, nodes, and suckers of the Girigaca cultivar



To determine if the treatments produced significant effects, an ANOVA was conducted, and the results are summarized in Appendix 5. The analysis showed that GA₃ had a substantial impact on the number of rhizomes, nodes, and suckers per plant (Figure 4.14). For means comparison, Turkey's test was used, and the results are given in Table 4.7.

Table 4.7*Effect of GA₃ on parameters of Arrowroot propagules*

GA ₃ (ppm)	Arrowroot cultivar	Rhizomes Per plant	Nodes Per plant	Suckers Per plant	Rhizome length (cm)	Rhizome girth (cm)
0	Girigaca	0.00±0.00 ^c	0.00±0.00 ^c	8.25±0.96 ^a	0.00±0.00 ^d	0.00±0.00 ^d
	Kienyeji	0.00±0.00 ^c	0.00±0.00 ^c	1.67±0.78 ^c	0.00±0.00 ^d	0.00±0.00 ^d
100	Girigaca	23.67±2.77 ^b	108.42±19.35 ^d	0.00±0.00 ^d	11.14±1.18 ^b	2.96±0.04 ^a
	Kienyeji	0.00±0.00 ^c	0.00±0.00 ^c	3.58±1.11 ^b	0.00±0.00 ^d	0.00±0.00 ^d
250	Girigaca	28.17±2.92 ^{ab}	134.17±27.22 ^c	0.00±0.00 ^d	12.61±1.55 ^b	2.88±0.04 ^{ab}
	Kienyeji	0.00±0.00 ^c	0.00±0.00 ^c	3.08±0.99 ^{bc}	0.00±0.00 ^d	0.00±0.00 ^d
500	Girigaca	28.42±3.23 ^{ab}	188.75±43.40 ^b	0.00±0.00 ^d	13.05±1.51 ^b	2.76±0.05 ^b
	Kienyeji	0.00±0.00 ^c	0.00±0.00 ^c	2.82±0.98 ^{bc}	0.00±0.00 ^d	0.00±0.00 ^d
750	Girigaca	36.08±4.82 ^a	245.83±64.26 ^a	0.00±0.00 ^d	16.15±1.90 ^a	2.22±0.09 ^c
	Kienyeji	0.00±0.00 ^c	0.00±0.00 ^c	2.83±0.96 ^{bc}	0.00±0.00 ^d	0.00±0.00 ^d

Means followed by the same letter along the column are not significantly different at a $p \leq 0.05$ probability level.

Count of rhizomes generated

The reaction of arrowroot cultivars to gibberellic acid application reveals intriguing insights into their growth mechanisms. The Girigaca cultivar exhibited a significant positive response to increasing concentrations of GA₃, culminating in a remarkable value of 36.08 rhizomes at a concentration of 750 ppm. This occurrence is monumental, considering each rhizome has several nodes that sprout into plantlets; the multiplier effect is enormous, so only a few potted plants are needed to generate sufficient planting material. On the other hand, the Kienyeji cultivar showed no signs of rhizome formation across various GA₃ concentrations. This suggests a lack of genetic capacity for rhizome development or the potential inadequacy of GA₃ dosage. Alternatively, the Kienyeji may require a different set of plant growth regulators (PGRs) to stimulate rhizome formation, as supported by findings from Zhang et al. (2021),

who claimed that a combination of PGRs is essential for achieving optimal yield and quality in hot pepper (*Capsicum annuum*) production.

The differential response to GA₃ between these two cultivars may stem from inherent genotypic variations specific to each cultivar's hormonal sensitivity. Previous research has underscored similar discrepancies in rhizomatous and tuberous plants, highlighting how genetic factors influence vegetative reproduction (Ud-Deen, 2009). Singh et al. (2017) noted that the sensitivity to GA₃ is well documented for arrowroot.

Moreover, the role of environmental conditions in these plant responses cannot be understated. Gondim et al. (2018) noted that under low-light conditions, specific arrowroot cultivars tend to redirect the distribution of photoassimilates from corms to meristematic tissues, potentially facilitating rhizome growth and development. These findings are consistent with earlier studies that investigated the diverse effects of GA₃ in crop growth. For instance, Vreugdenhil & Helder (1992) observed that GA₃ stimulates stolon growth, while Barani et al. (2023) reported that it can inhibit tuber initiation in potatoes (*Solanum tuberosum*) by hindering starch synthesis.

However, Guo et al. (2020) in a review on the developmental regulation of stolon and rhizomes for vegetative propagation, reported a combination of high concentrations of carbohydrates after induction of axillary buds, attributed to the elevated rate of photosynthesis. Yoshida et al. (2016) investigated the initiation and growth of rhizomes instead of suckers in a wild rice species and revealed that the process was influenced by light intensity. This evidence suggests that, in addition to the influence of genes on rhizome-forming plants, environmental conditions play a role in activating axillary buds (Abelenda et al., 2011). This trait is of great significance, since it can be adopted for a faster method of arrowroot multiplication compared to the production of suckers. These mechanisms may indicate the genesis of rhizome growth in arrowroot cultivars responsive to gibberellic acid (Caliskan et al., 2021).

In addition to promoting physical growth, GA₃ is reportedly involved in breaking apical dormancy and increasing cormel production (Aljaser et al., 2021; Ibrahim et al., 2021). In these metabolic processes, the growth of axillary buds is suppressed by auxins produced in the apical bud; consequently, high doses of GA₃ seemed to override the effect of the GA₃-inhibitor that suppresses the auxin hormone responsible for apical dominance (Ud-Deen, 2009). These findings were collaborated by a study conducted by Mintah & Arhin (2020) on the initiation of axillary bud of plantain (*Musa AAB*) by applying natural PGRs via coconut water (CW) and auxin (IAA), the results demonstrated that both substances induced significant proliferation of axillary bud and shoot formation of plantain, that were similar to those observations made after treatment of arrowroot (*Girigaca* cultivar) with gibberellic acid under investigation. Wang et al. (2020) reinforced this hypothesis by illustrating how GA₃ counters auxin's inhibitory effects, thereby facilitating the emergence and growth of axillary buds from dormancy.

Furthermore, GA₃ enhances the biosynthesis of cytokinins or amplifies their signaling pathways, thus promoting the activation of axillary buds (Asante et al., 2022). This hormonal interplay is essential, as GA₃ induces cell elongation and division in these axillary buds, modulating the expression of genes crucial for transitioning out of dormancy and subsequent growth and development into rhizomes or suckers (Guo et al., 2020).

Importantly, the apical bud serves as a crucial sink for nutrients and sugars. Zheng et al. (2018) suggested that the modulation of resource distribution driven by GA₃ is instrumental in activating the dormant buds, effectively reallocating essential materials and energy to support their growth. This multifaceted action of GA₃ and its interaction with various growth regulators emphasize the complexity of plant development and the significance of genetic and environmental factors in these processes (Guo et al., 2020).

Qiu et al. (2018) investigated the impact of auxin and cytokinins, plant growth regulators, on breaking dormancy and initiating axillary bud growth in strawberry (*Fragaria vesca* L.) in stolons. Their findings concluded that a reduction in auxin accumulation stimulated the regeneration of vegetative shoots in dormant axillary buds, and that the exogenous application of cytokinins produced a similar effect. Moreover, Quo et al. (2020) highlighted recent research that has shed new light on the mechanisms involving phytohormones (GA₃ and ABA), as well as the influences of high sugar levels and light intensity (Ainsworth & Bush, 2011). This research elucidates their role in regulating axillary bud extensions. As suggested by Aljaser & Anderson (2021), a comparable mechanism is likely involved in the growth and development of rhizomes from arrowroot corms as observed in the current study.

This study investigated the emergence of rhizomes 120 days after transitioning potted arrowroot plants from a greenhouse setting, characterized by elevated temperatures and high-intensity light conditions, to a cooler environment with 50% shade. Notably, the external application of gibberellic acid (GA₃) significantly stimulated rhizome formation under tropical conditions. This phenomenon may be attributed to enhanced nutrient utilization as resources are redirected from the shoot system due to increased photosynthetic output (Masuda et al., 2012). The boost in photosynthesis provides a strong foundation for overall plant growth (Gent & Seginer, 2012).

As a result of this treatment, the arrowroot plants demonstrated increased uptake of nutrients and water while exhibiting reduced transpiration rates. These modifications improved gaseous exchange, heightened nutrient translocation, and facilitated the accumulation of sugars and other metabolites. Such physiological changes likely triggered the plants' pathways for the rapid formation of additional storage organs, such as rhizomes (Ainsworth & Bush, 2011; Chaudhary et al., 2019).

When non-structural carbohydrates (NSC), which are critical for energy and structural integrity, produced by the leaves exceed the demands of new shoot growth and development, particular plant species (Aluko et al., 2021), such as arrowroot (*Colocasia esculenta* L.), respond by developing rhizomes (Takahashi et al., 2018). This aligns with findings from Gent & Seginer (2012), indicating that, in this ecological context, the availability of carbohydrates significantly influences whether plants develop additional storage structures or prioritize new growth. Bhuiyan et al. (2015) explain that this response can act as a secondary adaptive mechanism to cope with environmental shocks, leading to the conversion of non-structural carbohydrates (NSCs) into a storable form and the development of rhizomes.

The existing literature has not documented this particular phenomenon observed in this study, where dormant lateral axillary buds on arrowroot corm were stimulated to produce rhizomes through the application of foliar gibberellic acid (GA₃) under greenhouse conditions, combined with the intensive use of organic manure, organic fertilizer, and biochar amendment. This research exemplifies the first comprehensive report detailing a protocol for inducing corm-rhizome development by integrating exogenous GA₃ application, environmental stimuli, temperature variations, and substantial nutrient supplementation.

The findings of this study highlight the significant role of exogenous GA₃ application and the abundance of sucrose supplied from source tissues, which is driven by a high photosynthesis rate resulting from elevated temperatures in the greenhouse (Gent & Seiner, 2012). Takahashi et al. (2018) proposed that this is a crucial step in initiating axial growth, which ultimately leads to the formation of rhizomes. This research highlights the intricate interplay between plant growth regulators (PGRs) and carbohydrate availability, which is crucial for promoting vigorous growth patterns in arrowroot and deepening our understanding of the strategies plants employ to develop in response to varying environmental conditions.

Masuda et al. (2012) investigated the transformation of rhizomes into storage organs in Lotus (*Nelumbo nucifera* Gaertn.), a plant characterized by its rhizomatous growth. The researchers suggested that this transformation is significantly influenced by plant growth regulators (PGRs), particularly gibberellic acid (GA₃) and abscisic acid (ABA). While this study examines explicitly how GA₃ affects the growth and development of arrowroots, the corms produce numerous storage rhizomes, similar to those of the Lotus (*Nelumbo nucifera* Gaertn) plant. These observations, made after the foliar application of GA₃ to the selected local cultivars of arrowroot, revealed the role of gibberellic acid in the rhizome formation process. However, further research is necessary to understand the mechanisms that trigger rhizome development in the Dasheen-type arrowroot cultivars.

The foliar application of GA₃ caused visible damage to the shoots of the potted mother plants, with varying responses depending on the cultivar. Notably, the Girigaca cultivar exhibited a distinct dose-dependent increase in shoot damage, indicating its heightened sensitivity to higher concentrations of GA₃. Despite experiencing petiole deformation and retention of some juvenile leaves, these plants eventually resumed normal growth, although specific data regarding this recovery are not provided in the current analysis.

In contrast, the Kienyeji cultivar demonstrated remarkable resilience, consistently showing minimal shoot damage across a range of GA₃ concentrations. This resilience suggests that Kienyeji possesses inherent resistance mechanisms that allow it to withstand GA₃ stress and fluctuating environmental conditions more effectively than its counterparts.

Caliskan et al. (2021) investigated the effects of different dosages of gibberellic acid (GA₃) applied as a foliar treatment on the growth, yield, and quality traits of potato (*Solanum tuberosum* L.). Their findings indicated that GA₃ caused deformities in potato tubers, with the severity of these deformities increasing with the elevation of GA₃ dosage. This finding supports

the current study, which observed clear deformations in arrowroot shoots. These included the retraction of the youngest leaves and entrapment within the petiole groove; in more severe cases, the twisting of the shoot ultimately led to shoot death. Such observations underscore the need for further investigation into the effects of plant growth regulators on arrowroot. Gaining a deeper understanding of how varying concentrations of GA₃ impact plant cell wall integrity, polyphenol pathways, and genetic variability may help elucidate these observed phenomena.

Number of nodes per rhizome

The analysis of the Girigaca cultivar exposed an extraordinary response to GA₃ treatments, resulting in a significant increase in the number of nodes per rhizome. Specifically, the average number of nodes increased from 108.42 at a GA₃ concentration of 100 ppm to a remarkable 245.83 nodes at 750 ppm. This considerable increase highlights a clear dose-dependent relationship, whereby GA₃ effectively stimulates the dormant corm lateral axillary buds to proliferate rhizomes, after which it triggers internodal elongation, resulting in substantial rhizome growth (Yang et al., 2015).

In contrast, the Kienyeji cultivar had no nodes across all GA₃ treatment levels. This outcome suggests that the cultivar's inherent limitations in rhizome development under the experimental conditions of GA₃ application and greenhouse conditions render it unsuitable for propagation strategies that depend on rhizome production.

The remarkable increase in nodes per rhizome observed in the Girigaca cultivar signifies a significant advancement in understanding the mechanisms of rhizome development. This breakthrough enhances scientific knowledge surrounding arrowroot macropropagation and paves the way for large-scale production and commercialization of vegetative propagation materials (Plantlets) generated from rhizomes. Such advancements could significantly support farmers in addressing planting material shortages, subsequently improving their productivity

and strengthening food security. Furthermore, the implications for agricultural sustainability are profound, as optimized cultivation practices may adopt more resilient farming systems capable of adapting to market demands and the environmental challenges associated with arrowroot cultivation.

Number of suckers

In the investigation of sucker production among the two cultivars, the Kienyeji cultivar exhibited a conspicuously low average of 3.58 suckers when treated with the lowest concentration of GA₃. In contrast, the Girigaca cultivar produced the highest average number of suckers (8.25) without any GA₃ treatment, with distilled water as the control. This finding raises intriguing questions, particularly for the Kienyeji cultivar. It appears that an increase in GA₃ concentration did not lead to a proportional increase in sucker production compared to the control treatment. This observation suggests that GA₃ may not be an effective stimulant for sucker activation in this cultivar, highlighting the need for further investigation into the hormonal signaling pathways that influence arrowroot growth.

Additionally, the observed increase in sucker production for Kienyeji, along with the lack of significant rhizome development, indicates a potential tendency for this cultivar to produce aerial suckers rather than the subterranean growth typically associated with rhizomes. This phenomenon may be attributed to specific hormonal signaling pathways within the plant, as discussed by Kumar et al. (2020) and Besso-Uehara et al. (2018) which mediate growth responses.

According to research conducted by Melis and Van Stadin (1984) plant growth regulators (PGRs) generally work together to promote plant development, with each serving a distinct function. For example, GA₃ significantly influences tuberization by affecting the rate of shoot growth. Other PGRs, such as cytokinins, auxins, and abscisic acid, play a key role in regulating

sink activity, which includes controlling the processes of cell division and enlargement essential for shoot growth. The interaction among these various hormones is crucial for optimizing plant development.

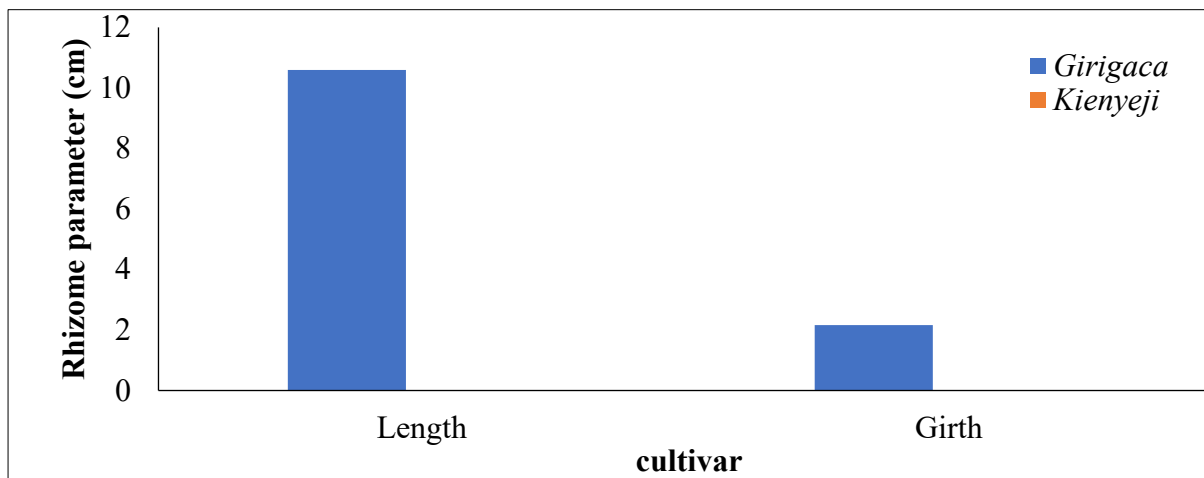
The findings of this study are supported by those of Masuda et al. (2012) who observed that the transition of rhizomes into storage tissues primarily originates from the plant's stems, such as corms, and is initiated by GA₃. It is also essential to consider the roles of other plant growth regulators (PGRs) in this process. Arrowroot usually propagates from the apical buds formed on actively growing corms, while the axillary buds remain dormant until they are activated to produce new propagules (Asante et al., 2012). This trait presents a valuable opportunity for future strategies to multiply the vegetative propagation materials of arrowroot. By leveraging this rapid and cost-effective cultivation method, farmers can enhance productivity and sustainability in their arrowroot farming operations. For instance, GA₃ significantly impacts tuberization by influencing the rate of shoot growth, while other PGRs, such as cytokinins, auxins, and abscisic acid, help regulate sink activity, which includes controlling cell division and enlargement necessary for shoot growth. The interplay among various hormones is essential for optimizing plant development.

4.2.3 Effect of GA₃ on rhizome length and girth parameters

Figure 4.15 presents a comparative analysis of the rhizome development responses observed in the Girigaca and Kienyeji cultivars. The Girigaca cultivar demonstrated a significant advantage, exhibiting notably longer rhizomes than the Kienyeji cultivar, which did not produce rhizomes. Specifically, as shown in Table 4.9, the Girigaca cultivar achieved a mean rhizome length slightly above 10 cm and a girth of around 2 cm following the foliar application of gibberellic acid (GA₃). In contrast, the Kienyeji cultivar showed a complete absence of rhizome growth; the experimental plant failed to form rhizomes.

Figure 4.15

Effect of GA₃ on rhizome length and girth



To determine if the treatments produced significant effects, an ANOVA was conducted, and the results are summarized in Appendix 5. The results showed that GA₃ has a substantial impact on rhizome length and girth. For means comparison, Turkey's test was used, and the results are given in Table 4.8.

Table 4.8*Effect of GA3 on parameters of the propagules*

GA3 Conc. (ppm)	Time (Day)	Girigaca					Kienyeji
		Number of Rhizomes	Rhizome length (cm)	Rhizome girth (cm)	Number of Suckers	Nodes per rhizome	Number of Suckers
0	60	0.00±0.00 ^g	0.00±0.00 ^g	0.00±0.00 ^b	0.00±0.00 ^c	0.00±0.00 ^g	0.00±0.00 ^c
	120	0.00±0.00 ^g	0.00±0.00 ^g	0.00±0.00 ^b	10.33±3.18 ^a	0.00±0.00 ^g	0.00±0.00 ^c
	180	0.00±0.00 ^g	0.00±0.00 ^g	0.00±0.00 ^b	5.33±0.88 ^b	0.00±0.00 ^g	0.67±0.67 ^d
	240	0.00±0.00 ^g	0.00±0.00 ^g	0.00±0.00 ^b	9.33±1.45 ^a	0.00±0.00 ^g	6.00±0.58 ^b
100	60	25.67±9.17 ^e	6.35±1.11 ^f	2.97±0.03 ^a	0.00±0.00 ^c	39.00±2.52 ^{ef}	0.00±0.00 ^c
	120	17.00±4.16 ^f	9.00±1.46 ^c	3.07±0.07 ^a	0.00±0.00 ^c	52.33±8.21 ^e	0.00±0.00 ^c
	180	25.33±5.36 ^e	14.65±0.67 ^c	2.83±0.09 ^a	0.00±0.00 ^c	180.67±5.93 ^{cd}	6.33±0.67 ^b
	240	26.67±2.85 ^e	14.56±0.96 ^c	2.97±0.03 ^a	0.00±0.00 ^c	161.67±10.99 ^d	8.00±0.58 ^a
250	60	22.00±7.37 ^{ef}	7.58±0.55 ^f	2.83±0.12 ^a	0.00±0.00 ^c	41.00±14.36 ^{ef}	0.00±0.00 ^c
	120	28.67±7.26 ^{de}	11.17±1.83	2.97±0.03 ^a	0.00±0.00 ^c	62.00±13.00 ^e	0.00±0.00 ^c
	180	27.33±1.76 ^{de}	14.65±1.56	2.90±0.06 ^a	0.00±0.00 ^c	221.67±11.41 ^c	6.00±1.53 ^b
	240	34.67±6.06 ^{cd}	17.04±4.59 ^{bc}	2.83±0.12 ^a	0.00±0.00 ^c	212.00±44.68 ^c	6.33±0.33 ^b
500	60	19.00±4.58 ^f	7.87±1.27 ^f	2.87±0.03 ^a	0.00±0.00 ^c	37.00±10.79 ^f	0.00±0.00 ^c
	120	21.67±4.84 ^{ef}	8.83±1.50 ^{ef}	2.57±0.09 ^a	0.00±0.00 ^c	55.00±9.17 ^e	0.00±0.00 ^c
	180	40.33±3.93 ^b	17.91±1.25 ^{bc}	2.73±0.09 ^a	0.00±0.00 ^c	320.67±11.68 ^b	7.33±0.67 ^a
	240	32.67±4.67 ^{cd}	17.59±0.76 ^{bc}	2.87±0.03 ^a	0.00±0.00 ^c	342.33±12.55 ^b	3.00±0.58 ^c
750	60	29.67±4.33 ^d	11.37±1.55 ^d	2.33±0.29 ^a	0.00±0.00 ^c	52.00±8.89 ^e	0.00±0.00 ^c
	120	19.67±3.53 ^f	9.92±1.67 ^{de}	2.40±0.00 ^a	0.00±0.00 ^c	39.00±2.08 ^{ef}	0.00±0.00 ^c
	180	59.00±6.03 ^a	23.88±2.81 ^a	2.07±0.18 ^a	0.00±0.00 ^c	478.33±79.20 ^a	7.67±0.33 ^a
	240	36.00±5.00 ^c	19.43±0.19 ^b	2.07±0.18 ^a	0.00±0.00	414.00±56.05 ^a	3.67±0.33 ^c

Means followed by the same letter along the column are not significantly different at a $p \leq 0.05$ probability level.

Rhizome length and girth

At a concentration of 750 ppm, the increase in rhizome length was most significant, measuring approximately 16.15 cm. Similarly, the increase in girth peaked at 2.22 cm, conspicuously, for the Kienyeji cultivar; no rhizomes were formed at any of the GA₃ concentrations, and hence no measurements for rhizome length or girth could be recorded. The findings from earlier research conducted by Guo et al. (2020) have shown that exogenous foliar application of GA₃ has a positive influence on rhizome elongation. This enhancement in lateral rhizome growth suggests that applying GA₃ externally is crucial in stimulating cell division and elongation processes (Mehdi et al., 2024).

Interestingly, while GA₃ promotes the elongation of rhizomes, it appears to inhibit girth thickening. This was confirmed by results from research conducted by Guo et al. (2020), which showed that GA₃ treatment may modify the expression of genes that regulate growth-related physiological processes and metabolic pathways, resulting in this effect. The trend observed in the girth measurements indicates a consistent decline as the concentration of GA₃ increases, suggesting that under exogenous GA₃ influence, the plant prioritizes rhizome elongation over radial growth (Aluko et al., 2021). This observation highlights the complexities of how hormonal signals regulate the balance between rhizome elongation and storage functions (Qiu et al., 2021).

Despite gaps in understanding the precise mechanisms governing rhizome initiation and development (Guo, 2020), it is established that the interplay of hormones, including GA, ABA, and auxins (IAA), plays a crucial role in regulating these processes through modulation of gene expression, as articulated by Ma & Huang (2016). Furthermore, Bessho-Uehara et al. (2018) proposed that both GA₃ and auxin are integral to the developmental processes of rhizomes, influencing signaling pathways that ultimately affect their morphology. This is further supported by Yoshida et al. (2016) who studied rhizome initiation and development in wild

rice (*Oryza longistaminata*), reporting that axillary bud activation in a rhizome is sensitive to environmental conditions, such as temperature and light (Guo et al., 2020).

These findings have significant implications, as the enhanced elongation of rhizomes increases their capacity for vegetative propagation. Additionally, it facilitates the production of longer rhizomes that can generate more nodes. This increase in nodal cuttings for every rhizome ultimately enhances the potential for a rapid multiplication of propagation materials while preserving the cultivar's genotypes. Further insights are illustrated in Figure 4.15, which documents a pronounced response in rhizome elongation and thickening as the GA₃ dosage increased. At higher levels of GA₃, rhizome length showed significant growth, while the girth remained relatively consistent. No rhizome growth was observed in the control treatment that lacked GA₃ (0 ppm), establishing a baseline of inactivity. GA₃ concentrations increased from 100 to 750 ppm, resulting in a progressive increase in rhizome length, starting at 5.57 cm at 100 ppm and reaching a maximum of 8.07 cm at 750 ppm. Conversely, rhizome girth exhibited a declining trend as GA₃ concentrations increased, decreasing from 1.48 cm at 100 ppm to 1.11 cm at 750 ppm.

Table 4.9 presents a detailed analysis of the statistically significant correlations observed among various rhizome traits, highlighting a strong relationship between the length of the rhizome and the number of nodes per rhizome, with a correlation coefficient (r) of 0.851 and a highly significant p -value of less than 0.001. Additionally, the data indicate an even stronger correlation between the number of rhizomes and the length of each rhizome ($r = 0.934$, $p < 0.001$), as well as a strong correlation between the number of rhizomes and their girth ($r = 0.824$, $p < 0.001$).

These findings suggest that the increased rhizomes are primarily attributable to pronounced improvements in their length and girth, which can be interpreted as a favorable physiological

response to the application of gibberellic acid treatment. Furthermore, statistical analysis revealed a significant interaction between different cultivars and GA₃ concentrations, indicating that the effects of GA₃ treatment varied among the cultivars tested.

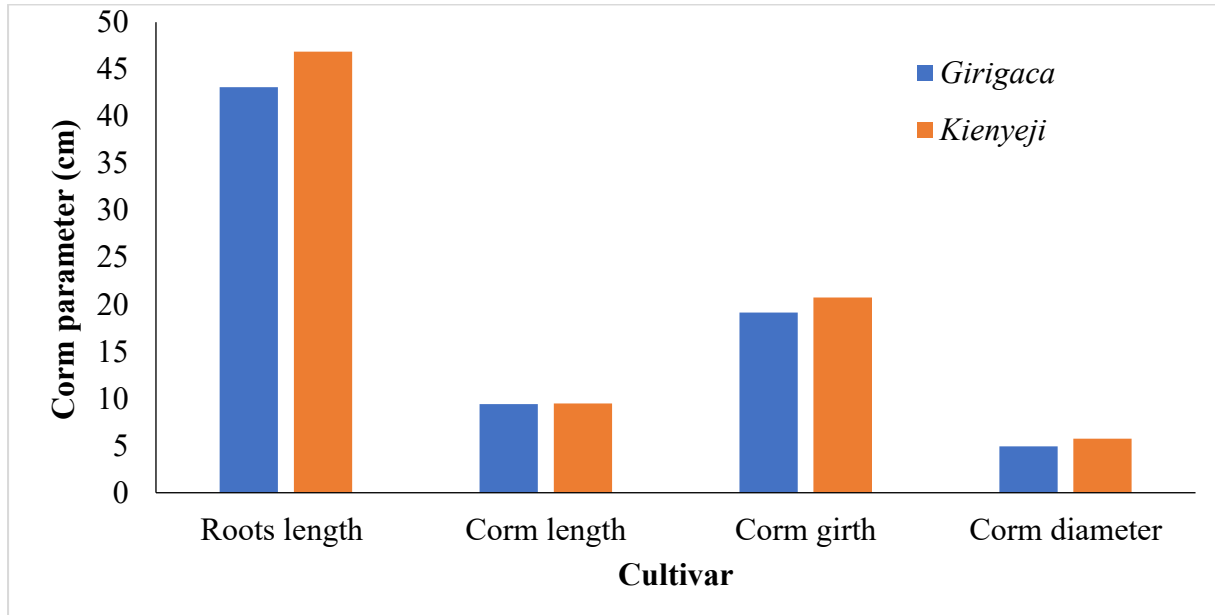
The Girigaca cultivar exhibited a pronounced enhancement in rhizome development, particularly when the GA₃ concentration was optimized at 750 ppm, suggesting that this cultivar is more responsive to hormonal treatment. In contrast, the Kienyeji cultivar exhibited a comparatively subdued response in terms of rhizome length and girth. However, it demonstrated a remarkable capability for sucker production, particularly at lower GA₃ application rates. This distinct response stresses the importance of both cultivar selection and hormonal treatment concentration in maximizing rhizome and sucker yield within these arrowroot cultivars.

4.2.4 Effect of GA₃ on the mother plant subterranean parameters

Figure 4.16 presents the results of the analysis of the effect of GA₃ on the growth parameters of the mother plant: root length, corm length, girth, and diameter observed in the Girigaca and Kienyeji cultivars. The root length of both cultivars responded positively; moreover, the Kienyeji cultivar had a slight edge over the Girigaca cultivar. The corm length was diminished for both cultivars. The corm girth was almost double the corm length, and both cultivars were short, while the corm diameter was severely reduced, as shown in Figure 4.16.

Figure 4.16

Effect of GA₃ on mother plant corm parameters



To determine if the treatments produced significant effects, an ANOVA was conducted, and the results are summarized in Appendix 5. The analysis revealed that GA₃ had a substantial impact on root length, corm length, girth, and diameter. For means comparison, Turkey's test was used, and the results are given in Table 4.9.

Table 4.9*Effect of GA₃ concentration treatment on root, corm, and cormel parameters*

GA₃	Roots	Roots	Corm	Corm	Corm	Corm	Cormel	Cormel
(ppm)	length (cm)	weight (g)	Length (cm)	girth (cm)	Diameter (cm)	weight (g)	number	weight/plant (g)
0	43.13±2.38 ^a	160.83±13.04 ^a	8.93±0.53 ^a	20.10±0.53 ^a	5.48±0.18 ^a	193.33±19.75 ^a	4.04±0.94 ^a	135.63±32.81 ^a
100	41.80±3.21 ^a	143.96±13.93 ^a	9.08±0.50 ^a	19.65±0.59 ^a	5.13±0.14 ^a	142.29±10.71 ^b	3.42±0.82 ^a	106.67±26.56 ^a
250	47.89±3.08 ^a	159.79±12.61 ^a	11.11±2.21 ^a	19.58±0.72 ^a	5.25±0.15 ^a	175.42±16.16 ^{ab}	3.71±1.05 ^a	108.54±26.58 ^a
500	44.23±3.73 ^a	153.00±13.58 ^a	9.22±0.57 ^a	20.40±0.54 ^a	5.42±0.17 ^a	203.91±17.08 ^a	3.78±0.99 ^a	114.39±36.27 ^a
750	47.72±2.67 ^a	158.96±13.95 ^a	8.88±0.49 ^a	19.90±0.55 ^a	5.39±0.16 ^a	184.17±15.88 ^a	4.46±1.11 ^a	147.92±38.82 ^a

Means followed by the same letter along the column are not significantly different at a $p \leq 0.05$ probability level.

Table 4.9 and Figure 4.16 comprehensively analyze root length, root weight, and corm parameters, illustrating the varying effects of different gibberellin dosages on these measurements. Among the treatments, the most pronounced root length, measuring 47.89 cm, was observed at a GA₃ concentration of 250 ppm. Regarding root weight, the "Mother corm" exhibited optimum development at a GA₃ concentration of 500 ppm, achieving a maximum weight of 203.91 g.

The Kienyeji cultivar exhibited variability in cormel numbers and weight per plant across the different treatments applied. However, the data did not reveal a definitive trend across the differing concentrations of GA₃. Remarkably, the Girigaca cultivar did not yield any cormels under any of the GA₃ treatments, which raises questions about its sensitivity to gibberellin hormone treatments. Conversely, the Kienyeji cultivar consistently produced cormels and showed marked improvement in root weight, corm weight, and the number of cormels as GA₃ concentrations increased. For instance, at a concentration of 750 ppm, the Gikuyu Kienyeji cultivar reached its highest number of cormels at 8.92 and attained a significant weight per plant of 295.83 g.

The results depicted in Figure 4.16 illustrate the impact of different arrowroot cultivars and varying concentrations of gibberellic acid on the extent of shoot damage. This study explicitly compares two distinct cultivars, Girigaca and Kienyeji, across a range of GA₃ concentrations: 0 ppm, 100 ppm, 250 ppm, 500 ppm, and 750 ppm.

Conspicuously, the Girigaca cultivar exhibited notable sensitivity to GA₃ treatment, showing a progressive increase in shoot damage as the GA₃ concentration elevated. The damage was absent at zero ppm, recorded at 1.00 ± 0.00 , indicating a healthy shoot condition. However, as the concentration rose to 750 ppm, the shoot damage intensified significantly, reaching a peak of 4.33 ± 0.19 . This upward trend in damage highlights Girigaca's vulnerability to higher GA₃

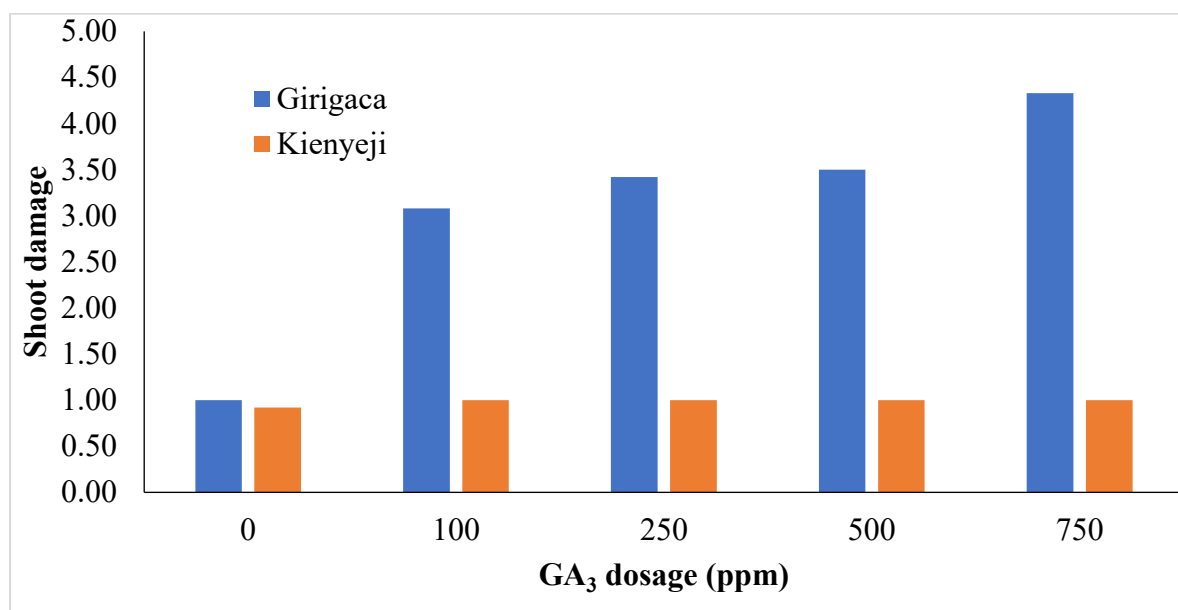
concentrations, suggesting that this cultivar may experience adverse physiological effects when exposed to excessive hormone levels (Plate 4.2).

In contrast, the Kienyeji cultivar demonstrated remarkable resilience to GA₃ treatment, showing no noticeable shoot damage at any of the concentrations tested, consistently maintaining a score of 1.00 ± 0.00 . This stability across all GA₃ levels suggests that the Kienyeji cultivar has a robust tolerance to gibberellic acid, making it less susceptible to the potential detrimental effects of increased hormone exposure.

Overall, the findings highlight the differential responses of these cultivars to GA₃ treatment, with the Girigaca cultivar exhibiting heightened sensitivity and the Kienyeji cultivar displaying significant resilience. This information is critical for understanding the physiological impacts of GA₃ on arrowroot cultivars and can inform future agricultural practices and cultivar selection based on hormone sensitivity.

4.2.5 Effect of GA₃ on mother plant shoot parameters

Table 4.10 shows the results of the analysis of the effect of GA₃ on mother plant shoot parameters: shoot damage, stem girth, height, leaf area, and the number of leaves in the Girigaca and Kienyeji cultivars. For the Girigaca cultivar, the damage due to the application of GA₃ at 100, 250, and 500 ppm was comparable; however, at the highest dose of 750 ppm, it was severe. It was observed that the Kienyeji cultivar was not affected by any of the GA₃ doses; there were no detectable visible morphological deformations, as presented in Figure 4.17.

Figure 4.17*Effect of cultivar and GA₃ treatment on shoot damage***Table 4.10***Effect of GA₃ concentration on mother plant shoot parameters*

GA ₃ (ppm)	Stem girth (cm)	Height (cm)	Leaf area (cm ²)	Number of leaves	Shoot damage
0	17.63±0.65 ^a	61.22±2.05 ^b	449.32±31.14 ^{ab}	12.54±1.27 ^a	0.96±0.04 ^b
100	17.59±0.82 ^a	59.90±2.90 ^b	396.34±33.28 ^b	13.08±1.29 ^a	2.04±0.25 ^a
250	18.31±0.64 ^a	61.84±2.02 ^a	403.65±27.91 ^b	12.92±1.22 ^a	2.21±0.31 ^a
500	18.16±0.62 ^a	63.85±2.17 ^{ab}	482.89±32.17 ^a	12.96±1.28 ^a	2.25±0.30 ^a
750	18.43±0.57 ^a	65.42±2.10 ^a	452.30±32.86 ^{ab}	12.63±1.24 ^a	2.67±0.36 ^a

Means followed by the same letter along the column are not significantly different at a $p \leq 0.05$ probability level.

In a detailed comparative analysis of the two cultivars, Girigaca and Kienyeji, several key morphological and physiological traits were evaluated to assess their growth parameters and resilience. The Kienyeji cultivar exhibited a notably wider stem girth, measuring an impressive

19.16 cm, which was significantly larger than that of the Girigaca cultivar, which measured 16.89 cm. However, in terms of height, the Girigaca cultivar showed superior growth, reaching an impressive height of 68.07 cm compared to the Kienyeji cultivar, which measured 56.82 cm. This height advantage may indicate a distinct growth pattern in response to environmental conditions or genetic factors inherent to the Girigaca cultivar.

Additionally, the leaf count favored the Girigaca cultivar, which averaged 14.75 leaves per plant, indicating more prolific leaf development than the Kienyeji cultivar, which had an average of only 10.90 leaves per plant. The higher leaf count in Girigaca could enhance its photosynthetic capacity, contributing to the overall vigor of the plant. Despite the differences in height and leaf production, the measurements of leaf area did not reveal any significant variations between the two cultivars. This suggests that while the number of leaves differed, the overall leaf size was relatively comparable, maintaining functional parity in terms of photosynthetic efficiency.

When evaluating shoot damage levels on the mother plant, an essential aspect of plant resilience was highlighted. The Kienyeji cultivar showed a remarkably lower level of shoot damage, receiving a rating of 0.98, while the Girigaca cultivar recorded a notably higher damage rating of 3.07. This indicates that the Kienyeji cultivar exhibits enhanced resilience or tolerance to potential stressors introduced during GA₃ treatment, suggesting its vigor in adverse conditions. While both cultivars exhibit distinct advantages, Kienyeji, with its thicker stems and resilience, and Girigaca, with its height and leaf count, these findings provide valuable insights into their growth characteristics and potential applications in agronomic practices. The study's findings indicate that gibberellic acid (GA₃) has a significant impact on the growth parameters of arrowroot mother plants. The results demonstrate a substantial increase in plant height with rising GA₃ concentrations, with the tallest plants measuring 65.42 cm at a concentration of 750 ppm. This suggests that elevated levels of GA₃ effectively promote

vertical growth, likely due to its role in stimulating cell elongation and overall growth processes.

In contrast to height, stem girth remained relatively stable across the different GA₃ treatments. This lack of significant variation indicates that while GA₃ may enhance height, it does not necessarily contribute to increased stem thickness, which may be influenced by other physiological factors and possibly genetic characteristics.

Outstandingly, the maximum leaf area was recorded at a GA₃ concentration of 500 ppm, indicating that this level optimally supports leaf expansion. In comparison, lower concentrations of 100 and 250 ppm resulted in significantly reduced leaf area, potentially limiting the plant's photosynthetic capacity and subsequently impacting overall growth.

However, it is essential to highlight a concerning outcome associated with increased GA₃ concentrations: the severity of shoot injury intensified as the dosage increased, reaching a peak at 750 ppm. This finding emphasizes the risk of potential phytotoxicity at elevated doses, suggesting that while GA₃ can enhance specific growth parameters, excessive application may have detrimental effects on plant health, as illustrated in Figure 4.16. These insights enhance our understanding of the optimal utilization of GA₃ in arrowroot cultivation, underscoring the necessity for careful dosage to balance growth promotion with plant safety.

4.2.6 Effect of GA₃ on mother plant parameters

Table 4.10 presents a comprehensive analysis of how varying concentrations of GA₃ (gibberellic acid) treatment interact with two distinct arrowroot cultivars, namely Girigaca and Kienyeji. This analysis focuses particularly on the characteristics of the mother plant shoots, shedding light on their growth responses to GA₃ application.

The findings indicate that the Girigaca cultivar demonstrates a notably positive response to GA₃ treatment, characterized by substantial increases in both plant height and the number of leaves produced. Specifically, the application of GA₃ not only stimulated vertical growth but also enhanced foliar development, which is crucial for the plant's photosynthetic capacity.

In contrast, the Kienyeji cultivar exhibited consistently superior stem girth across all tested concentrations of GA₃. This suggests that while Kienyeji may not respond in terms of height or leaf quantity as significantly as Girigaca, its ability to develop thicker stems could be interpreted as a desirable trait for resistance to physical stressors and improved structural integrity.

Among the various concentrations applied, 500 ppm emerged as the most effective treatment level, demonstrating an optimal balance of growth characteristics for both cultivars. This concentration not only boosted plant height and leaf production but also contributed to enhanced overall vigor and development. Such improvements in growth parameters are critical for achieving higher yields in arrowroot cultivation.

These results highlight the potential of GA₃ as a viable growth regulator that can be strategically utilized to enhance arrowroot cultivation. Furthermore, the differential responses observed between the two cultivars underscore the importance of tailoring GA₃ applications to maximize the growth potential of each cultivar, paving the way for more effective and informed cultivation practices in arrowroot farming.

The reaction of arrowroot cultivars to varying concentrations of gibberellic acid reveals intriguing insights into their growth mechanisms. The Girigaca cultivar exhibited a significant positive response to increasing concentrations of GA₃, culminating in a remarkable value of 36.08 at a concentration of 750 ppm. In stark contrast, the Kienyeji cultivar exhibited no rhizome formation across various GA₃ concentrations. This suggests a lack of genetic capacity

for rhizome development or the potential inadequacy of GA₃ dosage. Alternatively, the Kienyeji may require a different set of plant growth regulators (PGRs) to stimulate rhizome formation, as supported by findings from Zhang et al. (2021), who posited that a combination of PGRs is essential for achieving optimal yield and quality in hot pepper (*Capsicum annuum*) production.

The differential response to GA₃ between these two cultivars may stem from inherent genotypic variations specific to each cultivar's hormonal sensitivity. Previous research has underscored similar discrepancies in rhizomatous and tuberous plants, highlighting how genetic factors influence vegetative reproduction (Ud-Deen, 2009). Singh et al. (2017) noted that the sensitivity to GA₃ is well documented for arrowroot.

Moreover, the role of environmental conditions in these plant responses cannot be understated. Gondim et al. (2018) noted that under low-light conditions, specific arrowroot cultivars tend to redirect the distribution of photoassimilates from corms to meristematic tissues, potentially facilitating rhizome growth and development. These findings are consistent with earlier studies that investigated the diverse effects of GA₃ in crop growth. For instance, Vreugdenhil & Helder (1992) observed that GA₃ stimulates stolon growth, while Barani et al. (2023) reported that it can inhibit tuber initiation in potatoes (*Solanum tuberosum*) by hindering starch synthesis.

However, Guo et al. (2020), in a review on the developmental regulation of stolon and rhizomes for vegetative propagation, reported a combination of high concentrations of carbohydrates after induction of axillary buds, attributed to the elevated rate of photosynthesis. Yoshida et al. (2016) investigated the initiation and growth of rhizomes instead of suckers in a wild rice species and revealed that the process was influenced by light intensity. This evidence suggests that, in addition to the influence of genes on rhizome-forming plants, environmental conditions play a role in activating axillary buds (Abelenda et al., 2011). This trait is of great significance,

since it can be adopted for a faster method of arrowroot multiplication compared to the production of suckers. These mechanisms may indicate the genesis of rhizome growth in arrowroot cultivars responsive to gibberellic acid (Caliskan et al., 2021).

In addition to promoting physical growth, GA₃ is reportedly involved in breaking apical dormancy and increasing cormel production (Aljaser et al., 2021; Ibrahim et al., 2021). In these metabolic processes, the growth of axillary buds is suppressed by auxins produced in the apical bud; consequently, high doses of GA₃ seemed to override the effect of the GA₃-inhibitor that suppresses the auxin hormone responsible for apical dominance (Ud-Deen, 2009). These findings were collaborated by a study conducted by Mintah & Arhin (2020) on the initiation of axillary bud of plantain (*Musa AAB*) by applying natural PGRs via coconut water (CW) and auxin (IAA), the results demonstrated that both substances induced significant proliferation of axillary bud and shoot formation of plantain, that were similar to those observations made after treatment of arrowroot (*Girigaca* cultivar) with gibberellic acid under investigation. Wang et al. (2020) reinforced this hypothesis by illustrating how GA₃ counters auxin's inhibitory effects, thereby facilitating the emergence and growth of axillary buds from dormancy.

Furthermore, GA₃ enhances the biosynthesis of cytokinins or amplifies their signaling pathways, thus promoting the activation of axillary buds (Asante et al., 2022). This hormonal interplay is essential, as GA₃ induces cell elongation and division in these axillary buds, modulating the expression of genes crucial for transitioning out of dormancy and subsequent growth and development into rhizomes or suckers (Guo et al., 2020).

Importantly, the apical bud serves as a crucial sink for nutrients and sugars. Zheng et al. (2018) suggested that the modulation of resource distribution driven by GA₃ is instrumental in activating the dormant buds, effectively reallocating essential materials and energy to support their growth. This multifaceted action of GA₃ and its interaction with various growth regulators

emphasize the complexity of plant development and the significance of genetic and environmental factors in these processes (Guo et al., 2020).

Qiu et al. (2018) investigated the impact of auxin and cytokinins, plant growth regulators, on breaking dormancy and initiating axillary bud growth in strawberry (*Fragaria vesca* L.) in stolons. Their findings concluded that a reduction in auxin accumulation stimulated the regeneration of vegetative shoots in dormant axillary buds, and that the exogenous application of cytokinins produced a similar effect. Moreover, Quo et al. (2020) highlighted recent research that has shed new light on the mechanisms involving phytohormones (GA₃ and ABA), as well as the influences of high sugar levels and light intensity (Ainsworth & Bush, 2011). This research elucidates their role in regulating axillary bud extensions. As suggested by Aljaser & Anderson (2021), a comparable mechanism is likely involved in the growth and development of rhizomes from arrowroot corms as observed in the current study.

This study investigated the emergence of rhizomes 120 days after transitioning potted arrowroot plants from a greenhouse setting, characterized by elevated temperatures and high-intensity light conditions, to a cooler environment with 50% shade. Notably, the external application of gibberellic acid (GA₃) significantly stimulated rhizome formation under tropical conditions. This phenomenon may be attributed to enhanced nutrient utilization as resources are redirected from the shoot system due to increased photosynthetic output (Masuda et al., 2012). The boost in photosynthesis provides a strong foundation for overall plant growth (Gent & Seginer, 2012).

As a result of this treatment, the arrowroot plants demonstrated increased uptake of nutrients and water while exhibiting reduced transpiration rates. These modifications improved gaseous exchange, heightened nutrient translocation, and facilitated the accumulation of sugars and other metabolites. Such physiological changes likely triggered the plants' pathways for the

rapid formation of additional storage organs, such as rhizomes (Ainsworth & Bush, 2011; Chaudhary et al., 2019).

When non-structural carbohydrates (NSC), which are critical for energy and structural integrity, produced by the leaves exceed the demands of new shoot growth and development, particular plant species Aluko et al. (2021), such as arrowroot (*Colocasia esculenta* L.), respond by developing rhizomes (Takahashi et al., 2018). This aligns with findings from Gent & Seginer (2012), indicating that, in this ecological context, the availability of carbohydrates significantly influences whether plants develop additional structures or prioritize new growth. Furthermore, Bhuiyan et al. (2015) elaborate that this response can serve as a secondary adaptive mechanism for coping with environmental shocks.

The existing literature has not documented the specific phenomenon observed in this study, where dormant lateral axillary buds on arrowroot corms were stimulated to produce rhizomes through the application of foliar gibberellic acid (GA₃) under greenhouse conditions, combined with the intensive use of organic manure, organic fertilizer, and biochar. This research represents the first comprehensive report detailing a protocol for inducing corm-rhizome development by integrating exogenous GA₃ application, environmental stimuli, temperature variations, and organic fertilizer supplementation.

The findings of this study highlight the significant role of exogenous GA₃ application and the abundance of sucrose supplied from source tissues, which is driven by a high photosynthesis rate resulting from elevated temperatures in the greenhouse (Gent & Seiner, 2012). Takahashi et al. (2018) proposed that this is a crucial step in initiating axial growth, which ultimately leads to the formation of rhizomes. This research highlights the intricate interplay between plant growth regulators (PGRs) and carbohydrate availability, which is crucial for promoting

vigorous growth patterns in arrowroot and deepening our understanding of the strategies plants employ to develop in response to varying environmental conditions.

Masuda et al. (2012) investigated the transformation of rhizomes into storage organs in Lotus (*Nelumbo nucifera* Gaertn.), a plant characterized by its rhizomatous growth. The researchers suggested that this transformation is significantly influenced by plant growth regulators (PGRs), particularly gibberellic acid (GA₃) and abscisic acid (ABA). While this study examines explicitly how GA₃ affects the growth and development of arrowroots, the corms produce numerous storage rhizomes, similar to those of the Lotus (*Nelumbo nucifera* Gaertn) plant. These observations, made after the foliar application of GA₃ to the selected local cultivars of arrowroot, revealed the role of gibberellic acid in the rhizome formation process. However, further research is necessary to understand the mechanisms that trigger rhizome development in the Dasheen-type arrowroot cultivars.

The foliar application of GA₃ caused visible damage to the shoots of the potted mother plants, with varying responses depending on the cultivar. Notably, the Girigaca cultivar exhibited a distinct dose-dependent increase in shoot damage, indicating its heightened sensitivity to higher concentrations of GA₃. Despite experiencing petiole deformation and retention of some juvenile leaves, these plants eventually resumed normal growth, although specific data regarding this recovery are not provided in the current analysis.

In contrast, the Kienyeji cultivar demonstrated remarkable resilience, consistently showing minimal shoot damage across a range of GA₃ concentrations. This resilience suggests that Kienyeji possesses inherent resistance mechanisms that allow it to withstand GA₃ stress and fluctuating environmental conditions more effectively than its counterparts.

Caliskan et al. (2021) investigated the effects of different dosages of gibberellic acid (GA₃) applied as a foliar treatment on the growth, yield, and quality traits of potato (*Solanum*

tuberosum L.). Their findings indicated that GA₃ caused deformities in potato tubers, with the severity of these deformities increasing with the elevation of GA₃ dosage. This finding supports the current study, which observed clear deformations in arrowroot shoots. These included the retraction of the youngest leaves and entrapment within the petiole groove; in more severe cases, the twisting of the shoot ultimately led to shoot death. Such observations underscore the need for further investigation into the effects of plant growth regulators on arrowroot. Gaining a deeper understanding of how varying concentrations of GA₃ impact plant cell wall integrity, polyphenol pathways, and genetic variability may help elucidate these observed phenomena.

Number of nodes per rhizome

The analysis of the Girigaca cultivar revealed a notable response to GA₃ treatments, resulting in a significant increase in the number of nodes per rhizome. Specifically, the average number of nodes increased from 108.42 at a GA₃ concentration of 100 ppm to a remarkable 245.83 nodes at 750 ppm. This considerable increase highlights a clear dose-dependent relationship, whereby GA₃ effectively stimulates the proliferation of corm lateral axillary buds and enhances internodal elongation, resulting in substantial rhizome growth (Yang et al., 2015).

In contrast, the Kienyeji cultivar showed no nodes per rhizome across all GA₃ treatment levels. This outcome suggests that the cultivar's inherent limitations in rhizome development under the experimental conditions of GA₃ application and greenhouse conditions render it unsuitable for propagation strategies that depend on rhizome production.

The remarkable increase in nodes per rhizome observed in the Girigaca cultivar signifies a significant advancement in understanding the mechanisms of rhizome development. This breakthrough enhances scientific knowledge surrounding arrowroot macropropagation and paves the way for large-scale production and commercialization of vegetative propagation materials (Plantlets) generated from rhizomes. Such advancements could significantly support

farmers in addressing planting material shortages, subsequently improving their productivity and strengthening food security. Furthermore, the implications for agricultural sustainability are profound, as optimized cultivation practices may adopt more resilient farming systems capable of adapting to market demands and the environmental challenges associated with arrowroot cultivation.

Rhizome length and girth

At a concentration of 750 ppm, the increase in rhizome length was most significant, measuring approximately 16.15 cm. Similarly, the increase in girth peaked at 2.22 cm, conspicuously, for the Kienyeji cultivar; no rhizomes were formed at any of the GA₃ concentrations, and hence no measurements for rhizome length or girth could be recorded. The findings from earlier research conducted by Guo et al. (2020) have shown that exogenous foliar application of GA₃ has a positive influence on rhizome elongation. This enhancement in lateral rhizome growth suggests that applying GA₃ externally is crucial in stimulating cell division and elongation processes (Mehdi et al., 2024).

Interestingly, while GA₃ promotes the elongation of rhizomes, it appears to inhibit girth thickening. This was confirmed by results from research conducted by Guo et al. (2020), which showed that GA₃ treatment may modify the expression of genes that regulate growth-related physiological processes and metabolic pathways, resulting in this effect. The trend observed in the girth measurements indicates a consistent decline as the concentration of GA₃ increases, suggesting that under exogenous GA₃ influence, the plant prioritizes rhizome elongation over radial growth (Aluko et al., 2021). This observation highlights the complexities of how hormonal signals regulate the balance between rhizome elongation and storage functions (Qiu et al., 2021).

Despite gaps in understanding the precise mechanisms governing rhizome initiation and development (Guo, 2020), it is established that the interplay of hormones, including GA, ABA, and auxins (IAA), plays a crucial role in regulating these processes through modulation of gene expression, as articulated by Ma & Huang (2016). Furthermore, Bessho-Uehara et al. (2018) proposed that both GA₃ and auxin are integral to the developmental processes of rhizomes, influencing signaling pathways that ultimately affect their morphology. This is further supported by Yoshida et al. (2016), who studied rhizome initiation and development in wild rice (*Oryza longistaminata*), reporting that axillary bud activation in a rhizome is sensitive to environmental conditions, such as temperature and light (Guo et al., 2020).

These findings have significant implications, as the enhanced elongation of rhizomes increases their capacity for vegetative propagation. Additionally, it facilitates the production of longer rhizomes that can generate more nodes. This increase in nodal cuttings for every rhizome ultimately enhances the potential for a rapid multiplication of propagation materials while preserving the cultivar's genotypes.

Number of suckers

In the investigation of sucker production among two cultivars, the Kienyeji cultivar exhibited a particularly low average of 3.58 suckers when treated with the lowest (100 ppm) concentration of GA₃ (gibberellic acid). In contrast, the Girigaca cultivar produced the highest number of suckers (8.25) without any GA₃ treatment, serving as the control group. This finding raises intriguing questions, particularly for the Kienyeji cultivar. It appears that an increase in GA₃ concentration did not lead to a proportional increase in sucker production compared to the control treatment. This observation suggests that GA₃ may not be an effective stimulant for sucker activation in this cultivar, highlighting the need for further investigation into the hormonal signaling pathways that influence arrowroot growth.

Additionally, the observed increase in sucker formation for Kienyeji, along with the lack of significant rhizome development, indicates a potential tendency for this cultivar to produce aerial suckers rather than the subterranean growth typically associated with rhizomes. This phenomenon may be attributed to specific hormonal signaling pathways within the plant, as discussed by Kumar et al. (2020) and Besso-Uehara et al. (2018), which mediate growth responses.

According to research conducted by Melis and Van Stadin (1984), plant growth regulators (PGRs) generally work together to promote plant development, with each serving a distinct function. For example, GA₃ significantly influences tuberization by affecting the rate of shoot growth. Other PGRs, such as cytokinins, auxins, and abscisic acid, play a key role in regulating sink activity, which includes controlling the processes of cell division and enlargement essential for shoot growth. The interaction among these various hormones is crucial for optimizing plant development.

The findings of this study are supported by those of Masuda et al. (2012) who observed that the transition of rhizomes into storage tissues primarily originates from the plant's stems, such as corms, and is initiated by GA₃. It is crucial to consider the roles of other plant growth regulators (PGRs) in this process. Arrowroot usually propagates from the apical buds formed on actively growing corms, while the axillary buds remain dormant until they are activated to produce new propagules (Asante et al., 2012). This trait presents a valuable opportunity for future strategies to multiply the vegetative propagation materials of arrowroot. By leveraging this rapid and cost-effective cultivation method, farmers can enhance productivity and sustainability in their arrowroot farming operations. For instance, GA₃ significantly impacts tuberization by influencing the rate of shoot growth, while other PGRs, such as cytokinins, auxins, and abscisic acid, help regulate sink activity, which includes controlling cell division

and enlargement necessary for shoot growth. The interplay among various hormones is essential for optimizing plant development.

In conclusion, the research demonstrates strong positive correlations among the number of rhizomes, their physical dimensions, specifically length and girth, which provide compelling evidence that the application of gibberellic acid (GA_3) significantly enhances rhizome development in arrowroot cultivars. Notably, the study identified an inverse relationship between sucker production and rhizome-related traits. This finding is crucial for agricultural practices, as it suggests that cultivars or cultural methods aimed at promoting sucker generation may result in a reduced yield of rhizomes. Such insights highlight the crucial role of plant growth regulators (PGRs), which can effectively stimulate the activation of dormant lateral or axillary buds on the arrowroot corms. This induction helps to mitigate the typically dominant influence of the terminal bud, which usually prioritizes sucker development over rhizome growth (Tshipamba et al., 2021; Takahashi et al., 2018).

A related investigation conducted by Asante et al. (2022) evaluated how varying doses of benzyl adenine (BA) and coconut water (CW) influenced the activation of suckers and stolons in arrowroot corms. This study observed a significant enhancement in multiplication ratios, achieving ratios as high as 1:15 for suckers and 1:16 for stolons. In contrast, the current research specifically examined the effects of GA_3 at different concentrations, resulting in a comparatively lower sucker ratio of 1:4 for the distilled water control (Aljaser & Anderson, 2021). However, it yielded a markedly higher average rhizome production ratio of 1:36. This comparison clearly illustrates the trade-off between promoting various growth characteristics following GA_3 treatment, which is vital for devising an effective strategy for producing and multiplying propagation materials for arrowroot.

Furthermore, ideal growing conditions characterized by elevated temperatures, consistent availability of essential nutrients, and the strategic application of GA₃, particularly within the Girigaca cultivar, create favourable conditions for rhizome production. This tailored approach appears to prioritize the accumulation of storage rhizomes over the enlargement of the mother corm (Ainsworth & Bush, 2011). The timing of GA₃ application during the vegetative growth phase is particularly noteworthy, as it seems to create stronger nutrient sinks than the corms themselves, thereby stimulating an increase in rhizome production. This characteristic is especially significant for addressing the pressing shortage of viable propagation materials required for successful arrowroot cultivation.

Given these promising findings, there is a clear impetus for further investigation into the potential of GA₃ as a quick macropropagation method. This is especially pertinent for upland-grown and Dasheen-type cultivars, which hold considerable agricultural and culinary importance in Kenya. By exploring these avenues, researchers can contribute to more sustainable and productive farming practices for arrowroot, enhancing its viability in local and broader markets.

Figure 4.18

Greenhouse potted plants, propagation materials, and rhizomes



A: Potted Arrowroot in greenhouse



B: Emerging Rhizomes



D: Mature Rhizomes



C: Immature Rhizomes

Figure 4.19

Arrowroot potted plants showing developing rhizomes and GA₃ shoot damage



A: Suckers (Control)



B: Rhizomes (Highest GA₃ dose)



D: Leaf retention



C: Shoot deformation

Figure 4.20

Rhizomes and nodal cuttings



Figure 4.21

Rooting chambers and sprouted plantlets



Figure 4.22

Sprouted plantlets from rhizome nodal cutting



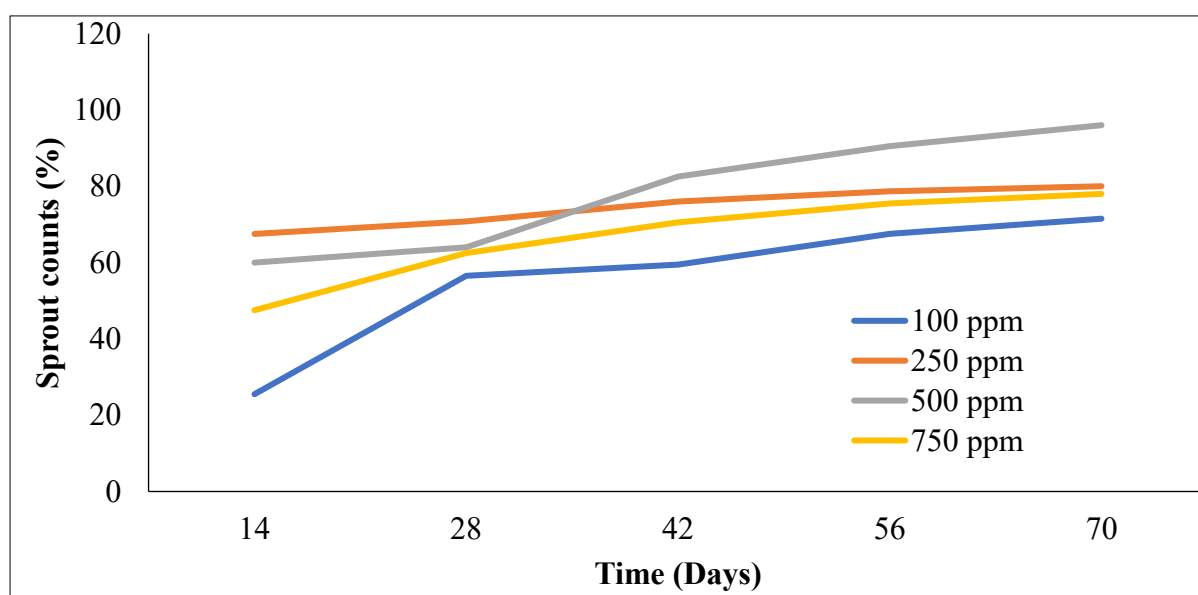
4.3 Experiment 3: Evaluation of Sprouting Capacity of Gibberellic Acid (GA₃) Induced Rhizomes

4.3.1 Sprout counts of rhizome nodal cutting

Figure 4.23 is a graphical representation of a comprehensive analysis of the responses of rhizome nodal cuttings obtained from arrowroot mother plants previously treated with variable concentrations of foliar-applied gibberellic acid (GA₃), named 100 ppm, 250 ppm, 500 ppm, and 750 ppm. This study examined four sets of specially prepared nodal cuttings after sowing them in pots, placing them in spouting chambers, and monitoring for sprouting. The observations indicate variations over time. For instance, the cumulative sprout counts 14 days after sowing were as follows, from highest to lowest: 250, 500, 750, and 100 ppm, starting from 42 days after sowing. However, a slight change was observed, as shown: 500 > 250 > 750 > 100 ppm. This trend was maintained throughout the experiment.

Figure 4.23

Effect of the mother plant GA₃ treatment on the sprout count of rhizome nodal cuttings.



To determine whether the treatments produced significant effects, an ANOVA was performed, and the results are summarized in Appendix 8. This demonstrated that GA₃ treatment had a substantial impact on nodal cutting sprouting into new plantlets. For means comparison, Turkey's test was used, and the results are given in Table 4.11.

Table 4.11

Effect of GA₃ treatment on sprout counts of rhizome nodal cuttings

GA ₃ (ppm)	Sprouting medium	Time (Days)				
		14	28	42	56	70
100	River sand	11.00±1.00 ^e	54.00±1.73 ^d	63.00±1.53 ^c	67.00±0.58 ^b	73.00±1.00 ^a
	Sawdust	40.00±1.53 ^c	59.00±0.58 ^b	56.00±2.31 ^b	68.00±1.15 ^a	70.00±2.08 ^a
250	River sand	75.00±1.73 ^b	75.00±1.15 ^b	77.00±1.15 ^b	79.33±1.20 ^{ab}	81.00±1.15 ^a
	Sawdust	60.00±1.15 ^c	66.67±1.20 ^b	75.00±1.73 ^a	78.00±1.53 ^a	79.00±0.58 ^a
500	River sand	78.00±1.15 ^d	78.00±1.73 ^d	85.00±1.53 ^c	94.00±0.58 ^b	96.00±0.58 ^a
	Sawdust	42.00±0.58 ^e	50.00±1.53 ^d	80.00±1.53 ^c	87.00±0.58 ^b	96.00±1.15 ^a
750	River sand	64.00±1.15 ^c	65.00±2.31 ^c	72.00±0.58 ^b	77.00±1.00 ^a	79.00±1.00 ^a
	Sawdust	31.00±1.15 ^e	60.00±1.73 ^d	69.00±0.58 ^c	74.00±0.58 ^b	77.00±0.58 ^a

Means followed by the same letter along the column are not significantly different at a $p \leq 0.05$ probability level.

The results presented show that among the rhizomes evaluated, the 500 ppm GA₃ treatment proved to be the most effective, with a remarkable sprouting percentage of 96%. This was followed by 250, 750, and 100 ppm, which recorded the lowest sprouting counts. The entire array of arrowroot mother plants subjected to GA₃ responded by producing rhizomes, making it crucial to determine the efficacy of GA₃. This high sprout count percentage suggests that the 500 ppm GA₃ dose provided the nodal cutting with an optimal hormonal balance favorable for activating the dormant axillary buds of the nodal cuttings. The GA₃, in conjunction with other

PRGs, as was suggested in a study on the effects of gibberellins on vegetative propagation of *Gladiolus* plants by Aljsaser & Anderson (2021) is likely to stimulate critical physiological processes, such as cell elongation and division, which play a vital role in promoting successful sprouting and overall plant development. The 250-ppm concentration followed closely, which achieved a commendable sprouting rate of 80%. Although this result is slightly lower than that of the 500-ppm treatment, it still indicates that this concentration provides a sufficiently favorable environment for germination, supporting substantial growth potential in the nodal cuttings.

Similarly, applying 750 ppm GA₃ resulted in a discernible decline in sprouting success, with a rate of only 78%. This decrease may indicate that excessively high concentrations of GA₃ could inhibit growth. Possible explanations for this trend include the onset of osmotic stress or biochemical imbalances that may prevent the physiological processes necessary for effective development, highlighting the delicate balance required in applying growth regulators.

Finally, the treatment with 100 ppm yielded the lowest sprouting performance, with a modest rate of 71.5% after 70 days. This outcome highlights that insufficient concentrations of GA₃ may fail to adequately stimulate the essential growth responses, leading to suboptimal sprouting outcomes. In brief, these findings demonstrate the pivotal role that varying concentrations of gibberellic acid play in influencing the growth potential of nodal cuttings. The results underscore the necessity for precise calibration of GA₃ levels within agronomic practices, as optimizing these concentrations is crucial for maximizing sprouting efficiency and developing a protocol for multiplying the new source of arrowroot propagules.

The effect of Gibberellic acid (GA₃) on the germination of arrowroot rhizome nodal cuttings has been established in this study, which is supported by previous research highlighting the role of GA₃ in promoting cell elongation and division, thereby enhancing growth and

development. These cellular processes are crucial for the activation of growth in dormant vegetative organs, such as cormels in rhizomatous plants, as exemplified by aroids, as elucidated by Aljaser & Anderson (2021) and Masuda et al. (2012). The study confirmed that foliar application of GA₃ at concentrations above 500 ppm on the mother plant did not provide additional benefits and may interfere with the normal arrowroot growth. This underscores the necessity of optimizing GA₃ dosage to maximize growth efficiency.

The study clarified the efficacy of enhancing arrowroot rhizome nodal cutting sprouting and establishment after treatment with doses of GA₃. This was aligned to confirm the possibility of use in advancing the production of arrowroot propagation materials, as often utilized in the propagation of many food crops (Caliskan et al., 2021). The studies focused on nodal cuttings containing two axillary buds from arrowroot rhizomes produced in a previous experiment; this technique had not been previously explored in detail for the propagation of arrowroot, as it does not naturally form rhizomes, as asserted by Bhuiyan et al. (2009). In a related study, Muktar et al. (2023) investigated the establishment of cassava using different stem cutting sizes. Their results indicated that stem cuttings with two nodes were optimal for promoting rooting. However, the results for arrowroot differed significantly due to their morphological differences (Eed et al., 2015). While the cassava nodal cutting generally sprouted from both axillary buds, only the proximal axillary bud of the arrowroot rhizome node sprouted (Pugalendhi & Velmurugan, 2020). This observation was crucial, as it highlights the presence of terminal dominance within the corm-rhizome structure of arrowroot (Aljaser & Anderson, 2021), which allows only one bud to sprout at a time, despite the presence of multiple axillary buds. This trait can be exploited to generate more plantlets from arrowroot-generated rhizomes during the division, ensuring each node cutting has at least one axillary bud, and the multiplier effect on the rhizome would be enormous.

Given the limited research in this area on arrowroot, the direct comparison method used in cassava and arrowroot may not be helpful. Nonetheless, the research findings offer invariable insights that could inform and transform the approach to addressing the severe scarcity of arrowroot propagation material (Sagoe et al., 2018). The findings introduce a novel approach for generating rhizomes from arrowroot corms following GA₃ induction, a method not previously documented in the existing literature. Through carefully designed protocols, it has been confirmed that rhizome nodal cuttings can be successfully sprouted into viable arrowroot plantlets, which may provide a sustainable source of alternative propagation material for small-scale farmers and large-scale commercial production. These plantlets represent a valuable propagation resource for arrowroot, as they can be produced quickly and cost-effectively, while also being simple to handle and transport.

4.3.2 Sprouting medium for rhizome nodal cuttings

Figure 4.19 presents a graphical representation of a comprehensive analysis of the responses of rhizome nodal cuttings obtained from arrowroot mother plants previously treated with varying concentrations of gibberellic acid (GA₃), specifically 100, 250, 500, and 750 ppm. During the initial stages of the rooting (14 days after sowing), river sand medium exhibited superior performance compared to sawdust, as evidenced by higher sprouting rates, faster emergence of plantlets, and increased vigour in the growing plantlets. Nevertheless, as the time progressed into the second week, the differences in growth performance between the two media began to diminish considerably. By the end of the experiment, the growth rates for the two media were found to be significantly equal.

The experiment evaluated the effect and efficiency of two types of sprouting media, river sand, and sawdust, on the growth parameters: Plantlet height, stem girth, root length, and leaf area

of nodal cutting plantlets, as demonstrated in Figures 4.24, 4.25, 4.26, and 4.27. The results are outlined in Table 4.12.

Figure 4.23 illustrates the impact of different sprouting media on the sprout count of rhizome nodal cuttings. The results indicate a significant variation in sprout development among the two media used in the experiment. A similar finding was reported by Muktar et al. (2023), who tested suitable media for rooting cassava cuttings and found that sawdust had a similar effect in encouraging the rooting of cassava stem cuttings compared to commercial rooting media. From the findings, we can infer that certain types of media provide a more favorable environment for sprouting, probably due to factors such as nutrient availability, moisture retention, and aeration (Pugalendhi & Velmurugan, 2020). Higher sprout counts in specific media suggest that these conditions may enhance the growth potential of rhizome nodal cuttings. In this study, river sand and sawdust supported high percentages of sprouts. Equally, rooting media that results in lower sprout counts may pose challenges, whether due to a lack of essential nutrients, poor drainage, or insufficient oxygen, leading to the death of nodal cuttings (Bhende & Kurien, 2015). The data obtained in the study underscore the importance of selecting appropriate growing media to optimize the sprouting and overall health of rhizome plantlets. Sagoe et al. (2018) examined the effect of growth media for vegetative propagules and seed, they observed that the media influenced the rooting of the stem cutting, further stated that river sand supported it earlier. Higher germination rates were observed in this experiment, thereby confirming the results reported by Ahmed et al. (2022) which yielded the same findings. In summary, the findings emphasize the significant role that sprouting media play in the sprouting and growth of rhizome nodal cuttings. The information presented will inform future cultural practices in propagation techniques (Norman et al., 2022).

Figure 4.24

Effect of sprouting media on the sprout count of rhizome nodal cuttings

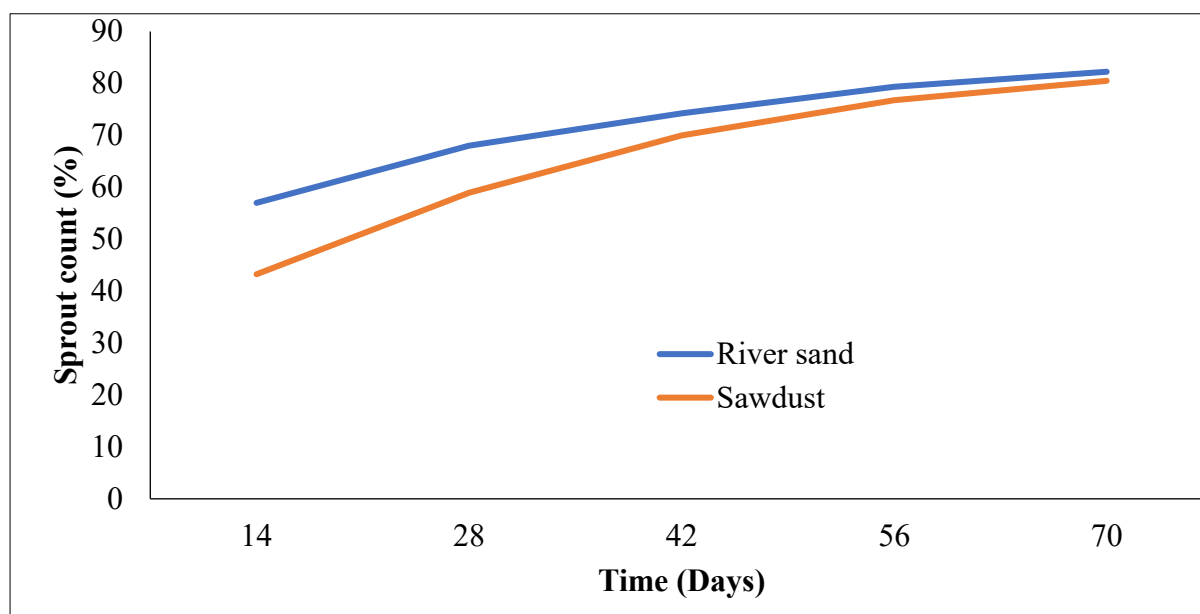


Figure 4.24 illustrates the effect of various sprouting media on the growth parameters of nodal cutting plantlets: stem girth and root length. From the data presented, it appears that different media influence both the stem girth and the root lengths of the plantlets; these results were consistent with those posted by Eed et al. (2015). A notable trend is observed where specific media promote greater stem thickness, indicating enhanced structural development, while others encourage longer roots, suggesting improved nutrient uptake capabilities (Rahman et al., 2018). The results suggest that selecting a suitable sprouting medium is crucial for optimizing growth in nodal cuttings. Media that enhance stem girth and root length (Figure 4.25) may provide a more supportive environment for plantlet development (Sagoe et al., 2018), leading to healthier and more vigorous plants. Further analysis might reveal the underlying mechanisms driving these differences, such as nutrient content, moisture retention, or pH levels in the sprouting media (Lakitan et al., 2021). Understanding these relationships

could help select the most effective rooting media for propagating plantlets from arrowroot rhizome nodal cuttings.

Figure 4.25

Effect of sprouting medium on the stem girth and root length of nodal cuttings plantlets

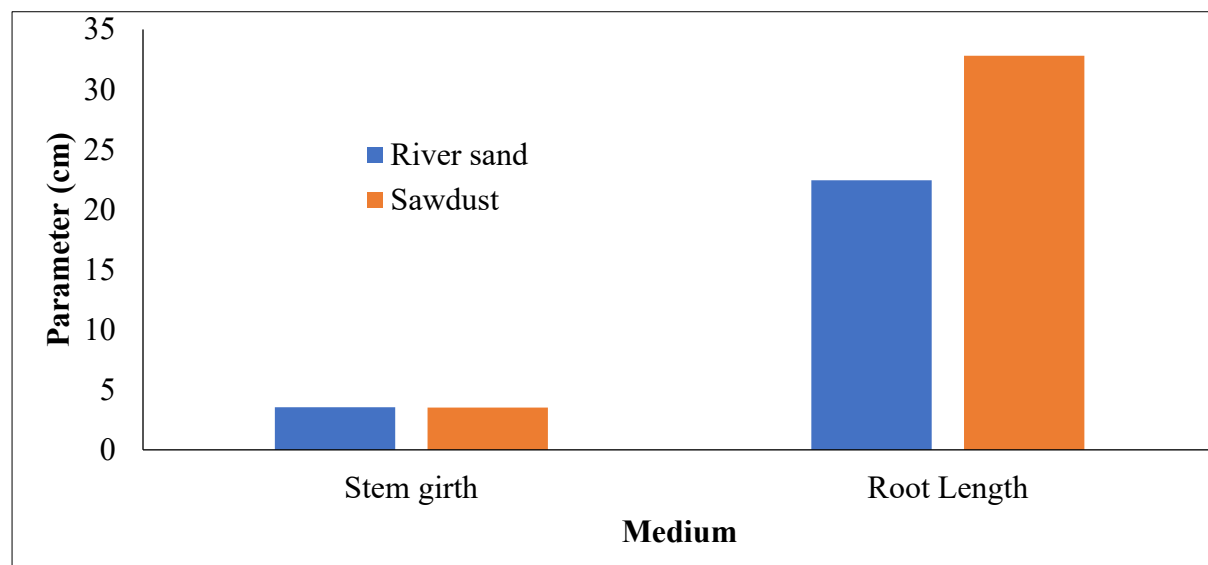
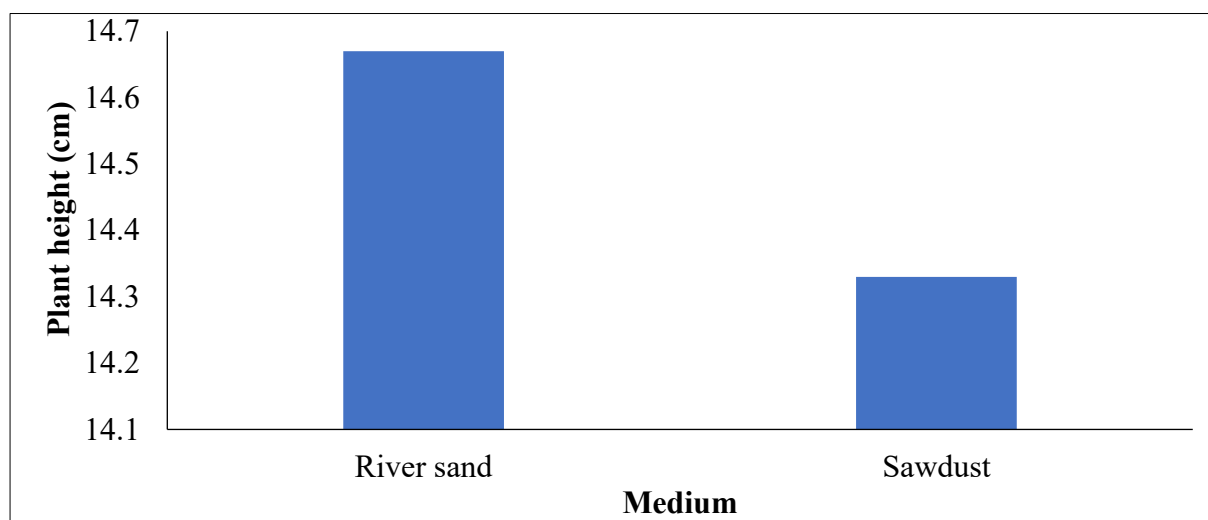


Figure 4.26 illustrates the effect of sprouting medium on the plant height of nodal cutting plantlets. According to Caliskan et al. (2021), it may be inferred that the response of root length may have been due to the effect of GA₃. The data indicate variations in plantlet growth that can be attributed to both the type of medium used for rooting and the influence of GA₃ applied to the mother plant. This view is proposed in a study on the regulation of rhizomes using gibberellins conducted by Masuda et al. (2012). The results confirm that selecting the correct sprouting medium in conjunction with GA₃ treatment optimizes the growth conditions of nodal cuttings, improving plant height and providing better overall vigour (Ahmed et al., 2021). Moreover, any noticeable trends or statistical significance presented in the figure would help identify the most effective media and treatment strategy for maximizing the growth of plantlets from nodal cuttings. The present presentation aligns

with the findings of Pugalendhi & Velmurugan. (2020) developed a protocol for combining selected rooting media, chips, and nodal cutting for rapid propagation material multiplication for cassava.

Figure 4.26

Effect of sprouting media on the plant height of nodal cutting plantlets

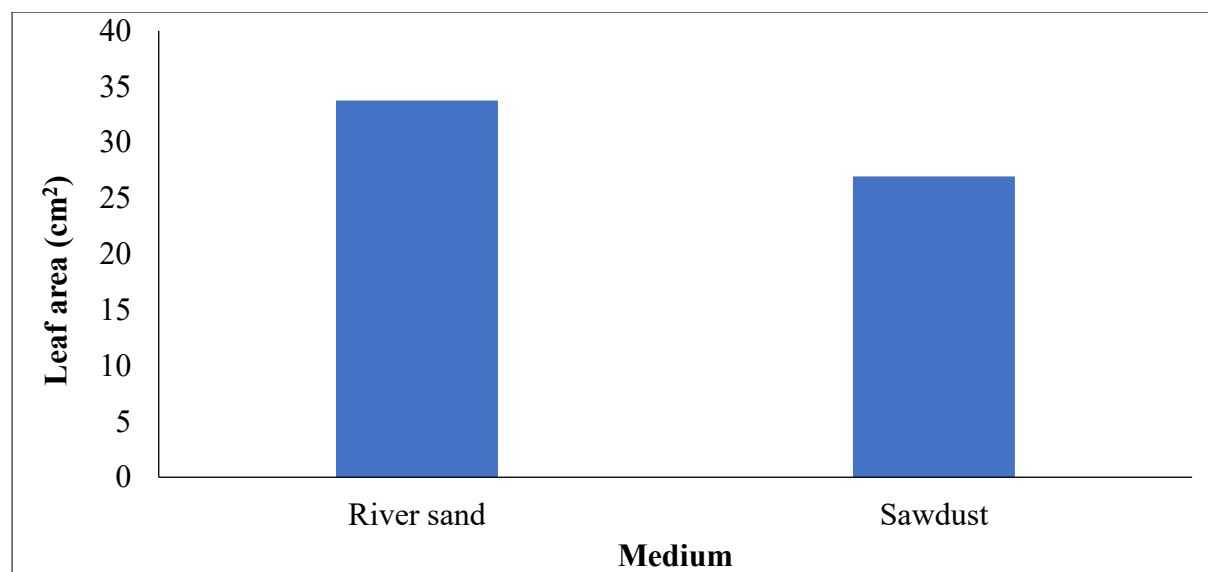


The results depicted in Figure 4.27 highlight the influence of different media on the leaf area of nodal cuttings plantlets. It appears that the variation in media affects the growth and development of the plantlets, potentially leading to differences in leaf area. Comparable results were reported in a study conducted by Guo et al. (2020). If specific media types were compared, it is possible to observe that particular formulations promote greater leaf expansion, which could be tied to nutrient availability, moisture retention, and aeration (Sagoe et al., 2018). For example, a media rich in organic matter may support larger leaf area than a more inert substrate (Norman et al., 2022), suggesting that the plantlets benefit from enhanced nutrient uptake and overall health. Additionally, the results may indicate optimal sprouting conditions that maximize leaf area, highlighting the importance of selecting the appropriate media for

propagating nodal cuttings (Mukhtar et al., 2023). A larger leaf area is often associated with better photosynthetic capability, indicating healthier plantlets that are more likely to thrive in subsequent growth stages.

Figure 4.27

Effect of sprouting media on the leaf area of nodal cuttings plantlets



To determine whether the treatments produced significant effects, an ANOVA was performed, and the results are summarized in Appendix 9. This demonstrated that GA₃ treatment has a substantial impact on nodal cutting sprouting, resulting in the formation of new plantlets. For means comparison, Turkey's test was used, and the results are presented in Table 4.12.

Table 4.12

Effect of GA₃ treatment and sprouting media on the growth of nodal cuttings plantlets

GA ₃ (ppm)	Time (Days)	Plantlet height (cm)		Stem diameter (mm)		Root length (cm)		Leaf area (cm ²)	
		River sand	Sawdust	River sand	Sawdust	River sand	Sawdust	River sand	Sawdust
100 ppm	55	4.43±0.52 ^b	5.03±0.34 ^d	1.24±0.07 ^c	2.33±0.27 ^c	7.17±0.92 ^d	8.17±2.05 ^c	2.69±0.32 ^d	3.25±0.51 ^d
	70	6.77±0.60 ^b	9.43±1.28 ^c	4.35±0.26 ^a	3.55±0.08 ^b	10.00±0.00 ^c	18.67±0.88 ^b	4.28±0.84 ^c	12.49±3.78 ^c
	85	20.13±2.14 ^a	19.97±0.59 ^b	3.45±0.38 ^b	5.51±0.70 ^a	26.00±0.95 ^b	58.83±0.62 ^a	32.94±4.13 ^b	47.74±3.82 ^b
	100	17.73±1.21 ^a	24.70±0.71 ^a	4.03±0.35 ^a	5.47±0.06 ^a	29.40±1.92 ^a	59.80±2.63 ^a	54.19±9.09 ^a	73.39±5.48 ^a
250 ppm	55	5.03±0.23 ^d	4.80±0.70 ^d	1.70±0.11 ^c	2.27±0.06 ^d	8.83±1.48 ^d	10.00±0.58 ^c	3.10±1.28 ^c	2.44±0.07 ^c
	70	9.13±0.41 ^c	7.87±0.30 ^c	4.13±0.39 ^b	3.12±0.09 ^c	16.67±2.33 ^c	13.33±1.20 ^b	13.70±1.72 ^b	7.02±2.33 ^b
	85	22.70±0.86 ^a	19.97±0.69 ^b	5.09±0.11 ^a	4.95±0.19 ^a	33.00±3.25 ^b	59.87±1.88 ^a	64.36±22.24 ^a	35.35±4.53 ^a
	100	23.10±0.75 ^b	22.73±0.95 ^a	4.63±0.20 ^{ab}	4.36±0.30 ^b	38.20±3.47 ^a	56.67±2.40 ^a	68.06±6.88 ^a	46.86±7.40 ^a
500 ppm	55	4.40±0.35 ^c	5.20±0.15 ^d	1.56±0.21 ^c	1.78±0.07 ^b	12.67±1.45 ^d	12.00±0.00 ^d	4.60±1.20 ^d	4.29±0.19 ^d
	70	7.20±0.62 ^b	8.10±0.15 ^c	2.89±0.07 ^b	3.56±0.13 ^a	17.00±1.53 ^c	21.17±2.20 ^c	12.27±1.87 ^c	8.16±1.04 ^c
	85	22.67±1.19 ^a	16.20±1.01 ^b	4.88±0.20 ^a	3.37±0.29 ^a	33.43±1.44 ^a	35.27±2.92 ^b	82.99±10.67 ^a	27.75±6.24 ^b
	100	22.77±1.30 ^a	22.43±0.45 ^a	4.90±0.48 ^a	3.66±0.28 ^a	28.40±0.81 ^b	47.07±3.01 ^a	59.05±8.30 ^b	53.19±12.47 ^a
750 ppm	55	6.27±0.13 ^b	4.23±0.27 ^d	1.41±0.06 ^c	1.40±0.11 ^c	10.00±1.15 ^d	10.03±1.30 ^d	4.93±1.20 ^c	2.49±0.51 ^d
	70	9.47±0.52 ^b	10.04±0.15 ^c	3.36±0.17 ^b	2.79±0.32 ^b	14.33±1.20 ^c	16.83±0.60 ^c	12.61±5.67 ^b	6.29±0.47 ^c
	85	27.40±2.58 ^a	21.23±0.52 ^b	4.71±0.15 ^a	4.32±0.15 ^a	39.10±1.87 ^a	59.53±3.99 ^a	64.12±17.19 ^a	44.91±3.12 ^b
	100	25.50±0.10 ^a	27.40±2.53 ^a	4.27±0.31 ^a	4.01±0.26 ^a	34.87±1.20 ^b	37.80±3.16 ^b	56.00±6.95 ^a	55.45±3.94 ^a

Means with the same letter along the column within each GA₃ treatment level are not significantly different at a $p \leq 0.05$ probability levels.

The results outlined in Table 4.12 indicate that plantlet height significantly increases with higher concentrations of GA₃, particularly at the 750-ppm level in river sand, which recorded the highest mean plantlet height. In contrast, lower concentrations, such as 100 ppm, exhibit significantly lower heights; the results are in agreement with those presented by Setyawan et al. (2021). For the stem girth, the results suggest that treatment with 100 ppm of GA₃ in sawdust produced the most significant stem girth compared to other therapies. This trait was linked to several factors, including GA₃, cultivar, and environment, as reported by Caliskan et al. (2021). Meanwhile, the differences among the high GA₃ concentrations are less pronounced, indicating that stem diameter does not increase as significantly with increasing GA₃, particularly in river sand (Rahman et al., 2018). Root length data show a significant response to different GA₃ levels, with the best results recorded at lower concentrations in sawdust. The peak root length at 100 ppm suggests that overly high concentrations of GA₃ may not benefit root development, as indicated by the lower root lengths at 500 ppm and 750 ppm. The analysis of leaf area reveals that 100 and 250 ppm levels in sawdust and river sand outperform the higher concentrations, emphasizing that moderate GA₃ levels may be more effective for expanding leaf area early in growth. A similar outcome was confirmed by Aljaser & Anderson (2021), who reported an increase in leaf area after treating *Gladiolus x hybridus* with gibberellins. While specific parameters benefit from higher GA₃ concentrations, others indicate a threshold beyond which effectiveness diminishes. The differing responses in various media further reinforce the importance of considering both GA₃ concentration and planting medium to optimize growth in nodal cuttings, as declared by (Ahmed et al., 2021).

The study examining the effects of river sand and sawdust on sprouting efficiency revealed significant performance differences over time, highlighting the dynamic nature of the arrowroot plant growth. Initial assessments indicated that river sand outperformed sawdust in promoting sprouting, likely due to its superior drainage and aeration properties. These

characteristics create an optimal environment for germination, enabling rhizome node cuttings to access the necessary oxygen while avoiding waterlogging, which can hinder early growth.

A noticeable shift was observed as the research progressed over 12 weeks; the sprouting percentages for both media began to converge, ultimately resulting in no significant difference between them by the end of the observation period. This change suggests that while river sand may facilitate faster germination and initial growth, sawdust may provide long-term benefits that become more evident over time. Sawdust's moisture retention capabilities likely played a crucial role in sustaining seedling growth, ensuring a consistent supply of water and nutrients throughout the growth period (Sagoe et al., 2018).

The variation in sprouting efficiency underscores the importance of understanding the physical properties of different growth media, particularly in terms of moisture retention and air circulation (Pugalendhi & Velmurugan, 2020). These factors are vital for influencing root and shoot development, ultimately impacting plants' overall health and viability (Setyawan et al., 2021). This study suggests that growers should consider tailoring their choice of growth medium to align with the specific needs of their plants and the anticipated duration of the growth cycle, striking a balance between the immediate advantages of particular media and the long-term benefits of others (Ubalua et al., 2016). By doing so, they can enhance the likelihood of successful plant establishment and development.

4.3.3 Agronomic impact of gibberellic acid exploitation for arrowroot production

Gibberellic acid (GA₃) has gained significant attention in agronomic practices due to its efficacy in enhancing the production of food crops Ahmed et al. (2022); Caliskan et al. (2021); Rahman et al. (2018) and ornamental plants (Aljaser & Anderson, 2021; Eed et al., 2015). Recent research conducted by Manju et al. (2017) revealed that GA₃ effectively improves yield and plays a central role in rapidly multiplying propagation material. This is particularly helpful when traditional propagation methods, which can be labor-intensive and costly, are impractical.

The application of GA₃ may enable growers to achieve faster sprouting of nodal cuttings, resulting in the synchronized emergence of plantlets that develop into uniform planting material. This efficiency is especially valuable in addressing the limited availability of propagation materials (Njuguna et al., 2023). Traditional arrowroot cultivation methods often require substantial planting materials Muthoni and Shimelis (2023), which can be challenging to source or financially unfeasible for small-scale farmers. In contrast, utilizing GA₃ to generate propagules from corm-rhizomes presents a low-cost and effective alternative that supports appropriate agronomic practices (Tumuhimbise et al., 2016). It meets the rising demand for propagation materials.

This innovative method enhances the production rate of arrowroot, as observed in a study involving the application of plant growth regulators (PGRs) in *Capsicum annuum* L. conducted by (Ahmed et al., 2023). It addresses the challenges of planting material scarcity Njuguna et al. (2023) paving the way for improved accessibility and affordability of arrowroot establishment for subsistence and commercial growers. According to numerous researchers and growers in the arrowroot sector, obtaining healthy planting materials in adequate quantities is a significant challenge to production. If scaled up, the multiplication protocol developed in this study holds considerable potential for commercialization.

The study recommends using gibberellic acid to improve large-scale arrowroot propagation. This approach leads to faster sprouting, higher growth rates, and more uniform crop development, which is essential for meeting the increasing demand for arrowroot planting materials, as documented in this study. Future research should focus on optimizing the river sand-to-sawdust ratio for improved large-scale production of propagation materials. Finally, before implementing this propagation technique commercially, it is essential to assess its scalability under various field conditions to ensure optimal yield and adaptability. Greenhouse trials will test the practical application of GA₃, evaluating the transfer of plantlets from

controlled chambers to open fields and their yield potential in various environments. Successful validation could lead to broader adoption, enhancing productivity and profitability in arrowroot farming.

CHAPTER FIVE

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Introduction

The study meticulously investigates the growth, development, physiological responses, and yield performance of arrowroot (*Colocasia esculenta* L. Schott) when cultivated under upland conditions. Over the course of two years, comprehensive field and greenhouse experiments were conducted to evaluate the efficacy of the moisture pit technique for planting arrowroot, alongside the application of gibberellic acid (GA₃) to stimulate the regeneration of propagules. This extended duration was essential for capturing the interannual variability in climatic conditions and the corresponding responses of the arrowroot plants.

The two-year research provided a rigorous assessment of treatment effects, thereby enhancing the reliability and validity of the findings. The combination of controlled greenhouse environments with real-world field conditions allows for a thorough examination of how these variables interact under varying circumstances. This dual approach not only strengthens the data but also equips farmers and researchers with practical insights to enhance arrowroot resilience in the face of environmental uncertainties.

Furthermore, this research examines the intricate interaction between the moisture pit planting technique and the plant growth regulator gibberellic acid (GA₃), aiming to quantify their combined effects on arrowroot growth metrics, overall yield, and the effective regeneration of propagules. By integrating rigorous methodologies across two consecutive growing seasons, the study makes a significant contribution to understanding the interactions between arrowroot and its environment. It supports the development of more sustainable and efficient agronomic practices, ultimately benefiting both agricultural productivity and ecological balance.

5.2 Summary of Findings of the Study

Arrowroot is a vital tuber food crop that significantly enhances food and nutritional security for rural small-scale farmers and consumers. However, it remains largely ignored and underutilized, often seen as a “poor man’s or luxury crop”. The study investigated the effect of varying moisture pit depths on the growth and yield of arrowroot (*Colocasia esculenta* L. Schott) in Kenya. Four different depths were tested: 20 cm, 30 cm, 45 cm, and 60 cm. The results revealed that the deepest pits had a positive influence on both corm size and weight, with a depth of 60 cm producing the highest corm weight of 2.67 kg and an average yield of 44.63 tons per hectare. The study recommends implementing pit depths between 30 and 60 cm, taking into account specific farm conditions. Additionally, it addresses propagation challenges faced by arrowroot cultivation and highlights the efficacy of gibberellic acid (GA₃) in enhancing plantlet multiplication, particularly for the Girigaca cultivar. The findings underscore the need for sustainable production systems of arrowroot propagation materials to meet the increasing demand for arrowroot products.

5.3 Conclusion

Based on the research findings, it was determined that the arrowroot of the Dasheen-type has exceptional adaptability to grow in upland and drier conditions, making it a suitable cultivar for production in comparable agroecological zones that receive adequate and well-distributed rainfall. The results have shown that the moisture pit planting technique, with pit dimensions of 30 cm in width and a depth of 30 cm to 60 cm, effectively enables the growth and production of arrowroot in the non-traditional, upland conditions. The planting depth significantly influenced the growth, development, and yield, as well as the yield components, of arrowroot (*Colocasia esculenta* L.); notably, this technique led to high yields of corms and cormels. The increased pit depth significantly positively influenced yield parameters, including corm length, diameter, and girth, which was contrary to earlier reported findings from wetland arrowroot production studies. The technique demonstrated that arrowroot planted using pits produced suckers at a further distance from the “mother plant”, enabling easy and safe separation, thereby providing suckers for propagation before the crop's maturity. Additionally, non-significant correlations were recorded between the distance of the suckers from the mother plant and both corm yield per plant (0.347) and stem girth (0.297). These findings suggest that further investigation is needed to understand the dynamics in these specific measurements, as they did not demonstrate a strong correlation with overall yield outcomes.

This research provides original documented evidence of the central role of gibberellic acid in inducing axillary buds to produce rhizomes and transforming them into storage organs in corm-forming arrowroot cultivars. Various environmental factors, such as a nutrient-rich organic regimen and temperature fluctuations, from high to low, in greenhouse settings and shade nets, significantly influence this transition and greatly affect the growth and development of arrowroot.

The study identifies the optimal doses of gibberellic acid (GA₃) required to enhance rhizome production in arrowroot, ranging from 100 to 750 parts per million (ppm). Notably, the most effective concentration for promoting sprouting in arrowroot rhizome nodal cuttings has been determined to be 500 ppm. This concentration significantly improved both the sprouting rate and overall growth vigor.

Over an extensive eight-month cultivation period, the average yield of rhizomes per potted plant was 36, with an average of 246 nodes per plant. These findings indicate the remarkable potential of the Girigaca cultivar to produce a high number of arrowroot plantlets under the gibberellic acid (GA₃) treatment protocol.

The growing of arrowroots, irrespective of the system used, wetland or upland, presents challenges, particularly the procurement of propagation materials required, which are both scarce and bulky. Traditional methods for sourcing such substantial quantities can be labor-intensive and cumbersome. However, this study discovered an innovative propagation technique that achieves a multiplication ratio of 1:108 at a gibberellic acid dosage of 100 ppm and 1:246 at 750 ppm. As a result, a small number of 185 (100 ppm) and 81 (750 ppm) potted plants are needed in a greenhouse to generate enough propagation materials for planting one hectare.

The study suggests a strategic approach in which a relatively small number of potted plants can effectively supply abundant propagation material. This results in significant time and resource savings throughout the arrowroot production process. Moreover, the sprouted plantlets demonstrated improved storability and transportability, streamlining distribution logistics and increasing the viability of arrowroot in broader markets. When mature arrowroot rhizomes are correctly sectioned into nodal cuttings and placed in a temperature and humidity-controlled rooting chamber, they develop into viable propagation materials (plantlets) within a short time. This rapid macropropagation accelerates the expansion of arrowroot-growing areas and facilitates increased overall production, responding effectively to the acute shortage of propagation materials.

The rooting media tested for sprouting the arrowroot rhizome nodal cuttings, river sand, has been identified as the most effective substrate during the initial growth stages of arrowroot due to its excellent drainage properties and aeration capabilities, which promote strong root development. While river sand is the preferred medium, sawdust is a viable alternative for retaining moisture and improving nutrient availability.

5.4 Recommendations

According to the findings of the research, the following suggestions are proposed:

- i. The innovative moisture retention pit, with a 30 cm width and depths ranging from 30 cm to 60 cm, should be adopted as a planting technique for growing upland arrowroots. It will increase corm yields more than four to five times the national average.
- ii. To facilitate further research, the arrowroot moisture retention pit cultivation technique is proposed to be implemented in various agroecological zones (AEZs) at low and medium altitudes. The objective is to determine the optimal planting depth that maximizes arrowroot yield in these distinct environments.

- iii. To conduct further studies to evaluate the effect of early sucker removal on the growth and productivity of the mother plant. Aimed to improve management strategies for harvesting suckers for propagation before crop maturity. This development aims to establish systems that ensure a consistent supply of suckers to growers.
- iv. Future research should identify the ideal growth stages for maximizing rhizome production while maintaining the plant's tolerance to GA₃ concentrations above 500 ppm. It is essential to explore the long-term effects of GA₃ on yield and the plant's overall resilience against various biotic and abiotic stressors. This will help establish best practices in arrowroot cultivation and improve overall outcomes.
- v. The findings strongly advocate for the strategic application of GA₃ in large-scale arrowroot propagation, especially as upland production systems are increasingly gaining prominence in agricultural practices. Given the projected rise in demand for high-quality planting materials, it is imperative to establish a continuous production system for suckers, thereby facilitating operational scaling and ensuring sustainability in the supply chains.
- vi. Additional trials should be conducted to refine this finding further, exploring a range of concentrations surrounding the 500-ppm benchmark. This research could enhance sprouting efficiency and provide valuable insights into the economic implications of varying GA₃ levels, enabling farmers to make informed decisions about their practices.
- vii. Advocate for using gibberellic acid, both synthetic and natural, in large-scale arrowroot propagation to enhance efficiency and increase yields. It promotes faster

germination, improved growth rates, and more uniform crop development, which helps meet the rising demand for arrowroot propagation materials.

- viii. Future research should focus on the rooting media, optimizing the ratio of river sand to sawdust for improved large-scale production of propagation materials.
- ix. Before implementing this propagation method commercially, assessing its scalability under varied field conditions is essential to ensure optimal yield and adaptability. Greenhouse trials will test the practical application of GA₃, evaluating the transfer of plantlets from controlled chambers to open fields and their yield potential in various environments. Successful validation could lead to broader adoption, enhancing productivity and profitability in arrowroot farming.
- x. The study has confirmed that the technique involves innovative breeding strategies in arrowroot cultivation. Approaches such as rhizome grafting and other manipulations should be explored to improve the quality and market value of arrowroot corms while enhancing overall crop resilience.

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APPENDICES

1. Mean Squares for the Analysis of Variance of the effect of pit depth, season, growth period, and blocking of growth parameters

SOV	DF	Plant height	Leaf length	Leaf width	Leaf Area
Treatment	3	3006.58***	2289.92***	1581.40***	4996914.77***
Block	3	26.66***	15.15***	10.14 ^{ns}	34440.42 ^{ns}
Season	1	506.93***	49.09***	58.89***	29980.35***
Time	3	13064.93***	3129.70***	2422.75***	8285485.89***
Treatment*Block	9	97.87***	19.67***	19.81***	63814.45***
Treatment*Season	3	823.97***	413.14***	315.47***	1154678.35***
Treatment*Time	9	284.99***	193.17***	158.50***	586962.32***
Season*Time	3	679.16***	120.64***	75.23***	211165.04***
Treatment*Season*Time	9	161.42***	26.90***	24.55***	93142.60***
Error	84	31.22	20.47	19.22	57458.76
R ²	-	0.9569	0.9212	0.9034	0.9132
CV	-	8.37	12.11	13.52	23.54

Key: SOV= Source of Variation; DF= Degree of Freedom; CV=Coefficient of Variation; R²=Coefficient of determination; *=significant at p≤0.05; ***= Significant at p<0.001

2. Mean Squares for the Analysis of Variance of the effect of pit depth and season on shoot parameters

SOV	DF	Mother-sucker dist	No. of suckers	Cormel yield/plant	Stem girth	No. of leaves
Treatment (T)	3	105.609***	87.281***	3.260***	597.884***	155.448***
Season (S)	1	7.556 ^{ns}	9.031 ^{ns}	0.477 ^{ns}	191.101 ^{ns}	34.031***
Block (B)	3	1.505 ^{ns}	4.531 ^{ns}	0.177*	13.115 ^{ns}	6.864 ^{ns}
T*S	3	10.386*	20.615*	0.191*	260.757*	11.698*
T*B	9	2.651 ^{ns}	4.281 ^{ns}	0.076 ^{ns}	20.155 ^{ns}	5.254 ^{ns}
Error	12	2.363	3.969	0.042	63.258	2.115
C.V	-	17.802	25.810	19.386	27.550	5.573
R ²	-	0.926	0.889	0.960	0.797	0.958

Key: SOV= Source of Variation; DF= Degree of Freedom; CV=Coefficient of Variation; R²=Coefficient of determination; *=significant at p≤0.05; ***= Significant at p<0.001

3. Mean Squares for the Analysis of Variance of the effect of pit depth, season, and blocking of corm parameters of arrowroot

SOV	DF	Corm length	Corm girth	Corm diameter	Corm weight/ plant
Treatment (T)	3	2091.080***	370.563***	175.308***	8.008***
Season (S)	1	44.651*	86.525*	53.107*	0.623*
Block (B)	3	28.960 ^{ns}	2.638 ^{ns}	14.247 ^{ns}	0.038 ^{ns}
T*S	3	52.587*	75.315*	55.967*	0.239*
T*B	9	18.896 ^{ns}	2.950 ^{ns}	17.209 ^{ns}	0.017 ^{ns}
Error	12	17.696	37.523	16.820	0.074
C.V	-	12.760	5.326	4.235	17.349
R ²	-	0.969	0.969	0.795	0.966

Key: SOV= Source of Variation; DF= Degree of Freedom; CV=Coefficient of Variation; R²=Coefficient of determination; *=significant at p≤0.05; ***= Significant at p<0.001

4. Mean Squares for the Analysis of Variance of the effect of planting pit depth and season on corms and cormel yield of arrowroots in tonnes/ha

s.o.v	DF	Corms yield (ton/ha)	Cormel yield (ton/ha)
Pit depth	3	2106.227***	1561.306***
Season	1	24.065 ^{ns}	141.498 ^{ns}
Rep	3	26.323	170.865
Pit depth* Season	3	93.977*	57.117 ^{ns}
Error	21	22.413	55.148
C.V	-	15.757	32.262
R ²	-	0.934	0.826

Key: SOV= Source of Variation; DF= Degree of Freedom; CV=Coefficient of Variation; R²=Coefficient of determination; *=significant at p≤0.05; ***= Significant at p<0.001; ns= Not significant at p≤0.05

5. Mean Squares for the Analysis of Variance of the effect of cultivar, GA₃ hormone, and growth period on propagule parameters of arrowroot

SOV	DF	Rhizomes number	Rhizomes length	Rhizome's girth	Number of suckers	Number of nodes
Cultivar (C)	1	16240.133***	3364.125***	140.400***	36.300***	550265.633***
GA ₃ (H)	4	1134.446***	230.199***	9.281***	57.883***	51156.779***
Day (D)	3	271.933***	116.280***	0.015 ^{ns}	66.600***	95784.678***
Rep	2	5.308	2.349	0.028	0.175	3104.758
V*H	4	1134.445***	230.198***	9.281***	111.508***	51156.779***
V*D	3	271.933***	116.280***	0.015 ^{ns}	87.567***	95784.678***
H*D	12	90.968***	11.403***	0.020 ^{ns}	10.294***	12080.907***
V*H*D	12	90.968***	11.403***	0.020 ^{ns}	2.775*	12080.907***
Error	78	35.214	3.869	0.016	1.406	899.015
C.V	-	5.101	3.715	11.549	5.389	4.428
R ²	-	0.914	0.953	0.994	0.924	0.963

Key: SOV= Source of Variation; DF= Degree of Freedom; CV=Coefficient of Variation; R²=Coefficient of determination; *=significant at p≤0.05; ***= Significant at p<0.001

6. Mean Squares for the Analysis of Variance of the effect of cultivar, GA₃ hormone, and growth period of corm parameters of arrowroot

SOV	DF	Roots length	Roots dry weight	Corm Length	Corm girth	Corm Diameter	Corm dry weight	Cormel number	Cormel weight/plant
Cultivar (V)	1	424.155*	29.418*	0.166 ^{ns}	76.042***	19.876***	13015.623***	1824.048***	1821870.397***
GA ₃ (H)	4	179.877 ^{ns}	6.598 ^{ns}	21.211 ^{ns}	2.852 ^{ns}	0.504 ^{ns}	395.056***	3.622 ^{ns}	758.119 ^{ns}
Time (T)	3	3500.392***	179.987***	128.814***	128.682***	3.337***	1340.342***	56.994***	63833.610***
Rep	2	34.806	2.933	20.116	5.125	0.423	56.140	5.974	2879.005
V*H	4	76.969 ^{ns}	16.474 ^{ns}	23.823 ^{ns}	2.148 ^{ns}	0.064 ^{ns}	599.323***	3.670 ^{ns}	7630.064***
V*T	3	510.467***	85.622***	27.595 ^{ns}	73.794***	5.655***	1102.408***	58.797***	64278.518***
H*T	12	203.010*	34.316***	30.186 ^{ns}	4.469*	0.246 ^{ns}	256.234***	6.177 ^{ns}	17526.862***
V*H*T	12	166.281 ^{ns}	31.597***	23.373 ^{ns}	2.683 ^{ns}	0.250 ^{ns}	161.353*	6.322 ^{ns}	17772.960***
Error	78	93.658	7.672	26.518	2.015	0.199	72.748	3.738	2685.607
C.V	-	21.526	25.971	54.519	7.125	8.359	22.728	4.980	4.224
R ²	-	0.720	0.744	0.395	0.838	0.785	0.840	0.891	0.929

Key: SOV= Source of Variation; DF= Degree of Freedom; CV=Coefficient of Variation; R²=Coefficient of determination; *=significant at p≤0.05; ***= Significant at p<0.001

7. Mean Squares for the Analysis of Variance of the effect of cultivar, GA₃ hormone, and growth period on shoot parameters of arrowroot

SOV	DF	Stem girth	Height (cm)	Leaf area	Number of leaves	Shoot damage
Cultivar (C)	1	155.269***	3798.000***	2638.500 ^{ns}	444.675***	130.208***
GA ₃ (H)	4	3.683 ^{ns}	114.924*	31545.679*	1.279***	9.804***
Time (T)	3	179.806***	1662.155***	268433.523***	1275.008***	3.631***
Rep	2	1.785	1.789	25754.083	0.025	0.075
V*H	4	1.625 ^{ns}	34.368 ^{ns}	14026.503 ^{ns}	0.613 ^{ns}	8.771***
V*T	3	72.347***	284.028***	125576.703***	18.764***	3.363***
H*T	12	3.387 ^{ns}	79.843 ⁸	20649.767 ^{ns}	0.585*	0.415*
V*H*T	12	3.905 ^{ns}	32.359 ^{ns}	11348.490 ^{ns}	1.674***	0.482*
Error	78	2.622	39.855	13688.262	0.316	0.186
C.V	-	8.984	10.110	26.779	4.380	21.304
R ²	-	0.833	0.788	0.628	0.994	0.942

Key: SOV= Source of Variation; DF= Degree of Freedom; CV=Coefficient of Variation; R²=Coefficient of determination; *=significant at p≤0.05; ***= Significant at p<0.001

8. Mean Squares for the Analysis of Variance of the effect of GA₃ hormone, type of propagation media, and growth period of sprout count of arrowroot

SOV	DF	Sprout counts
Treatment	3	2947.675***
Media	1	1184.408***
Time	4	3789.783***
Rep	2	6.175
Treatment * Media	3	539.075***
Treatment * Time	12	262.717***
Media * Time	4	152.950***
Treatment * Media* Time	12	280.450***
Error	78	4.961
C.V	-	3.227
R ²	-	0.989

Key: SOV= Source of Variation; DF= Degree of Freedom; CV=Coefficient of Variation; R²=Coefficient of determination; *=significant at p≤0.05; ***= Significant at p<0.001

9. Mean Squares for the Analysis of Variance of the effect of GA₃ hormone, type of propagation media, and growth period of nodal cutting plantlet

SOV	DF	Stem girth	Root length	Plant height	Leaf area
Treatment (Trt)	3	1.682 ^{***}	56.171 [*]	44.043 ^{***}	31.301 ^{ns}
Media (M)	1	0.002 ^{ns}	2582.338 ^{***}	2.690 ^{ns}	1110.440 ^{***}
Time (T)	3	40.870 ^{***}	7075.074 ^{***}	2008.367 ^{***}	18556.082 ^{***}
Rep	2	0.052	10.007	7.020	105.717
Trt*M	3	2.489 ^{***}	192.293 ^{***}	21.761 ^{***}	911.022 ^{***}
Trt*T	9	0.284 ^{ns}	139.333 ^{***}	6.427 [*]	115.616 ^{ns}
M*T	3	0.824 [*]	618.025 ^{***}	38.729 ^{***}	632.137 ^{***}
Trt*M*T	9	1.302 ^{***}	102.233 ^{***}	5.335 ^{ns}	280.464 ^{ns}
Error	62	0.204	11.709	2.811	148.841
C.V	-	12.782	12.385	11.561	4.021
R ²	-	0.923	0.975	0.974	0.876

Key: SOV= Source of Variation; DF= Degree of Freedom; CV=Coefficient of Variation; R²=Coefficient of determination; *=significant at p≤0.05; ***= Significant at p<0.001

10. Mean Monthly Rainfall (mm) and Temperature (°C) at Njoro in 2023 and 2024

Month	2023				2024			
	Temperature (°C)			Rainfall (mm)	Temperature (°C)			Rainfall (mm)
	Max.	Min.	Mean		Max.	Min.	Mean	
January	24.68	7.42	16.05	0.7	23.61	11.42	17.52	134.4
February	26.89	7.57	17.23	0.0	26.24	9.10	17.67	18.4
March	26.36	9.82	18.09	59.3	27.10	9.87	18.48	79.6
April	23.07	10.25	16.66	142.7	23.25	12.47	17.86	278.1
May	23.82	9.79	16.80	92.0	24.32	11.39	17.85	405.2
June	22.50	10.71	16.61	96.9	23.17	9.43	16.30	53.4
July	23.50	9.86	16.68	19.0	22.31	9.03	15.67	176.4
August	24.89	8.64	16.77	36.7	19.58	9.68	14.63	163.4
September	24.18	9.04	16.61	97.6	23.13	9.00	16.07	138.9
October	24.79	10.32	17.55	43.2	23.00	9.71	16.35	196.0
November	21.82	11.39	16.61	175.0	22.70	10.44	16.57	196.0
December	23.58	10.26	16.92	40.8	21.48	9.32	15.40	134.4
Total	-	-	-	803.9	-	-	-	1,841.4

*Climate data provided from Egerton University Weather Station, Njoro Campus

11. Mean Monthly Temperature in the Greenhouse

Month	Maximum (°C)	Minimum (°C)	Mean (°C)
January	39.23	15.55	27.39
February	42.11	15.18	28.64
March	40.48	11.58	26.03
April	35.77	9.93	22.85
May	36.68	11.71	24.19
June	35.80	11.53	23.67
July	33.68	11.65	22.66
August	36.61	10.19	23.40
September	36.00	11.73	23.87
October	36.32	11.58	23.95
November	38.57	9.67	24.12
December	36.68	9.39	23.03

12. Visual assessments scale of Arrowroot shoot damage due to Gibberellic acid (GA₃) foliar application.

Score	Arrowroot damage	Visual characteristics
1	Normal leaf and petiole	No signs of leaf folding or obstruction
2	Slight leaf deformation, and the petiole groove is closed	Slight leaf folding and margin necrosis, petiole groove partially closed
3	Leaf scorching, folding, and retention	Severe leaf folding or compacted
4	Severe leaf damage and broken petioles	Complete leaf retention and petiole twisted/malformed
5	Leaf, shoot decapitated or dead	Leaf damaged and shoot retained or dead

13. DATA FOR EXPERIMENTS ONE, TWO, AND THREE

A. CORMS AND CORMEL_EXPT. 1

DATA ArrowRoot_1A;

```
INPUT Season Block      Trtment      corm_length corm_girth  corm_diameter
      cormwt_pit  mom_suckerdist  No_suckers  cormeyield_plot
      stem_girth  No_leaves;
```

DATALINES;

1	1	20	17	24	2.8	0.44	6.43	4	0.21	19.2	17
1	1	30	23.6	35.33	10	1.08	5.18	13	0.99	34	25
1	1	45	37	35.83	12.5	2.01	11	10	0.7	12	26
1	1	60	45.5	38.4	10.5	2.445	10.14	11	1.18	36.4	26
1	2	20	16.8	24	2.2	0.36	4.99	2	0.15	16.2	19
1	2	30	19.6	31.6	9.8	0.85	5.54	8	1.3	34.6	30
1	2	45	37.83	35	11.8	1.77	12.9	12	1.03	44	25
1	2	60	38	36.2	10.29	1.93	9.5	10	1.755	30	25
1	3	20	15.8	23.6	3	0.34	3.1	3	0.18	11	20
1	3	30	28.17	30.83	32.8	0.99	5.92	9	1.39	40	28
1	3	45	38	34.17	11.83	1.76	16.17	9	1.46	11.5	27
1	3	60	56.4	37.83	10.56	2.21	9.8	10	1.09	32.4	31
1	4	20	15	24	3.2	0.34	4.15	4	0.26	15.2	18
1	4	30	23.4	32.5	10	1.04	5.31	10	0.99	40	27
1	4	45	38.5	39.33	12.7	2.53	11.43	7	0.9	11.1	28
1	4	60	58	41.4	11.19	2.81	8.83	10	1.36	35.2	29
2	1	20	13.4	24.6	3	0.37	5.89	3	0.15	17.1	21
2	1	30	29.51	36.33	11.2	1.59	5.75	5	1.87	32.3	26
2	1	45	31.39	32.36	11.5	2.03	14.25	8	0.84	43.6	29
2	1	60	60.6	40.8	11.56	2.925	10.23	12	1.54	35	29
2	2	20	15	22.4	2.8	0.3	3.94	4	0.22	16.8	19
2	2	30	29.67	34.44	8.8	1.64	6	3	1.97	31.9	32
2	2	45	34.39	35.64	12.2	1.99	13.64	11	1.08	33.5	31
2	2	60	55	42	11.55	3.345	9.44	17	2.45	38.8	28
2	3	20	15	23.2	2.8	0.32	6.19	4	0.13	18.7	22

2	3	30	28.28	34.72	10.2	1.34	5.5	4	1.47	30.6	29
2	3	45	37.28	37.09	11.2	2.02	13.58	6	1.09	42.4	31
2	3	60	49.8	41	10.8	3.045	13.71	9	2.04	36.8	29
2	4	20	16	23	2.4	0.34	8.63	3	0.08	15.9	20
2	4	30	28.34	35.17	11.02	1.42	8.33	5	1.15	31.2	27
2	4	45	37.94	37.72	12.7	2.05	11.75	12	1.15	43.6	28
2	4	60	64.8	38	10.96	2.645	9.11	9	1.62	32.8	33

```
;
PROC GLM;

CLASS Treatment Season Block;

MODEL corm_length corm_girth corm_diameter      cormwt_pit  mom_suckerdist
      No_suckers  cormeyield_plot  stem_girth  No_leaves= Trtment Season
      Block Season*Trtment Trtment*Block/SS1;

LSMEANS Trtment Season Block Season*Trtment Trtment*Block/pdiff=all
ADJUST=tukey lines;

RUN;

proc means mean stderr maxdec=2;

class Treatment;

var corm_length corm_girth corm_diameter  cormwt_pit  mom_suckerdist
    No_suckers  cormeyield_plot  stem_girth  No_leaves;

run;

proc means mean stderr maxdec=2;

class Season;

var corm_length corm_girth corm_diameter  cormwt_pit  mom_suckerdist
    No_suckers  cormeyield_plot  stem_girth  No_leaves;

run;

proc means mean stderr maxdec=2;

class Treatment Season;

var corm_length corm_girth corm_diameter cormwt_pit  mom_suckerdist
    No_suckers cormeyield_plot  stem_girth  No_leaves;

run;

proc corr;

var corm_length corm_girth corm_diameter cormwt_pit  mom_suckerdist
    No_suckers cormeyield_plot  stem_girth  No_leaves;

run;
```

B. GROWTH PARAMETERS_EXPT. 1

DATA ArrowRoot_1B;

INPUT Season Block Treatment Time plant_hgt L_length L_width
 L_area;

DATALINES;

1	1	20	60	35	24	21.2	381.60
1	1	20	120	45.8	26.4	24	475.20
1	1	20	180	61	24	22.2	399.60
1	1	20	240	68	30	24.6	553.50
1	1	30	60	44.26	26.46	23.83	472.91
1	1	30	120	57.3	34.3	29	746.03
1	1	30	180	75.6	49	46.67	1715.12
1	1	30	240	95.49	49.67	44.17	1645.44
1	1	45	60	44.4	25.26	18.36	347.83
1	1	45	120	60.6	38.3	34.3	985.27
1	1	45	180	74.3	48	41.6	1497.60
1	1	45	240	81.6	50.3	43	1622.18
1	1	60	60	53.93	35	30.3	795.38
1	1	60	120	68.6	46	41	1414.50
1	1	60	180	75.6	50.6	42	1593.90
1	1	60	240	86	56	47.33	1987.86
1	2	20	60	40	21.4	19.4	311.37
1	2	20	120	45.6	23	24	414.00
1	2	20	180	64	23	21	362.25
1	2	20	240	71	25.2	21.2	400.68
1	2	30	60	56.5	34.3	29	746.03
1	2	30	120	64	39	35.3	1032.53
1	2	30	180	72	44.6	40.3	1348.04
1	2	30	240	83.6	56.6	47.3	2007.89
1	2	45	60	43.76	29.36	22.96	505.58
1	2	45	120	64.6	38.2	34.3	982.70
1	2	45	180	71.6	43	38	1225.50
1	2	45	240	90	52.33	49	1923.13

1	2	60	60	51.16	29.16	22.63	494.92
1	2	60	120	61.3	38.3	35	1005.38
1	2	60	180	78.6	53.3	44.3	1770.89
1	2	60	240	89.33	53	46.33	1841.62
1	3	20	60	35	18.4	16.4	226.32
1	3	20	120	38.8	23	20.6	355.35
1	3	20	180	53	25	21.8	408.75
1	3	20	240	65	21	20	315.00
1	3	30	60	61.4	33.6	30.6	771.12
1	3	30	120	69.3	40.3	35.3	1066.94
1	3	30	180	73.67	47	40.67	1433.62
1	3	30	240	77	43.6	46.3	1514.01
1	3	45	60	40.5	22.36	17.5	293.48
1	3	45	120	67.5	43.6	39.6	1294.92
1	3	45	180	76	50.3	42.3	1595.77
1	3	45	240	89	56.3	48	2026.80
1	3	60	60	53.37	33.63	29.8	751.63
1	3	60	120	68.03	43.6	38.6	1262.22
1	3	60	180	73.3	50.6	43.3	1643.24
1	3	60	240	89.33	58	46.67	2030.15
1	4	20	60	40.9	22.2	20	333.00
1	4	20	120	49.8	26.8	21.4	430.14
1	4	20	180	64	27	24.6	498.15
1	4	20	240	66	23	20.8	358.80
1	4	30	60	31.3	21.23	17.33	275.94
1	4	30	120	57.3	34.3	29	746.03
1	4	30	180	65.33	39	36.33	1062.65
1	4	30	240	79	52	45.3	1766.70
1	4	45	60	41.83	38	33	940.50
1	4	45	120	55	35	30	787.50
1	4	45	180	64.33	42.67	35.33	1130.65
1	4	45	240	78.6	53	43.6	1733.10
1	4	60	60	61.4	32.5	26	633.75

1	4	60	120	71	44.33	37.33	1241.13
1	4	60	180	96.56	51.33	43	1655.39
1	4	60	240	116	62.13	54.95	2560.53
2	1	20	60	44	25	22.2	416.25
2	1	20	120	49	27	23.4	473.85
2	1	20	180	62	26.2	24	471.60
2	1	20	240	62.2	22	21	346.50
2	1	30	60	40.75	20	18.8	282.00
2	1	30	120	66.25	37.78	34	963.39
2	1	30	180	87.66	50.66	48.66	1848.84
2	1	30	240	108.33		53.4	46.17 1849.11
2	1	45	60	44.4	25.26	18.36	347.83
2	1	45	120	77.3	46.6	41.3	1443.44
2	1	45	180	83.3	55	45.6	1881.00
2	1	45	240	118	57.83	50	2168.63
2	1	60	60	40.5	18.25	15.75	215.58
2	1	60	120	54.75	38.75	22.5	653.91
2	1	60	180	63.33	32.66	31.33	767.43
2	1	60	240	99	49.5	44	1633.50
2	2	20	60	33	20	18	270.00
2	2	20	120	53	24	21	378.00
2	2	20	180	66	23	20.8	358.80
2	2	20	240	68	30	24.6	553.50
2	2	30	60	45	22.5	19.25	324.84
2	2	30	120	63.63	33.88	33	838.53
2	2	30	180	83.66	49	46.67	1715.12
2	2	30	240	110.65		55.93	50.4 2114.15
2	2	45	60	50.23	25.23	22.97	434.65
2	2	45	120	72	46.6	39	1363.05
2	2	45	180	80.3	54.3	46	1873.35
2	2	45	240	124	61.66	45.66	2111.55
2	2	60	60	44.75	18	16.75	226.13
2	2	60	120	61.5	28.5	22.25	475.59

2	2	60	180	69.33	40	37.33	1119.90
2	2	60	240	105	52.7	47.13	1862.81
2	3	20	60	30	21.2	17.6	279.84
2	3	20	120	40.5	24.2	20	363.00
2	3	20	180	62.4	23.8	21.8	389.13
2	3	20	240	64.8	23	21.2	365.70
2	3	30	60	40.5	18.75	15.75	221.48
2	3	30	120	53.63	36	30	810.00
2	3	30	180	88.66	48.66	31.53	1150.69
2	3	30	240	123.15		50.65	45.2 1717.04
2	3	45	60	46.23	21.36	19	304.38
2	3	45	120	68.6	46.3	39.6	1375.11
2	3	45	180	84.67	56.33	47.3	1998.31
2	3	45	240	113	59	55	2433.75
2	3	60	60	38.5	18	16	216.00
2	3	60	120	57.5	27.5	22	453.75
2	3	60	180	66.33	38.66	29.33	850.42
2	3	60	240	100.5	48.03	44.43	1600.48
2	4	20	60	38	21.2	18	286.20
2	4	20	120	52	21.4	20.2	324.21
2	4	20	180	50.4	24	20	360.00
2	4	20	240	54	59.66	51.26	2293.63
2	4	30	60	43	23	20.5	353.63
2	4	30	120	61.38	37.75	30.5	863.53
2	4	30	180	82.33	53	50	1987.50
2	4	30	240	107.65		51	41 1568.25
2	4	45	60	44.6	28.53	31.23	668.24
2	4	45	120	67	44	38	1254.00
2	4	45	180	89.33	53	46.33	1841.62
2	4	45	240	126	61.66	55	2543.48
2	4	60	60	40.5	20.5	19	292.13
2	4	60	120	54.5	28	22	462.00
2	4	60	180	64	37.66	27.33	771.94

2	4	60	240	113.33	55.56	48.2	2008.49
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PROC GLM;

CLASS Treatment Block Season Time;

MODEL plant_hgt L_length L_width L_area= Treatment Block Season Time
Treatment*Block Treatment*Season Treatment*Time Season*Time
Treatment*Season*Time/SS1;

LSMEANS Treatment Block Season Time Treatment*Block Treatment*Season
Treatment*Time Season*Time Treatment*Season*Time/PDIFF=ALL ADJUST= TUKEY
LINES;

RUN;

proc means mean stderr maxdec=2;

class Treatment Time;

var plant_hgt L_length L_width L_area;

run;

proc means mean stderr maxdec=2;

class Treatment Season Time;

var plant_hgt L_length L_width L_area;

run;

C. YIELD CHARACTERISTICS EXPT. 1

DATA Expt1_c;

INPUT Treat Rep Season corm_ha cormel_ha TotalYld_ha;

DATALINES;

30	1	1	36600	27466.66667	64066.66667
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45	1	1	35300	26600	61900
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20	1	1	8800	2000	10800
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60	1	1	33016.66667	23650	56666.66667
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20	2	1	7266.66667	1666.66667	8933.33333
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60	2	1	38733.33333	38300	77033.33333
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30	2	1	22166.66667	27716.66667	49883.33333
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45	2	1	41266.66667	29100	70366.66667
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30	3	1	29333.33333	9216.66667	38550
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45	3	1	35200	26666.66667	61866.66667
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20	3	1	6800	3000	9800
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60	3	1	42216.66667	17866.66667	60083.33333
30	4	1	28466.66667	19866.66667	48333.33333
20	4	1	9600	1333.333333	10933.33333
60	4	1	41533.33333	27250	68783.33333
45	4	1	50550	52933.33333	103483.3333
30	1	2	31833.33333	37473.33333	69306.66667
45	1	2	26286.66667	22973.33333	49260
20	1	2	7533.333333	3633.333333	11166.66667
60	1	2	44556.66667	25750	70306.66667
20	2	2	6166.666667	3733.333333	9900
60	2	2	50683.33333	45643.33333	96326.66667
30	2	2	33860	39406.66667	73266.66667
45	2	2	37306.66667	45976.66667	83283.33333
30	3	2	28290	29450	57740
45	3	2	40476.66667	30560	71036.66667
20	3	2	6533.333333	2833.333333	9366.666667
60	3	2	52083.33333	24673.33333	76756.66667
30	4	2	26126.66667	22960	49086.66667
20	4	2	7600	1666.666667	9266.666667
60	4	2	54210	32310	86520
45	4	2	41056.66667	32910	73966.66667

```

;
PROC GLM;
CLASS Treat Season Rep;
MODEL corm_ha cormel_ha TotalYld_ha= Treat Season Rep Treat*Season/SS1;
LSMEANS Treat Season Treat*Season/pdiff=all adjust=tukey lines;
RUN;
PROC MEANS mean maxdec=2;
CLASS Treat;
VAR corm_ha cormel_ha TotalYld_ha;
RUN;
PROC MEANS mean stderr maxdec=2;
CLASS Treat Season;

```

```
VAR corm_ha cormel_ha TotalYld_ha;
```

```
RUN;
```

D. EXPERIMENT 2 GREENHOUSE

```
DATA Expt_2;
```

```
INPUT Variety $ Hormone Day Rep StemGirth Height leaf_length leaf_width
Rhizomes_No Rhizome_Length No_nodes_rhiz Suckers_No
Roots_length Fresh_Root_wt Root_Dry_wt Corm_length
Corm_Girth Corm_Diameter corm_fresh_wt corm_Dry_wt leaves_plant
cormel_plant cormel_wt_plant Shoot_damage;
```

```
DATALINES;
```

Girigaca	0	60	1	18	72	28	25	0	0	0	9
57	195	2.1	7	19.2	5.4	150	12.9	6	0	0	1
Girigaca	0	60	2	20	76	21	19	0	0	0	7
34	210	10.21	7.3	22.4	5.2	105	35.32	6	0	0	1
Girigaca	0	60	3	17.5	68.1	26.1	21	0	0	0	8
48.9	140	4.11	8	18.6	5.1	145	34.14	5	0	0	1
Girigaca	100	60	1	18.9	85	23.8	22	16	4.8	34	0
44.2	80	3.26	7.3	20	5.1	110	18.19	7	0	0	2
Girigaca	100	60	2	19	78	25.2	22.8	44	5.75	41	0
42	70	2.38	7	20.9	5.2	125	39.47	5	0	0	3
Girigaca	100	60	3	17.1	82.1	30	29.1	17	8.5	42	0
50	115	6.68	6.8	19.6	5.1	160	48.97	6	0	0	3
Girigaca	250	60	1	18.8	81	25.4	23	36	6.5	63	0
38	160	8.72	8	20.4	5	135	34.88	7	0	0	5
Girigaca	250	60	2	19	89.5	31	27	19	8	14	0
43.1	155	3.46	6.9	19.2	5.5	145	16.48	6	0	0	2
Girigaca	250	60	3	16	65	26.3	22.1	11	8.25	46	0
83	185	8.87	6.4	17.4	4.2	135	24.25	7	0	0	5
Girigaca	500	60	1	19	77	32	27.9	25	8	57	0
42.1	245	23.03	7.8	21.8	5.2	120	31.18	6	0	0	3
Girigaca	500	60	2	17	74	26.5	23	22	10	34	0
40	160	9.2	8	22	4.9	125	37.32	5	0	0	4
Girigaca	500	60	3	19.1	76.1	28.2	23.3	10	5.6	20	0
78	220	21.05	7	21.6	5.6	115	37.11	6	0	0	5
Girigaca	750	60	1	21.4	90	28.5	23.9	34	12.5	65	0
46.4	265	3.66	7.4	19.4	6	205	27.23	6	0	0	5
Girigaca	750	60	2	18	74	24.2	22.1	21	8.3	56	0
30	90	3.66	7.3	19.2	5.1	135	17.35	6	0	0	4
Girigaca	750	60	3	19.4	83	38.2	32	34	13.3	35	0
47	230	7.74	7.2	20	5.8	175	21.32	7	0	0	5
Kienyeji	0	60	1	18	50	25	26	0	0	0	0
40.1	160	5.86	7.2	18	6.4	85	38.77	4	10	215	1

Kienyeji	0	60	2	17.1	51	25.1	29.8	0	0	0	0
61	140	7.81	6.2	20	6.1	125	41.79	4	9	160	1
Kienyeji	0	60	3	20	61	26.3	29.2	0	0	0	0
57.2	215	9.31	5	18	6	75	34.46	4	15	165	1
Kienyeji	100	60	1	25	61.5	22	24	0	0	0	0
52	145	8	6	21	6.1	100	44.5	4	9	225	1
Kienyeji	100	60	2	21.8	56	20.9	28.1	0	0	0	0
61	230	7.42	9	21	6.1	175	43.38	4	6	200	1
Kienyeji	100	60	3	18.9	58	30.2	31.2	0	0	0	0
67.9	145	5.8	6.1	17.3	5.2	80	37.24	4	12	170	1
Kienyeji	250	60	1	22	67	29.9	31	0	0	0	0
60	185	7	5.3	19	6	120	41.12	5	7	310	1
Kienyeji	250	60	2	20.4	60.1	24.4	27	0	0	0	0
58.8	255	5.44	8.1	16.4	5.1	80	37.82	4	20	180	1
Kienyeji	250	60	3	19	55.4	23.2	25.1	0	0	0	0
79.8	150	9.76	6.2	16.1	5.4	75	36.63	4	12	115	1
Kienyeji	500	60	1	19	60	29.9	32.8	0	0	0	0
40.8	225	6.61	6	19	6.1	235	39.7	4	8		1
Kienyeji	500	60	2	20	51	24.4	29.9	0	0	0	0
33	170	4.89	5.3	16	5.2	70	38.27	4	6	160	1
Kienyeji	500	60	3	22.1	67.3	34	35.2	0	0	0	0
76	305	9.04	5.3	22	6.1	120	42.77	4	11	180	1
Kienyeji	750	60	1	21.4	68	35.1	32	0	0	0	0
57	275	9.31	5.2	20	6.4	125	44.65	4	9	285	1
Kienyeji	750	60	2	22	61	27.6	29.5	0	0	0	0
54	250	10.78	8.2	20	6	205	45.37	4	11	265	1
Kienyeji	750	60	3	21.3	65	27.2	32	0	0	0	0
59.8	280	8.88	5.3	17	5.3	80	54.79	4	18	235	1
Girigaca	0	120	1	21	70	26	22.8	0	0	0	10
46.2	220	16.75	9.4	17.2	6.2	265	74.12	10	0	0	1
Girigaca	0	120	2	18.2	68	24.4	29	0	0	0	16
52.8	260	14.24	6.8	18.2	5.2	140	39.94	12	0	0	1
Girigaca	0	120	3	19	78	31	27.8	0	0	0	5
52.2	220	12.85	5.6	16.4	5.6	175	43.02	10	0	0	1
Girigaca	100	120	1	19.8	77	29	25	11	6.75	36	0
38.6	195	10.63	9	18.9	5.4	165	25.5	12	0	0	2
Girigaca	100	120	2	18.8	79.2	32	23.8	15	8.5	62	0
66.2	255	11.64	5.8	17.1	4.4	135	28.2	13	0	0	3
Girigaca	100	120	3	20	80.2	30.2	27.4	25	11.75	59	0
70.2	320	11.9	8.4	17.4	5.2	155	17.94	12	0	0	2
Girigaca	250	120	1	17.8	67.8	25	21	17	7.75	39	0
40	190	10.16	8.8	16	5.6	150	23.65	10	0	0	2

Girigaca	250	120	2	15.8	68	29.8	21	27	11.75	63	0
53.2	110	12.22	8.8	17	5.2	170	25.39	11	0	0	2
Girigaca	250	120	3	17	70	26	20	42	14	84	0
23	65	12.52	7.8	15.8	5	170	31.37	12	0	0	2
Girigaca	500	120	1	18.5	75	27.6	24	26	8	67	0
40.2	210	9.56	8.2	19.8	5.8	170	19.22	12	0	0	2
Girigaca	500	120	2	17.2	80	32.47	20.9	12	6.75	37	0
47	120	9.72	7.4	18.2	5	115	15.79	12	0	0	3
Girigaca	500	120	3	19.8	85.6	34	28	27	11.75	61	0
53	180	8.53	7.2	17.8	5.8	185	23.53	13	0	0	3
Girigaca	750	120	1	20.8	83.8	23.2	19.9	13	9.5	42	0
53	185	12.18	8.5	19.4	5.4	140	10.34	12	0	0	4
Girigaca	750	120	2	18	75	27	22.6	21	7.25	40	0
60	160	12.35	7.8	16.4	5.8	175	10.27	11	0	0	4
Girigaca	750	120	3	19	71	29	25	25	13	35	0
56	180	13.42	6.2	19.8	5.4	120	24.5	12	0	0	4
Kienyeji	0	120	1	17.2	68.1	29.2	25	0	0	0	0
38.9	160	6.88	6	18	6	85	40.19	9	9	245	1
Kienyeji	0	120	2	21.8	67	31.5	31.1	0	0	0	0
64.8	280	9.44	7	18	5.1	100	45.77	9	7	330	1
Kienyeji	0	120	3	18.8	57	24.2	26	0	0	0	0
56	150	7.34	6.2	16	5.4	75	34.91	8	6	185	1
Kienyeji	100	120	1	21.3	55	23.9	25	0	0	0	0
45.2	160	9.2	7	16	6	85	37.77	8	12	270	1
Kienyeji	100	120	2	18.2	60.5	27	27.8	0	0	0	0
46	230	5.8	6.1	19.3	6	105	37.24	9	8	250	1
Kienyeji	100	120	3	20	65	30	29.5	0	0	0	0
45	180	9.9	7	14	5	75	33.6	8	6	200	1
Kienyeji	250	120	1	23	60	25	26.5	0	0	0	0
67.8	300	7.17	5.3	17.3	5.3	95	43.82	9	7	225	1
Kienyeji	250	120	2	22.2	63	25	28	0	0	0	0
48.9	275	7.12	7.1	17	5.3	80	55.39	9	6	130	1
Kienyeji	250	120	3	22	71	32.6	32	0	0	0	0
65	205	5.22	61	13.2	5.1	65	45.42	9	11	285	1
Kienyeji	500	120	1	21	66	31	34	0	0	0	0
78	205	6.1	6.2	19.3	6.1	135	37.97	9	12	265	1
Kienyeji	500	120	2	23	64.5	28	27	0	0	0	0
77.2	225	7.08	6.2	19	6.3	300	40.48	9	7	110	1
Kienyeji	500	120	3	21	56	26	27	0	0	0	0
60	195	6.71	5.4	15	5.4	330	30.39	8	9	110	1
Kienyeji	750	120	1	19	55	26.2	27.2	0	0	0	0
56.7	190	12	5.3	16	5	75	42.61	8	13	150	1

Kienyeji	750	120	2	21	59	26	27.8	0	0	0	0
70.8	170	10.78	6.2	14.3	5.2	70	45.37	8	6	260	1
Kienyeji	750	120	3	19	62	29	26.3	0	0	0	0
77.9	185	14.19	7.2	16.4	6.1	115	40.31	8	9	295	1
Girigaca	0	180	1	17.1	58.2	31.8	26	0	0	0	4
31.6	55	11.68	10.2	19	3.5	190	29.61	18	0	0	1
Girigaca	0	180	2	14.6	62	25.4	22	0	0	0	5
18.9	90	11.3	11.2	20	4.8	225	18.79	18	0	0	1
Girigaca	0	180	3	15	60.2	24.6	21	0	0	0	7
22.2	80	6.86	12.2	22.8	6.4	315	46.47	18	0	0	1
Girigaca	100	180	1	15	68.2	29	20.2	21	15.44	172	0
34	125	14.99	11	19.1	4.4	215	35.11	19	0	0	5
Girigaca	100	180	2	17.2	61.6	22	18.2	36	13.32	178	0
41.6	145	25.27	11.2	20.4	4.6	20	7.62	19	0	0	4
Girigaca	100	180	3	10	42	26.2	28.2	19	15.2	192	0
44.2	170	15.39	11	18.6	4.8	170	27.7	19	0	0	4
Girigaca	250	180	1	16.8	65	27.4	21	24	12.1	204	0
47.4	185	11.93	11	20.8	4.8	210	29.34	19	0	0	5
Girigaca	250	180	2	15.2	54	18	13.8	28	14.36	218	0
49.2	105	19.31	9.8	16.6	3.6	115	20.6	19	0	0	5
Girigaca	250	180	3	17.8	53.8	24.8	18.4	30	17.48	243	0
48	145	12.83	13	19.4	4.6	215	25.19	19	0	0	4
Girigaca	500	180	1	15.4	61.6	19.4	17.2	38	16.44	310	0
20.4	90	10.38	11.2	17.8	4.6	190	15.76	20	0	0	5
Girigaca	500	180	2	15.8	64.2	34.4	22.4	35	20.4	308	0
45.6	125	10.25	11	18.8	4.2	175	14.36	20	0	0	4
Girigaca	500	180	3	14.4	64	26.4	19.4	48	16.88	344	0
26	85	7.05	13	18.8	4.2	180	27.6	20	0	0	5
Girigaca	750	180	1	15	69	23.6	24	66	22.04	494	0
43.4	95	10.67	9.8	19	4	170	27.96	20	0	0	5
Girigaca	750	180	2	13.4	60.8	24.8	19.8	64	29.4	334	0
46.8	95	11.21	13	19.8	3.4	230	9.63	20	0	0	5
Girigaca	750	180	3	16.4	64	30	22.2	47	20.2	607	0
38	110	10.34	11.4	21.4	4.6	265	20.77	20	0	0	5
Kienyeji	0	180	1	22.4	48.1	26.6	21.6	0	0	0	0
43	230	9.66	8.3	23.8	6.8	180	38.77	14	8	365	1
Kienyeji	0	180	2	22.6	59.8	25.2	21.8	0	0	0	2
34.8	195	12.37	9.5	24	6.9	215	43.75	14	7	475	1
Kienyeji	0	180	3	22	55.8	22.9	20.1	0	0	0	0
48.2	145	12.48	8.5	24.6	6.8	240	41.79	14	9	435	1
Kienyeji	100	180	1	21	52.1	27.2	22	0	0	0	7
29	100	4.56	9.2	23.1	6	225	40.42	15	5	55	1

Kienyeji	100	180	2	21.8	53.4	22.5	18.4	0	0	0	5
37.2	110	5.24	9	20.9	5.8	205	44.67	15	4	85	1
Kienyeji	100	180	3	18.9	53	22.2	22.2	0	0	0	7
56.2	110	7.2	8.9	22.2	5.9	180	39.24	15	5	80	1
Kienyeji	250	180	1	21.8	56.2	21	20.8	0	0	0	5
41.8	115	11.17	8.9	24.6	6.6	215	27.55	14	2	130	1
Kienyeji	250	180	2	22	54.4	25.6	24.2	0	0	0	4
37.2	195	9.76	10	23.8	6.6	255	36.63	14	3	150	1
Kienyeji	250	180	3	23.4	53.6	23.2	19.8	0	0	0	9
37.5	175	11.83	9	24.5	6.8	235	43.71	14	3	140	1
Kienyeji	500	180	1	21.8	56.6	22.4	22.6	0	0	0	6
29.9	105	9.04	9.3	24.5	6.8	265	42.77	13	4	195	1
Kienyeji	500	180	2	21	53.6	23.8	23.6	0	0	0	8
34.2	160	9.96	10.1	22.6	6.6	205	39.35	14	1	175	1
Kienyeji	500	180	3	22.4	54.6	25.2	26.6	0	0	0	8
32	110	4.33	9	22.8	6.6	170	46.31	15	4	135	1
Kienyeji	750	180	1	21.6	67.5	25	29.6	0	0	0	8
59.8	145	4.27	10.2	24.2	6.6	190	56.09	13	4	105	1
Kienyeji	750	180	2	22	63	23.2	28.2	0	0	0	8
34.2	155	8.88	9.1	22.2	6.8	240	54.79	13	3	125	1
Kienyeji	750	180	3	20.4	65.2	22.1	25.2	0	0	0	7
41	165	10.48	9.8	21.6	6.2	205	44.62	13	4	175	1
Girigaca	0	240	1	14	38.2	28.2	24.8	0	0	0	12
38.2	145	16.75	11.2	20.8	4.6	225	74.12	23	0	0	1
Girigaca	0	240	2	11.5	62	27.8	23.6	0	0	0	9
38.8	140	14.24	13.4	18.2	4	155	39.94	23	0	0	1
Girigaca	0	240	3	15	77.8	37.6	33.8	0	0	0	7
36	210	12.85	14.2	22.2	4.8	330	43.02	23	0	0	1
Girigaca	100	240	1	11	40.2	13.4	11.8	29	12.88	142	0
28	135	10.63	9.2	15.8	3.8	140	25.5	23	0	0	3
Girigaca	100	240	2	19	54.8	24.6	29.2	30	14.6	180	0
32.8	165	11.64	11.8	20.4	4.6	230	28.2	23	0	0	3
Girigaca	100	240	3	12.6	46	15.2	12.6	21	16.2	163	0
19.4	130	11.9	11.4	15.6	3.8	125	17.94	22	0	0	3
Girigaca	250	240	1	15	61.4	18.2	14	45	19.76	148	0
41.1	115	10.16	10.8	21.8	4.8	260	23.65	22	0	0	3
Girigaca	250	240	2	15.2	61	32.4	25.8	35	23.28	190	0
46.6	155	12.22	10	19.2	4.8	150	25.39	22	0	0	3
Girigaca	250	240	3	17.2	59	20	20	24	8.08	298	0
48	170	12.52	11.2	19.2	5	175	31.37	22	0	0	3
Girigaca	500	240	1	14.4	63.6	37.2	21.2	28	19	326	0
27.2	90	8.53	10.8	18.4	5	185	23.53	22	0	0	3

Girigaca	500	240	2	15.8	74.2	34	23	42	17.4	334	0
38.2	115	9.56	12.8	19	4.4	170	19.22	22	0	0	3
Girigaca	500	240	3	16	58.8	28.4	24	28	16.38	367	0
38	114	12.1	10	18.6	4.9	140	19.18	22	0	0	2
Girigaca	750	240	1	15.6	58.4	32.4	23	41	19.28	442	0
44.4	180	15.47	10.6	20.6	5	160	24.5	22	0	0	3
Girigaca	750	240	2	15.4	57.2	22,4	18.6	26	19.8	306	0
38	135	12.48	12	18.4	5	160	18.08	22	0	0	4
Girigaca	750	240	3	17.4	63.6	26	21.1	41	19.2	494	0
37.8	110	12.18	10	20.2	5.2	170	10.38	19	0	0	4
Kienyeji	0	240	1	12.8	53.2	17.2	16.8	0	0	0	7
33.6	60	11.76	12	21.2	5.2	275	64.16	16	3	140	0
Kienyeji	0	240	2	16.6	56.6	16.8	15.6	0	0	0	6
42	75	19.15	10.6	24	5.2	305	65.92	16	6	370	1
Kienyeji	0	240	3	12.8	51.2	21.8	19.6	0	0	0	5
38.6	85	15.33	11.2	21.8	4.8	460	72.61	17	8	170	1
Kienyeji	100	240	1	13.4	46.2	15.2	15.8	0	0	0	9
14.8	40	15.02	13.2	25.2	5	195	51.58	17	6	365	1
Kienyeji	100	240	2	10	41.2	15.4	14.8	0	0	0	7
19.8	50	11.49	13.8	24	4.8	115	46.57	17	5	330	1
Kienyeji	100	240	3	13.4	41.3	15.8	15.6	0	0	0	8
17.8	50	9.73	12.8	23.8	4.8	125	54.43	18	4	330	1
Kienyeji	250	240	1	14.2	54.2	24	21.8	0	0	0	7
30.2	90	20.81	11.2	24.8	5.2	300	84.76	18	4	175	1
Kienyeji	250	240	2	14.4	45.6	20	18.6	0	0	0	6
30.4	100	14.51	11.6	25.6	4.8	320	100.4	17	7	385	1
Kienyeji	250	240	3	13.4	48.2	23.6	17.4	0	0	0	6
31.4	50	23.22	10.4	24.8	5.6	340	76.26	17	7	380	1
Kienyeji	500	240	1	15.4	43.2	18.2	17.6	0	0	0	2
36.8	75	17.85	12.8	23.6	5.6	360	67.47	17	8	350	1
Kienyeji	500	240	2	13.2	54.2	20.6	16.4	0	0	0	3
28.4	80	9.82	13.6	24	5.2	345	68.66	17	13	470	1
Kienyeji	500	240	3	13.6	51.2	24.4	17.2	0	0	0	4
28.2	80	16.73	13.8	24.8	4.2	355	81.91	17	10	640	1
Kienyeji	750	240	1	15.4	56.6	19.2	16.4	0	0	0	3
36.6	65	11.17	12	24.6	5.2	355	46.1	17	8	510	1
Kienyeji	750	240	2	14.2	47.8	15.4	14.8	0	0	0	4
30.4	40	18.72	11	23.8	5.1	355	46	17	10	585	1
Kienyeji	750	240	3	15.2	50.1	18.8	18	0	0	0	4
26.2	60	17.17	12.4	24	4.8	300	74.86	17	12	560	1

;

```

PROC GLM;

CLASS Variety Hormone Day Rep;

MODEL StemGirth Height leaf_length leaf_width Rhizomes_No Rhizome_Length
      No_nodes_rhiz Suckers_No Roots_length Fresh_Root_wt
      Root_Dry_wt Corm_length Corm_Girth

Corm_Diameter corm_fresh_wt corm_Dry_wt leaves_plant cormel_plant
cormel_wt_plant Shoot_damage= Variety Hormone Day Rep Variety*Hormone
Variety*Day Hormone*Day Variety*Hormone*Day/SS1;

MEANS Variety Hormone Day/ TUKEY;

LSMEANS Variety*Hormone Variety*Day Hormone*Day
Variety*Hormone*Day/PDIFF=ALL ADJUST=TUKEY;

RUN;

PROC MEANS MEAN STDERR MAXDEC=2;

CLASS Variety;

VAR StemGirth Height leaf_length leaf_width Rhizomes_No Rhizome_Length
      No_nodes_rhiz Suckers_No Roots_length Fresh_Root_wt
      Root_Dry_wt Corm_length Corm_Girth

Corm_Diameter corm_fresh_wt corm_Dry_wt leaves_plant cormel_plant
cormel_wt_plant Shoot_damage;

RUN;

PROC MEANS MEAN STDERR MAXDEC=2;

CLASS Variety;

VAR StemGirth Height leaf_length leaf_width Rhizomes_No Rhizome_Length
      No_nodes_rhiz

Suckers_No Roots_length Fresh_Root_wt Root_Dry_wt Corm_length
      Corm_Girth

Corm_Diameter corm_fresh_wt corm_Dry_wt leaves_plant cormel_plant
cormel_wt_plant Shoot_damage;

RUN;

PROC MEANS MEAN STDERR MAXDEC=2;

CLASS Variety Hormone;

VAR StemGirth Height leaf_length leaf_width Rhizomes_No Rhizome_Length
      No_nodes_rhiz Suckers_No Roots_length Fresh_Root_wt
      Root_Dry_wt Corm_length Corm_Girth

Corm_Diameter corm_fresh_wt corm_Dry_wt leaves_plant cormel_plant
cormel_wt_plant Shoot_damage;

RUN;

PROC MEANS MEAN STDERR MAXDEC=2;

CLASS Variety Hormone day;

```

```

VAR StemGirth Height leaf_length leaf_width      Rhizomes_No Rhizome_Length
    No_nodes_rhiz      Suckers_No  Roots_length Fresh_Root_wt
    Root_Dry_wt Corm_length Corm_Girth

Corm_Diameter corm_fresh_wt  corm_Dry_wt leaves_plant cormel_plant
cormel_wt_plant Shoot_damage;

RUN;

PROC MEANS MEAN STDERR MAXDEC=2;

CLASS Hormone;

VAR StemGirth Height leaf_length leaf_width      Rhizomes_No Rhizome_Length
    No_nodes_rhiz      Suckers_No  Roots_length Fresh_Root_wt
    Root_Dry_wt Corm_length Corm_Girth

Corm_Diameter corm_fresh_wt  corm_Dry_wt leaves_plant cormel_plant
cormel_wt_plant Shoot_damage;

RUN;

PROC MEANS MEAN STDERR MAXDEC=2;

CLASS Hormone day;

VAR StemGirth Height leaf_length leaf_width      Rhizomes_No Rhizome_Length
    No_nodes_rhiz      Suckers_No  Roots_length Fresh_Root_wt
    Root_Dry_wt Corm_length Corm_Girth

Corm_Diameter corm_fresh_wt  corm_Dry_wt leaves_plant cormel_plant
cormel_wt_plant Shoot_damage;

RUN;

```

E. EXPERIMENT 2 GROWTH MEDIA

DATA Sprouts;

```

INPUT Treatment $ Media $ Day Rep    Height      S_girth      R_Length
Leaf_area;

```

DATALINES;

100	Sawdust	85	1	20.7	5.94	60	55.33
100	Sawdust	85	2	20.4	6.45	58.6	43.15
100	Sawdust	85	3	18.8	4.13	57.9	44.74
250	Sawdust	85	1	20.5	5.32	56.5	44.27
250	Sawdust	85	2	18.6	4.87	60.1	29.53
250	Sawdust	85	3	20.8	4.67	63	32.26
500	Sawdust	85	1	15.4	3.82	32.4	40.04
500	Sawdust	85	2	18.2	3.47	32.3	23.51
500	Sawdust	85	3	15	2.82	41.1	19.71
750	Sawdust	85	1	22.2	4.13	56	48.38

750	Sawdust	85	2	21.1	4.61	55.1	38.68
750	Sawdust	85	3	20.4	4.23	67.5	47.66
100	RiverSand	85	1	18.2	4.16	25.1	32.76
100	RiverSand	85	2	17.8	2.87	25	25.87
100	RiverSand	85	3	24.4	3.33	27.9	40.18
250	RiverSand	85	1	21.6	5.23	28.2	20.33
250	RiverSand	85	2	24.4	4.88	31.6	80.99
250	RiverSand	85	3	22.1	5.16	39.2	91.77
500	RiverSand	85	1	24.4	4.67	34.4	97.94
500	RiverSand	85	2	23.2	5.27	35.3	88.70
500	RiverSand	85	3	20.4	4.7	30.6	62.33
750	RiverSand	85	1	32.5	4.42	42.6	98.28
750	RiverSand	85	2	25.5	4.93	38.5	43.68
750	RiverSand	85	3	24.2	4.77	36.2	50.40
100	Sawdust	100	1	25.6	5.58	54.6	65.21
100	Sawdust	100	2	25.2	5.44	63.1	83.79
100	Sawdust	100	3	23.3	5.39	61.7	71.18
250	Sawdust	100	1	22.7	4.6	55	54.60
250	Sawdust	100	2	24.4	4.71	53.6	53.90
250	Sawdust	100	3	21.1	3.77	61.4	32.07
500	Sawdust	100	1	23.3	3.92	52.8	78.12
500	Sawdust	100	2	21.8	3.1	45.8	41.58
500	Sawdust	100	3	22.2	3.95	42.6	39.87
750	Sawdust	100	1	32.4	4.23	34.2	60.61
750	Sawdust	100	2	25.6	3.49	44.1	47.71
750	Sawdust	100	3	24.2	4.3	35.1	58.02
100	RiverSand	100	1	19.8	3.48	28	69.38
100	RiverSand	100	2	17.8	3.93	33.2	55.27
100	RiverSand	100	3	15.6	4.69	27	37.93
250	RiverSand	100	1	21.8	4.59	40	55.69
250	RiverSand	100	2	24.4	4.3	43.1	69.02
250	RiverSand	100	3	23.1	5	31.5	79.46
500	RiverSand	100	1	23	4.27	27.8	42.50

500	RiverSand	100	2	24.9	5.84	27.4	68.43
500	RiverSand	100	3	20.4	4.58	30	66.23
750	RiverSand	100	1	25.4	3.7	37.1	50.40
750	RiverSand	100	2	25.4	4.35	34.5	69.83
750	RiverSand	100	3	25.7	4.77	33	47.78
100	Sawdust	55	1	4.8	2.81	7.5	2.46
100	Sawdust	55	2	4.6	2.29	5	3.09
100	Sawdust	55	3	5.7	1.88	12	4.19
250	Sawdust	55	1	3.4	2.16	9	2.35
250	Sawdust	55	2	5.6	2.28	11	2.58
250	Sawdust	55	3	5.4	2.37	10	2.38
500	Sawdust	55	1	5.1	1.66	12	3.92
500	Sawdust	55	2	5.5	1.78	12	4.48
500	Sawdust	55	3	5	1.91	12	4.48
750	Sawdust	55	1	4.6	1.38	12.5	3.02
750	Sawdust	55	2	4.4	1.6	8.1	1.47
750	Sawdust	55	3	3.7	1.23	9.5	2.98
100	RiverSand	55	1	4.8	1.33	6.2	2.38
100	RiverSand	55	2	3.4	1.27	6.3	2.35
100	RiverSand	55	3	5.1	1.11	9	3.33
250	RiverSand	55	1	5.4	1.71	9.5	5.64
250	RiverSand	55	2	5.1	1.5	6	2.16
250	RiverSand	55	3	4.6	1.88	11	1.51
500	RiverSand	55	1	4.8	1.66	13	2.90
500	RiverSand	55	2	4.7	1.87	10	6.92
500	RiverSand	55	3	3.7	1.15	15	3.99
750	RiverSand	55	1	6.4	1.42	12	6.80
750	RiverSand	55	2	6.4	1.31	10	2.69
750	RiverSand	55	3	6	1.5	8	5.30
100	Sawdust	70	1	7.6	3.56	19	10.84
100	Sawdust	70	2	8.8	3.41	20	19.70
100	Sawdust	70	3	11.9	3.67	17	6.92
250	Sawdust	70	1	8	2.98	14	8.43

250	Sawdust	70	2	7.3	3.28	15	10.16
250	Sawdust	70	3	8.3	3.09	11	2.46
500	Sawdust	70	1	8.2	3.31	17	9.55
500	Sawdust	70	2	7.8	3.62	24.5	8.82
500	Sawdust	70	3	8.3	3.76	22	6.12
750	Sawdust	70	1	10.33	3.19	18	5.60
750	Sawdust	70	2	9.8	3.02	16	6.09
750	Sawdust	70	3	10	2.15	16.5	7.18
100	RiverSand	70	1	7.1	4.86	10	2.66
100	RiverSand	70	2	7.6	4.04	10	5.47
100	RiverSand	70	3	5.6	4.15	10	4.70
250	RiverSand	70	1	9.9	3.89	16	15.79
250	RiverSand	70	2	9	3.62	13	15.02
250	RiverSand	70	3	8.5	4.89	21	10.29
500	RiverSand	70	1	8.1	2.77	16	9.24
500	RiverSand	70	2	7.5	3.01	15	15.68
500	RiverSand	70	3	6	2.88	20	11.90
750	RiverSand	70	1	10.5	3.1	16	22.54
750	RiverSand	70	2	8.8	3.31	12	2.90
750	RiverSand	70	3	9.1	3.67	15	12.38

;

proc glm;

class Treatment Media Rep Day;

model Height S_girth R_Length Leaf_area= Treatment Media Day Rep
Treatment*Media Treatment*Day Media*Day Treatment*Media*Day/ssl;

means Treatment Media Day/Tukey;

lsmeans Treatment*Media Treatment*Day Media*Day
Treatment*Media*Day/pdiff=all adjust=tukey lines;

run;

proc means mean stderr maxdec=2;

class treatment day;

var Height S_girth R_Length Leaf_area;

run;

proc means mean stderr maxdec=2;

```

class Media Day;
var Height S_girth      R_Length Leaf_area;
run;

proc means mean stderr maxdec=2;
class treatment Media Day;
var Height S_girth      R_Length Leaf_area;
run;

```

F. SPROUT COUNTS

```

DATA SproutCounts;
INPUT Treatment    $ Media    $ Rep Day S_Count;
DATALINES;

```

100	Sawdust	1	14	41
100	Sawdust	2	14	37
100	Sawdust	3	14	42
250	Sawdust	1	14	62
250	Sawdust	2	14	60
250	Sawdust	3	14	58
500	Sawdust	1	14	42
500	Sawdust	2	14	41
500	Sawdust	3	14	43
750	Sawdust	1	14	31
750	Sawdust	2	14	29
750	Sawdust	3	14	33
100	RiverSand	1	14	12
100	RiverSand	2	14	9
100	RiverSand	3	14	12
250	RiverSand	1	14	75
250	RiverSand	2	14	78
250	RiverSand	3	14	72
500	RiverSand	1	14	78
500	RiverSand	2	14	76
500	RiverSand	3	14	80
750	RiverSand	1	14	64

750	RiverSand	2	14	66
750	RiverSand	3	14	62
100	Sawdust	1	28	59
100	Sawdust	2	28	60
100	Sawdust	3	28	58
250	Sawdust	1	28	69
250	Sawdust	2	28	65
250	Sawdust	3	28	66
500	Sawdust	1	28	49
500	Sawdust	2	28	48
500	Sawdust	3	28	53
750	Sawdust	1	28	60
750	Sawdust	2	28	63
750	Sawdust	3	28	57
100	RiverSand	1	28	54
100	RiverSand	2	28	57
100	RiverSand	3	28	51
250	RiverSand	1	28	75
250	RiverSand	2	28	77
250	RiverSand	3	28	73
500	RiverSand	1	28	78
500	RiverSand	2	28	81
500	RiverSand	3	28	75
750	RiverSand	1	28	65
750	RiverSand	2	28	61
750	RiverSand	3	28	69
100	Sawdust	1	42	56
100	Sawdust	2	42	52
100	Sawdust	3	42	60
250	Sawdust	1	42	75
250	Sawdust	2	42	78
250	Sawdust	3	42	72
500	Sawdust	1	42	79

500	Sawdust	2	42	83
500	Sawdust	3	42	78
750	Sawdust	1	42	69
750	Sawdust	2	42	68
750	Sawdust	3	42	70
100	RiverSand	1	42	61
100	RiverSand	2	42	62
100	RiverSand	3	42	66
250	RiverSand	1	42	77
250	RiverSand	2	42	75
250	RiverSand	3	42	79
500	RiverSand	1	42	86
500	RiverSand	2	42	82
500	RiverSand	3	42	87
750	RiverSand	1	42	72
750	RiverSand	2	42	73
750	RiverSand	3	42	71
100	Sawdust	1	56	66
100	Sawdust	2	56	70
100	Sawdust	3	56	68
250	Sawdust	1	56	75
250	Sawdust	2	56	79
250	Sawdust	3	56	80
500	Sawdust	1	56	87
500	Sawdust	2	56	88
500	Sawdust	3	56	86
750	Sawdust	1	56	74
750	Sawdust	2	56	73
750	Sawdust	3	56	75
100	RiverSand	1	56	67
100	RiverSand	2	56	66
100	RiverSand	3	56	68
250	RiverSand	1	56	77

250	RiverSand	2	56	80
250	RiverSand	3	56	81
500	RiverSand	1	56	95
500	RiverSand	2	56	93
500	RiverSand	3	56	94
750	RiverSand	1	56	76
750	RiverSand	2	56	76
750	RiverSand	3	56	79
100	Sawdust	1	70	69
100	Sawdust	2	70	67
100	Sawdust	3	70	74
250	Sawdust	1	70	78
250	Sawdust	2	70	80
250	Sawdust	3	70	79
500	Sawdust	1	70	94
500	Sawdust	2	70	96
500	Sawdust	3	70	98
750	Sawdust	1	70	78
750	Sawdust	2	70	76
750	Sawdust	3	70	77
100	RiverSand	1	70	74
100	RiverSand	2	70	71
100	RiverSand	3	70	74
250	RiverSand	1	70	81
250	RiverSand	2	70	79
250	RiverSand	3	70	83
500	RiverSand	1	70	96
500	RiverSand	2	70	97
500	RiverSand	3	70	95
750	RiverSand	1	70	78
750	RiverSand	2	70	78
750	RiverSand	3	70	81

;

```

proc glm;

class Treatment Media Rep Day;

model S_Count= Treatment Media Day Rep Treatment*Media Treatment*Day
Media*Day Treatment*Media*Day/ssl;

means Treatment Media Day/Tukey;

lsmeans Treatment*Media Treatment*Day Media*Day
Treatment*Media*Day/pdiff=all adjust=tukey lines;

run;

proc means mean stderr maxdec=2;

class treatment;

var S_Count;

run;

proc means mean stderr maxdec=2;

class treatment Media Day;

var S_Count;

run;

```

G. EXPERIMENT 3_SHOOT CHARACTERISTICS

DATA shoots;

INPUT	Variety	\$	Hormone	Day	Rep	StemGirth	Ht	Leaf_area
	No_leaves		shoot_D;					
DATALINES;								
Girigaca	0	60	1	18	72	490.00	6	1
Girigaca	0	60	2	20	76	279.30	6	1
Girigaca	0	60	3	17.5	68.1	383.67	5	1
Girigaca	100	60	1	18.9	85	366.52	7	2
Girigaca	100	60	2	19	78	402.19	5	3
Girigaca	100	60	3	17.1	82.1	611.10	6	3
Girigaca	250	60	1	18.8	81	408.94	7	5
Girigaca	250	60	2	19	89.5	585.90	6	2
Girigaca	250	60	3	16	65	406.86	7	5
Girigaca	500	60	1	19	77	624.96	6	3
Girigaca	500	60	2	17	74	426.65	5	4

Girigaca	500	60	3	19.1	76.1	459.94	6	5
Girigaca	750	60	1	21.4	90	476.81	6	5
Girigaca	750	60	2	18	74	374.37	6	4
Girigaca	750	60	3	19.4	83	855.68	7	5
Kienyeji	0	60	1	18	50	455.00	4	1
Kienyeji	0	60	2	17.1	51	523.59	4	1
Kienyeji	0	60	3	20	61	537.57	4	1
Kienyeji	100	60	1	25	61.5	369.60	4	1
Kienyeji	100	60	2	21.8	56	411.10	4	1
Kienyeji	100	60	3	18.9	58	659.57	4	1
Kienyeji	250	60	1	22	67	648.83	5	1
Kienyeji	250	60	2	20.4	60.1	461.16	4	1
Kienyeji	250	60	3	19	55.4	407.62	4	1
Kienyeji	500	60	1	19	60	686.50	4	1
Kienyeji	500	60	2	20	51	510.69	4	1
Kienyeji	500	60	3	22.1	67.3	837.76	4	1
Kienyeji	750	60	1	21.4	68	786.24	4	1
Kienyeji	750	60	2	22	61	569.94	4	1
Kienyeji	750	60	3	21.3	65	609.28	4	1
Girigaca	0	120	1	21	70	414.96	10	1
Girigaca	0	120	2	18.2	68	495.32	12	1
Girigaca	0	120	3	19	78	603.26	10	1
Girigaca	100	120	1	19.8	77	507.50	12	2
Girigaca	100	120	2	18.8	79.2	533.12	13	3
Girigaca	100	120	3	20	80.2	579.24	12	2
Girigaca	250	120	1	17.8	67.8	367.50	10	2
Girigaca	250	120	2	15.8	68	438.06	11	2
Girigaca	250	120	3	17	70	364.00	12	2
Girigaca	500	120	1	18.5	75	463.68	12	2
Girigaca	500	120	2	17.2	80	475.04	12	3
Girigaca	500	120	3	19.8	85.6	666.40	13	3
Girigaca	750	120	1	20.8	83.8	323.18	12	4
Girigaca	750	120	2	18	75	427.14	11	4

Girigaca	750	120	3	19	71	507.50	12	4
Kienyeji	0	120	1	17.2	68.1	511.00	9	1
Kienyeji	0	120	2	21.8	67	685.76	9	1
Kienyeji	0	120	3	18.8	57	440.44	8	1
Kienyeji	100	120	1	21.3	55	418.25	8	1
Kienyeji	100	120	2	18.2	60.5	525.42	9	1
Kienyeji	100	120	3	20	65	619.50	8	1
Kienyeji	250	120	1	23	60	463.75	9	1
Kienyeji	250	120	2	22.2	63	490.00	9	1
Kienyeji	250	120	3	22	71	730.24	9	1
Kienyeji	500	120	1	21	66	737.80	9	1
Kienyeji	500	120	2	23	64.5	529.20	9	1
Kienyeji	500	120	3	21	56	491.40	8	1
Kienyeji	750	120	1	19	55	498.85	8	1
Kienyeji	750	120	2	21	59	505.96	8	1
Kienyeji	750	120	3	19	62	533.89	8	1
Girigaca	0	180	1	17.1	58.2	578.76	18	1
Girigaca	0	180	2	14.6	62	391.16	18	1
Girigaca	0	180	3	15	60.2	361.62	18	1
Girigaca	100	180	1	15	68.2	410.06	19	5
Girigaca	100	180	2	17.2	61.6	280.28	19	4
Girigaca	100	180	3	10	42	517.19	19	4
Girigaca	250	180	1	16.8	65	402.78	19	5
Girigaca	250	180	2	15.2	54	173.88	19	5
Girigaca	250	180	3	17.8	53.8	319.42	19	4
Girigaca	500	180	1	15.4	61.6	233.58	20	5
Girigaca	500	180	2	15.8	64.2	539.39	20	4
Girigaca	500	180	3	14.4	64	358.51	20	5
Girigaca	750	180	1	15	69	396.48	20	5
Girigaca	750	180	2	13.4	60.8	343.73	20	5
Girigaca	750	180	3	16.4	64	466.20	20	5
Kienyeji	0	180	1	22.4	48.1	402.19	14	1
Kienyeji	0	180	2	22.6	59.8	384.55	14	1

Kienyeji	0	180	3	22	55.8	322.20	14	1
Kienyeji	100	180	1	21	52.1	418.88	15	1
Kienyeji	100	180	2	21.8	53.4	289.80	15	1
Kienyeji	100	180	3	18.9	53	344.99	15	1
Kienyeji	250	180	1	21.8	56.2	305.76	14	1
Kienyeji	250	180	2	22	54.4	433.66	14	1
Kienyeji	250	180	3	23.4	53.6	321.55	14	1
Kienyeji	500	180	1	21.8	56.6	354.37	13	1
Kienyeji	500	180	2	21	53.6	393.18	14	1
Kienyeji	500	180	3	22.4	54.6	469.22	15	1
Kienyeji	750	180	1	21.6	67.5	518.00	13	1
Kienyeji	750	180	2	22	63	457.97	13	1
Kienyeji	750	180	3	20.4	65.2	389.84	13	1
Girigaca	0	240	1	14	38.2	489.55	23	1
Girigaca	0	240	2	11.5	62	459.26	23	1
Girigaca	0	240	3	15	77.8	889.62	23	1
Girigaca	100	240	1	11	40.2	110.68	23	3
Girigaca	100	240	2	19	54.8	502.82	23	3
Girigaca	100	240	3	12.6	46	134.06	22	3
Girigaca	250	240	1	15	61.4	178.36	22	3
Girigaca	250	240	2	15.2	61	585.14	22	3
Girigaca	250	240	3	17.2	59	280.00	22	3
Girigaca	500	240	1	14.4	63.6	552.05	22	3
Girigaca	500	240	2	15.8	74.2	547.40	22	3
Girigaca	500	240	3	16	58.8	477.12	22	2
Girigaca	750	240	1	15.6	58.4	521.64	22	3
Girigaca	750	240	2	15.4	57.2	291.65	22	4
Girigaca	750	240	3	17.4	63.6	384.02	19	4
Kienyeji	0	240	1	12.8	53.2	202.27	16	0
Kienyeji	0	240	2	16.6	56.6	183.46	16	1
Kienyeji	0	240	3	12.8	51.2	299.10	17	1
Kienyeji	100	240	1	13.4	46.2	168.11	17	1
Kienyeji	100	240	2	10	41.2	159.54	17	1

Kienyeji	100	240	3	13.4	41.3	172.54	18	1
Kienyeji	250	240	1	14.2	54.2	366.24	18	1
Kienyeji	250	240	2	14.4	45.6	260.40	17	1
Kienyeji	250	240	3	13.4	48.2	287.45	17	1
Kienyeji	500	240	1	15.4	43.2	224.22	17	1
Kienyeji	500	240	2	13.2	54.2	236.49	17	1
Kienyeji	500	240	3	13.6	51.2	293.78	17	1
Kienyeji	750	240	1	15.4	56.6	220.42	17	1
Kienyeji	750	240	2	14.2	47.8	159.54	17	1
Kienyeji	750	240	3	15.2	50.1	236.88	17	1

;

PROC GLM;

CLASS Variety Hormone Day Rep;

MODEL StemGirth Ht Leaf_area No_leaves shoot_D = Variety Hormone Day Rep
Variety*Hormone Variety*Day Hormone*Day Variety*Hormone*Day/SS1;

LSMEANS Variety Hormone Day Rep Variety*Hormone Variety*Day Hormone*Day
Variety*Hormone*Day/PDIFF=ALL ADJUST=TUKEY LINES;

RUN;

PROC MEANS mean stderr maxdec=2;

CLASS Variety;

VAR StemGirth Ht Leaf_area No_leaves shoot_D;

RUN;

PROC MEANS mean stderr maxdec=2;

CLASS Hormone;

VAR StemGirth Ht Leaf_area No_leaves shoot_D;

RUN;

proc corr;

var StemGirth Ht Leaf_area No_leaves shoot_D;

run;

H. EXPERIMENT 3 PROPAGULE CHARACTERISTICS

DATA propagules;

INPUT	Variety	\$	Hormon	Day	Rep	No_Rhizo	L_Rhizomes	Rhiz_girth
	No_Suckers		No_nodes;					

DATALINES;

Girigaca	0	60	1	0	0	0	9	0
Girigaca	0	60	2	0	0	0	7	0
Girigaca	0	60	3	0	0	0	8	0
Girigaca	100	60	1	16	4.8	3	0	34
Girigaca	100	60	2	44	5.75	2.9	0	41
Girigaca	100	60	3	17	8.5	3	0	42
Girigaca	250	60	1	36	6.5	2.9	0	63
Girigaca	250	60	2	19	8	2.6	0	14
Girigaca	250	60	3	11	8.25	3	0	46
Girigaca	500	60	1	25	8	2.8	0	57
Girigaca	500	60	2	22	10	2.9	0	34
Girigaca	500	60	3	10	5.6	2.9	0	20
Girigaca	750	60	1	34	12.5	1.8	0	65
Girigaca	750	60	2	21	8.3	2.8	0	56
Girigaca	750	60	3	34	13.3	2.4	0	35
Kienyeji	0	60	1	0	0	0	0	0
Kienyeji	0	60	2	0	0	0	0	0
Kienyeji	0	60	3	0	0	0	0	0
Kienyeji	100	60	1	0	0	0	0	0
Kienyeji	100	60	2	0	0	0	0	0
Kienyeji	100	60	3	0	0	0	0	0
Kienyeji	250	60	1	0	0	0	0	0
Kienyeji	250	60	2	0	0	0	0	0
Kienyeji	250	60	3	0	0	0	0	0
Kienyeji	500	60	1	0	0	0	0	0
Kienyeji	500	60	2	0	0	0	0	0
Kienyeji	500	60	3	0	0	0	0	0
Kienyeji	750	60	1	0	0	0	0	0

Kienyeji	750	60	2	0	0	0	0	0
Kienyeji	750	60	3	0	0	0	0	0
Girigaca	0	120	1	0	0	0	10	0
Girigaca	0	120	2	0	0	0	16	0
Girigaca	0	120	3	0	0	0	5	0
Girigaca	100	120	1	11	6.75	3	0	36
Girigaca	100	120	2	15	8.5	3.2	0	62
Girigaca	100	120	3	25	11.75	3	0	59
Girigaca	250	120	1	17	7.75	3	0	39
Girigaca	250	120	2	27	11.75	2.9	0	63
Girigaca	250	120	3	42	14	3	0	84
Girigaca	500	120	1	26	8	2.4	0	67
Girigaca	500	120	2	12	6.75	2.6	0	37
Girigaca	500	120	3	27	11.75	2.7	0	61
Girigaca	750	120	1	13	9.5	2.4	0	42
Girigaca	750	120	2	21	7.25	2.4	0	40
Girigaca	750	120	3	25	13	2.4	0	35
Kienyeji	0	120	1	0	0	0	0	0
Kienyeji	0	120	2	0	0	0	0	0
Kienyeji	0	120	3	0	0	0	0	0
Kienyeji	100	120	1	0	0	0	0	0
Kienyeji	100	120	2	0	0	0	0	0
Kienyeji	100	120	3	0	0	0	0	0
Kienyeji	250	120	1	0	0	0	0	0
Kienyeji	250	120	2	0	0	0	0	0
Kienyeji	250	120	3	0	0	0	0	0
Kienyeji	500	120	1	0	0	0	0	0
Kienyeji	500	120	2	0	0	0	0	0
Kienyeji	500	120	3	0	0	0	0	0
Kienyeji	750	120	1	0	0	0	0	0
Kienyeji	750	120	2	0	0	0	0	0
Kienyeji	750	120	3	0	0	0	0	0
Girigaca	0	180	1	0	0	0	4	0

Girigaca	0	180	2	0	0	0	5	0
Girigaca	0	180	3	0	0	0	7	0
Girigaca	100	180	1	21	15.44	3	0	172
Girigaca	100	180	2	36	13.32	2.7	0	178
Girigaca	100	180	3	19	15.2	2.8	0	192
Girigaca	250	180	1	24	12.1	2.8	0	204
Girigaca	250	180	2	28	14.36	3	0	218
Girigaca	250	180	3	30	17.48	2.9	0	243
Girigaca	500	180	1	38	16.44	2.9	0	310
Girigaca	500	180	2	35	20.4	2.7	0	308
Girigaca	500	180	3	48	16.88	2.6	0	344
Girigaca	750	180	1	66	22.04	1.8	0	494
Girigaca	750	180	2	64	29.4	2	0	334
Girigaca	750	180	3	47	20.2	2.4	0	607
Kienyeji	0	180	1	0	0	0	0	0
Kienyeji	0	180	2	0	0	0	2	0
Kienyeji	0	180	3	0	0	0	0	0
Kienyeji	100	180	1	0	0	0	7	0
Kienyeji	100	180	2	0	0	0	5	0
Kienyeji	100	180	3	0	0	0	7	0
Kienyeji	250	180	1	0	0	0	5	0
Kienyeji	250	180	2	0	0	0	4	0
Kienyeji	250	180	3	0	0	0	9	0
Kienyeji	500	180	1	0	0	0	6	0
Kienyeji	500	180	2	0	0	0	8	0
Kienyeji	500	180	3	0	0	0	8	0
Kienyeji	750	180	1	0	0	0	8	0
Kienyeji	750	180	2	0	0	0	8	0
Kienyeji	750	180	3	0	0	0	7	0
Girigaca	0	240	1	0	0	0	12	0
Girigaca	0	240	2	0	0	0	9	0
Girigaca	0	240	3	0	0	0	7	0
Girigaca	100	240	1	29	12.88	3	0	142

Girigaca	100	240	2	30	14.6	2.9	0	180
Girigaca	100	240	3	21	16.2	3	0	163
Girigaca	250	240	1	45	19.76	2.9	0	148
Girigaca	250	240	2	35	23.28	2.6	0	190
Girigaca	250	240	3	24	8.08	3	0	298
Girigaca	500	240	1	28	19	2.8	0	326
Girigaca	500	240	2	42	17.4	2.9	0	334
Girigaca	500	240	3	28	16.38	2.9	0	367
Girigaca	750	240	1	41	19.28	1.8	0	442
Girigaca	750	240	2	26	19.8	2	0	306
Girigaca	750	240	3	41	19.2	2.4	0	494
Kienyeji	0	240	1	0	0	0	7	0
Kienyeji	0	240	2	0	0	0	6	0
Kienyeji	0	240	3	0	0	0	5	0
Kienyeji	100	240	1	0	0	0	9	0
Kienyeji	100	240	2	0	0	0	7	0
Kienyeji	100	240	3	0	0	0	8	0
Kienyeji	250	240	1	0	0	0	7	0
Kienyeji	250	240	2	0	0	0	6	0
Kienyeji	250	240	3	0	0	0	6	0
Kienyeji	500	240	1	0	0	0	2	0
Kienyeji	500	240	2	0	0	0	3	0
Kienyeji	500	240	3	0	0	0	4	0
Kienyeji	750	240	1	0	0	0	3	0
Kienyeji	750	240	2	0	0	0	4	0
Kienyeji	750	240	3	0	0	0	4	0

;

proc glm;

class Variety Hormon Day Rep;

model No_Rhizo L_Rhizomes Rhiz_girth No_Suckers No_nodes = Variety Hormon
Day Rep Variety*Hormon Variety*Day Hormon* Day Variety*Hormon*Day/ssl;

means Variety Hormone Day/Tukey;

lsmeans Variety*Hormon Variety*Day Hormon* Day Variety*Hormon*Day/
pdiff=all adjust=tukey lines;

```

run;

proc means mean stderr maxdec=2;
class Variety;
var L_Rhizomes Rhiz_girth;
run;

proc means mean stderr maxdec=2;
class Hormon;
var L_Rhizomes Rhiz_girth;
run;

proc means mean stderr maxdec=2;
class Variety Hormone;
var L_Rhizomes Rhiz_girth;
run;

proc corr;
var No_Rhizo L_Rhizomes Rhiz_girth No_Suckers No_nodes;
run;

```