# EXAMINATION OF THE POTENTIAL OF GINGER (*Zingiber officinale*) CULTIVATION IN THE STATE OF DELAWARE IN THE MID-ATLANTIC REGION OF THE UNITED STATES

by

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A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Science in Plant and Soil Sciences

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## TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES

## ABSTRACT

Ginger (*Zingiber officinale*) is a nutritious, medicinal, rhizomatous spice cultivated and consumed globally. Cultivation practices have a significant impact on the nutritional quality and post-harvest storage of ginger rhizomes. The cultivation of ginger requires 8 to 12 months for its matured, shelf-life stable rhizomes, while an alternative technique of halving the cultivation time, improves the nutritional quality of ginger rhizomes while affecting the shelf-life. Halfway cultivation technique (baby ginger) conserves production resources over traditional cultivation.

Yellow ginger sprouted and grown to seedling stage for 10 weeks and then planted in various production systems. Trials were conducted from February 2022 to February 2023 in Newark and Georgetown, Delaware. One set of trials focused on controlled environment production in soilless media and hydroponic solutions in the greenhouse. A second set of trials focused on field soils in high tunnel, rain shelter, mulched open-field, and bare ground open field systems with clay loam soils and loamy sand soils, Different irrigation frequency treatments were applied: 100% (greenhouse only), 80%, 60%, 40%, and 20% minimum depletion before replenishments. Data were collected on growth, phytocompound concentrations, and yield of plant components. After harvest, storage experiments were conducted by placing the immature rhizomes in several temperatures and humidity combinations, washing levels, packing materials, with or without absorbent polymers Within the storage experiment, the longevity of storage, rhizome quality changes, and storage diseases were monitored. The effects of all treatments in trials were evaluated through statistical analysis.

Results of production trials show the potential of baby ginger production in Delaware with an average potential of 40 tons $ha^{-1}$ under greenhouse conditions, 30 tons $ha^{-1}$ in high tunnels, and 22 tons $ha^{-1}$ in open fields under high water availability. Water usage was lowest in hydroponics and highest in tunnels (76.4 and 665 liters/kg ginger respectively). Ginger greenhouse yield is optimized at EC 3 and pH 6. Phytocompound concentration was ordered as follows: immature rhizomes>matured rhizomes>leaves>pseudo-stems>roots. Shelf-life of baby ginger could be extended from 3 days to 42 days at $4^0$C and 95% RH, with normal water wash. Dominant storage pathogens of ginger were, *Rhizoctonia, Pythium,* and *Fusarium*.

# Chapter 1

# BACKGROUND ON THE PRODUCTION OF GINGER (*Zingiber officinale*)

## General information

Ginger plant is a spice crop botanically known as *Zingiber officinal* Roscoe. The word ginger is interchangeably used between the plant itself and its commercial plant part "succulent rhizome" which is botanically known as parchymorph. Evidence points to its origination from south/east Asia (Wang et al., 2014). The history of usage dates back to 2000 years in the spice trade (Van Der Veen and Morales, 2015) and its ancient medicinal value within the Asian continent (Wang et al., 2014). Spices are typically expensive compared to vegetables and field crops, during the roman times (27 BC – 476 AD) they were available only to the upper class (Sharangi and Acharya, 2018). Ginger was once a valuable commodity involved in the spice trade (Nair, 2019). The spice trade involved historical civilizations in Asia, Northeast Africa, and Europe, and had involved other crops such as cinnamon, cassia, cardamom, pepper nutmeg, star anise, turmeric, and cloves. Ginger was introduced to the Mediterranean and Japan in the first and third centuries respectively, then later in England in the eleventh century. It then spread to America and Europe in the 15 – 16$^{th}$ century. Due to the spice trade, the Arabs brought it to East Africa in the 16$^{th}$ Century (Nair, 2019).

Ginger is a self-incompatible plant and has high rates of infertility; its genetic diversity only occurs via processes of mutation and natural selection. There is high difference in gene diversity among accessions/varieties of ginger revealing the presence of strong genetic structure between them and thus significant differences

exist in the genotypic diversity of ginger varieties (Palai and Rout, 2007). Genetic variability within ginger when grown in same locations or multi-locations, indicating increased species ability to adapt and survive; molecular markers can be an important tool for assessing ginger genetic diversity (Ismail et al., 2016; Jatoi et al., 2008). Ginger (*Zingiber officinale*) belongs to the family Zingiberaceae under the order Zingiberales which is the largest family in the order containing flowering plants. It has approximately 60 genera and about 1500 species. Major genera include *Alpinia* (200 species), *Etlingera* (110 species), *Curcuma* (100 species), Globba (100 species), *Zingiber* (100), *Renealmia* (75), *Riedelia* (75), *Amomum* (65), *Aframomum* (60), *Boesenbergia* (60), *Hedychium* (50), *Hornstedia* (50), and *Meisteria* (42). Many species within these genera are economically valuable for their spice nature, color, aroma, anti-microbial, and anti-ailment nature (Chen et al., 2008; Shahrajabian et al., 2019; Voravuthikunchai et al., 2006). Turmeric rhizomes (*Curcuma longa*) and cardamom (*Elettaria cardamomum*) are the closest valuable family members, commonly ground for culinary, decorative, medicinal, and cosmetic uses. Ginger has ornamental significance due to attractive flowers and foliage of certain species. Several species of shellflower (*Alpinia*) are cultivated as ornamentals. Ginger lily (*Hedychium*) produces beautiful flowers that are used in garlands and other decorations. Genus *Zingiber* is distributed throughout tropical Asia, and tropical Australia.

The basic chromosome number in ginger is x = 11. Most cultivated varieties are sterile and different cultivars vary in karyotype (Bennett, 2006). Chromosome numbers slightly differ within ginger varieties; *Z. officinale* Rosc. *Var. officinale* and *Z. officinale* Rosc. *Var. amarum* have 2n = 2x = 30, while *Z. officinale var. rubra* is 2n

= 2x = 22. They exist as tetraploids (2n = 44), aneuploid (2n = 24) or with normal chromosome number (2n = 2x = 22) (Daryono et al., 2012).

Popular names of ginger varieties come from their cultivation locations (Kizhakkayil and Sasikumar, 2011). Most prominent cultivars include Himachal, Rio de Janeiro, Nadia, Indian and Chinese ginger. Alternative naming depends on the rhizome's inner flesh color *i.e.*, yellow ginger, white ginger (with tan color), blue-ring ginger or red ginger. The recommended varietal characterization and identification should be based on distribution of meristematic activity in rhizomes which results in a continuous primary thickening of the stele, not the cortex width, rather than basing on the trait of vascular bundles collateral in a ring in endodermis since these vascular bundles are not present in the endodermis, but pericycle (Liu et al., 2020).

Ginger matures in 10-12 months and stores for up to 1 year. Immature (baby) ginger is grown for 3 – 6 months, half the required time for mature ginger. Baby ginger is less fibrous, bears short postharvest shelf life but has added pharmacological potential compared to the matured counterparts (Li et al., 2022; Siddiqui et al., 2020). Plants convert their phytocompounds into readily unavailable forms for human body system during their maturity phase for their storage organs (Harper, 1989). Ginger corresponds to the same principle, the content of available polyphenols, anti-oxidants, and other metabolites decreases as the plant/rhizomes matures (Siddiqui et al., 2020) due to their conversion into fibers.

Usage of soils in the field for production has dominated global agriculture. Open field culture accounts for about 99% of agricultural production (Sardare and Admane, 2019a). Technological advances allow for intensification and increased output per unit area (Nordey et al., 2020a, 2020a, 2020b). For the last 50 years, there

has been an increasing demand for agricultural products, exerting pressure on the soils (Abraham et al., 2014; Louwagie et al., 2011). These reinforcements have led to depletions and degradations in soils, compromising its productive capacity and ability to suit future needs (Jie et al., 2002; Steinmetz et al., 2016). The heavy feeding nature of rhizomatous plants, due to continuous crop turn over from their initial mother rhizomes and the declining trends of soil fertility status, challenges their production (Xizhen et al., 2016).

Ginger is a warm season crop native to tropical rain forests of Asia. Open fields dominate ginger production, despite challenges of continuous interaction of dynamic biotic interruptions from weeds, insect pests, and disease pathogens, complexing with abiotic factors of unstable climates, degraded soils, and weather season differentials (warm season summers vs cold seasons and winters) (Suzuki et al., 2014; Zandalinas et al., 2021). These all create challenges for open-field production. Global average production of ginger is 10.5 - 20 tons ha $^{-1}$ but in majority of sub-Saharan African countries including Tanzania, have production output of less than 2.5 tons ha $^{-1}$. The US has a high production output per area of land with yields of > 30 tons ha $^{-1}$. However, production is localized largely in Hawaii which has a tropical climate. Mature ginger cannot be field grown in US states experiencing cold winters with temperatures less than 15 $^{0}$C. which leads to heavy importation resulting in a high carbon footprint and high freight charges. The extremely low production output in the majority of sub-Saharan Africa is partly due to dependency on rainfed agriculture which limits production during unstable rainy seasons and off seasons (Arndt et al., 2012). Genotypes used, soil types, locations, seasons, cultural practices (Kizhakkayil and Sasikumar, 2011), pests and diseases also contribute to low output

(Annih Grace et al., 2019). The availability and use of water is the most limiting factor for sub-Saharan agriculture (Hamidov and Helming, 2020).

Ginger requires 8-12 months in the field, with abundant soil moisture, warmth, and partial shade. Cutting half the production cycle of ginger enables USA farmers exploit the short "tropical" window starting from end of spring through early fall, thus allowing for annual crop production, market availability of fresh ginger, sustainability in resource usage and more time for farmers/producers to pursue other economic endeavors. Halving the production cycle would enable Tanzanian farmers to take advantage of their 4 – 5 months rainy season. Irrigation in the agricultural sector plays an important role in increasing the use of inputs, extending farming seasons, enhancing crop intensification and productivity (Du et al., 2018; Wang, 2019; Wang et al., 2022). This goes hand in hand with increasing employment opportunities, reliability, and wage rate of agricultural labor (Katovich and Maia, 2018; Spicka et al., 2019).

The gradual changes in climatic variables, instability, and global warming have resulted in weather extremes creating harsh field conditions for crop production. To date the level of Carbon dioxide is 419 ppm compared with 291 ppm in early 90's, global temperature increased by 1.01 $^{0}$C since 1880, Arctic sea ice extent decreased by 13% per decade from 1979, ice sheets decreased by 427 billion metric tons per year since 2002, sea level rise increased by 10.16 cm (4 inches) since January 1993, and additional 337 zettajoules of ocean heat since 1955 (NASA, 2022). These dynamics have direct and indirect impact on availability, amount and distribution of rainfall over the course of years (Giorgi et al., 2019), affecting the availability of irrigation water. Climate change has led to excessive (Haque et al., 2019; Papalexiou and Montanari,

2019) or insufficient rains (Dai, 2011), making rainfed agriculture more difficult to manage. The consequences of climate change in agriculture, food security and the whole chain have serious consequences in Sub-Saharan Africa (Arndt et al., 2012).

Global warming because of accumulation of greenhouse gases traps excess heat leading to overall rise of global temperature, creating harsher field production environments. Secondary effects of global warming also extend to increased abiotic stress to plants, i.e. escalated droughts, salinity, and acidic soils (Munns and Gilliham, 2015). The ability to half the production cycle means reducing the cultivation period and targeting the most conducive months for successful production.

Ginger is vegetatively propagated from rhizomes of previously grown plants through splits or tissue culturing. Tissue culture is often employed to produce disease free plants in infected regions, facilitate plant regeneration and enable genetic conservation (Kasilingam et al., 2018). Propagation materials should be true to type and sourced from previously healthy plants. The rhizome propagules are cut into small pieces of 3 – 6 cm from a living rhizome cluster. Each piece should possess at least two - three visible buds which will produce shoots. The ginger sets can be pre-sprouted in pots or nurseries by either covering them with a layer of soil, potting them in a greenhouse using nursery media, or they can be planted directly at their final planting location. It takes a month for ginger propagules to initiate sprouting and another month for development before transplanting (Rafie et al., 2012). The performance of ginger in terms of growth and development in open fields is optimized with high rainfall amounts or irrigation water, lower light intensities, and warm temperatures during cultivation. These factors are all directly proportional to production output (Aly et al., 2019; Verma et al., 2019a). Ginger adapts to different

soils but prefers deep, loose, well-drained sandy loam soils with a pH range of 5.5 to 7, rich in organic matter content (Fariyike et al., 2016) with high availability of Nitrogen, Phosphorus, Potassium, Calcium, and other nutrients (Srinivasan et al., 2019). Potassium has been shown to be a key mineral nutrient needed at 300 kg $ha^{-1}$ (Azizah et al., 2022) .Optimum altitude for ginger cultivation ranges from sea-level up to 1500 m above sea level with optimum rainfall of 2500-3000 mm, well distributed over the year. Ginger is a humid and warm season crop and requires supplementary irrigation in rainfalls below 2000 mm or with uneven distribution, ginger hardly succeeds economically as an irrigated crop in semi-arid areas due to costs and benefits of water use.

Ginger plants are successfully cultivated in varying spacings (Azizah et al., 2022; Fariyike et al., 2016; Gatabazi et al., 2019a) although standard inter-row spacing required is 1 m (3.3 ft) raised ridges with central depth of 30 – 46 cm (12 – 18 inches) creating a furrow like structure, and intra-row spacing of 12.5 – 15 cm (5 – 6 inches) covered with 5 – 10 cm (2 – 4 inches) of soil (Ernst and Durbin, 2019). Standard practice is to clear and plow the field or specific planning area and add compost or well-decomposed manure into the soils at rates of 25 to 35 tons $ha^{-1}$ before planting (Thankamani et al., 2016). The initial furrow, which serves as the planting row, will eventually be the ridge at harvest. Ridges are created by earthing up the soil around the plant base to improve rhizomes development and end quality. Effective space economization and maximum yield per unit area requires spacing of 25 cm x 15 cm (Mahender et al., 2015; Tiwari et al., 2019), closer spacings tend to increase disease outbreaks and severity (Sharma et al., 2013). The cultivation fields should be weed free especially during initial establishments to reduce their competitive advantage over

young ginger plants (Thankamani et al., 2016). Weeds harbor insect pests such as (Meenu and Kaushal, 2017) *Agarotis* spp., aphids , or *Planococcus citri* which attack young shoots as they emerge and can be disease-vectors. An example is *Bemisia tabacci*. that is a vector for mosaic or chlorotic flex viral diseases. Devastating insect pests in ginger plants are *Conogethes punctiferalis* and *Ostrinia furnacalis* which bore in the pseudo-stems and *Chaeridiona mayuri* beetles attack leaves of ginger. The most important ginger rhizome diseases are rots caused by *Pythium* spp., *Fusarium* spp., and *Rosellinia* spp.; Nematodes (*Meloidogyne* spp.) that attack the roots also cause crop damage and are accompanied by several strains *of Ralstonia solanacearum* that attack ginger's conducting vessels (xylem tissue). *R. solanacearum* and *Meloidogyne* spp. have combined severity effects when occurring together since *Meloidogyne* spp. facilitates easy colonization through its feeding mechanism. Leaf spots caused by *Colletotrichum* spp., *Helminthosporum* spp., *Cercospora* spp. and *Septoria* spp. are the common foliar diseases for ginger (Meenu and Kaushal, 2017).

Global production and yield output of ginger in 2019 was slightly beyond 4 million metric tons largely contributed by India (38%), China (25%), Nigeria (15%), Nepal (6%), Indonesia (4%), Thailand (3%), Cameroon (2%), Bangladesh (2%), Japan (1%), and the rest (6%). India is the largest producer of ginger in the world by nearly 40% with productivity of 10.9 tons ha $^{-1}$, evolving from 3.5 tons ha $^{-1}$ of the past ten years. The world productivity trend from 2009 to 2019 increased by 60.38% from 6.4 to 10.6 tons ha$^{-1}$ respectively (FAO STATISTICS, 2021). The production output is normally at 1:8 – 1:12, ratio for weight of initial propagules to the final rhizome's weight at harvest. (Fariyike et al., 2016).

Ginger global exportation and market value worthed $1.5 B in 2020, as the world's 1520 most traded product. Between 2019 and 2020 the exports of Ginger grew by 34.7%, from $1.1B to $1.5B (Abubacker, 2011). Trade in Ginger represents 0.009% of total world trade. The price of organic ginger stood at approximately 4 USD per kilo reaching up to 7 USD per kilo before Covid 19 pandemic, jumping to 12 – 24 USD per kilo amid the pandemic to date. In past decade, top exporters of Ginger in USD were China ($758M), Netherlands ($127M), Peru ($111M), India ($94.2M), and Thailand ($64.1M) while top importers of Ginger were Netherlands ($174M), United States ($170M), Pakistan ($94.6M), Japan ($87.5M), and Bangladesh ($84.7M) (Karthick et al., 2015; Madan, 2016).

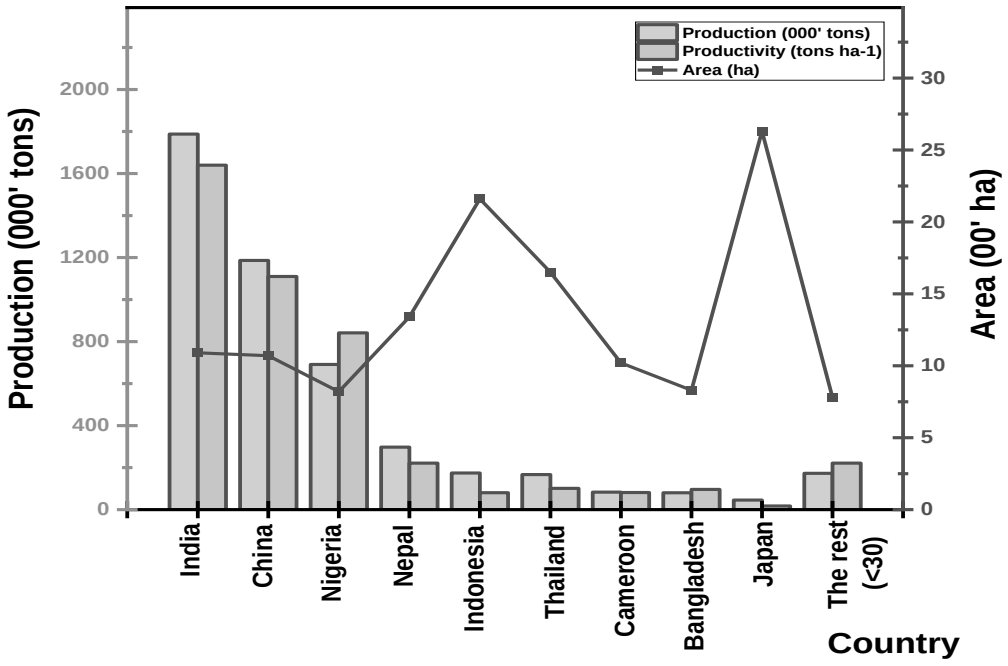



Figure 1.1: Annual ginger production from the most producing countries in 2019, data by Food and Agriculture Organization Statistics (FAO STAT).

## Ginger production in USA

Ginger in the United States is largely grown in Hawaii (Hepperly, 2017), and grown to a lesser extent in Southern Texas, Louisiana, Florida, Southern and coastal California, California Central Valley, Alabama, and Southern Arizona. Producers in the northeast have successfully produced ginger in high tunnels and greenhouses (Chawla et al., 2021; Hayden, 2006). USA is characterized with high levels of production per unit area (Figure 2); average production in 2019 was 30.38 tons ha-1 which is slightly lower compared to 2009 which was 34 tons ha-1 (statistical data of FAO, 2021).

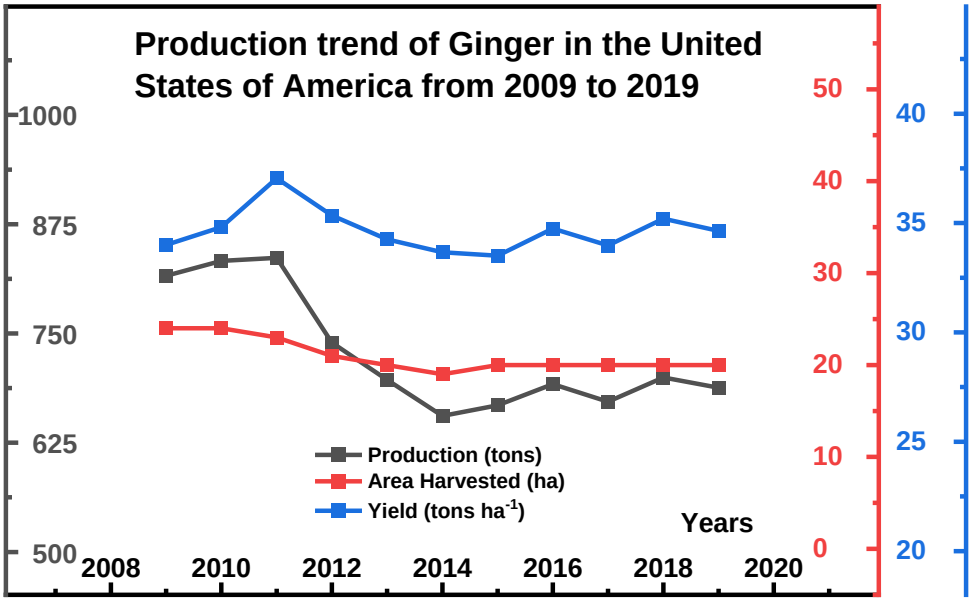



Figure 1.2: The production trend of Ginger in the United States of America from 2009 to 2019, data by Food and Agriculture Organization Statistics (FAO STAT).

## Ginger production in Tanzania

Ginger production in Tanzania is in several regions lying in different zones of Eastern (Coast, Tanga, and Morogoro regions), Northern (Kilimanjaro region),

Southern highland (Mbeya, and Ruvuma region), Western (Kigoma region) and Lake zone (Kagera region) (Mmasa and Mhagama, 2017; Sector, n.d.). Regardless of decades of ginger farming in Tanzania, the production per unit area is still low, less than 2.5 tons $ha^{-1}$ compared to other ginger producing countries in sub-Saharan Africa like Uganda, Mali, Cameroon, and Nigeria. Small holder farmers dominate ginger production in Tanzania, employing timeworn farming practices, using very low agricultural inputs, added with shortage of agronomic management and postharvest handling equipment and techniques. (Mmasa, 2017; Mmasa and Mhagama, 2017).

The low productivity from ginger farming is generally due to insufficient technology and knowledge on proper horticultural principles and practices. (Muzari et al., 2012), unstable and unsuitable climatic conditions (Buhaug et al., 2015), the use of inferior quality propagules (Minot, 2008), misuse of agrochemicals (Isgren and Andersson, 2021). Post-harvest mishandling, shortage of storage and packaging facilities, unavailability of automation (Ait-Oubahou, 2013), and unfavorable policies (Buhaug et al., 2015; Fuglie and Rada, 2013). Reliability of rain-fed agriculture in the tropics is another hurdle (Devendra and Thomas, 2002; Laryea, 1992). Total production output of ginger was 42 tons in 2019 with average production of 2.33 tones $ha^{-1}$, with a negligible increase over 10 years from 2.14 tons $ha^{-1}$ in 2009 (Figure 1.3:). Over the past 10 years, the production area has declined, due to low productivity and inefficient production. Tropical crop production is hindered by unstable market prices, biotic stress of pests, diseases and abiotic stresses of droughts, unpredictable rains and harsh climates (Nordey et al., 2017b). Dependency on rain-fed agriculture and the pressure from weed infestation significantly lowers the yields (Thankamani et al., 2016).

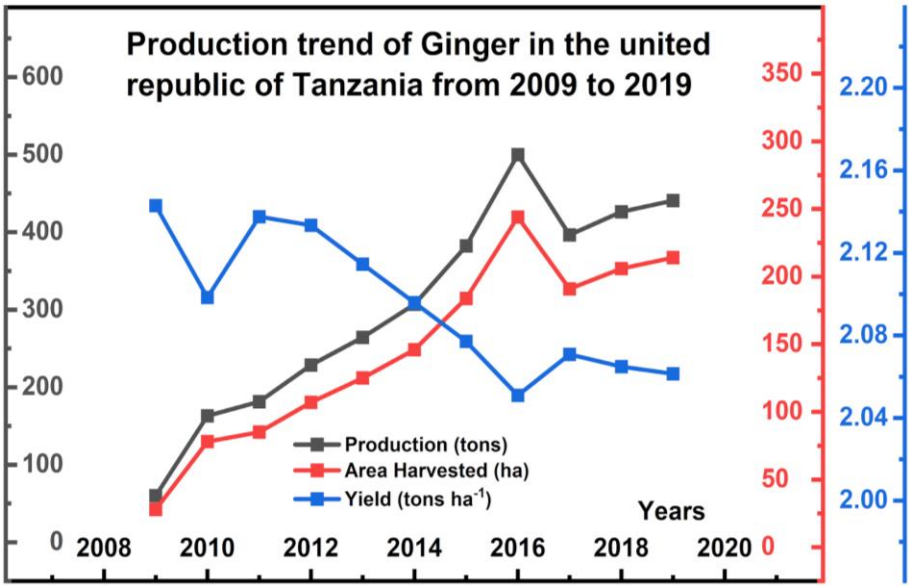



Figure 1.3: Production trends of ginger in Tanzania 2008-2020

The majority of soils in Tanzania have undergone profound weathering where the clay has released the leached aluminum, magnesium and iron oxides or hydroxides transforming into Ferric, Chromic and Eutric Cambisols, Rhodic and Haplic Ferralsols, and Humic Ferric Acrisols (Funakawa et al., 2012). Despite the complex climatic and topographic setting in Tanzania, there is sufficient land to allow substantial growth in agricultural production (Tilumanywa, 2013). Soils in the northern part of Tanzania, at the World Vegetable Center, Eastern and Southern Africa (WorldVeg – ESA), Arusha where trials are being conducted are loamy. Loamy soils can hold nutrients and have a texture that retains water, but also drains well,(Kahimba et al., 2014) . Land degradation in the form of physical loss of soil through either erosion or declining fertility due to continuous cropping without replenishment of

absorbed nutrients, are other issues limiting production in agricultural soils in Tanzania (Funakawa et al., 2012; Godlove Mtama, 2018).

## Ginger compounds and health benefits

There have been many studies of the health effects of ginger. The bioactive constituents of ginger possess pharmacological activities including anti-nausea anti-vomiting, analgesic, anti-diabetic, anti-inflammation, anti-obese, and other effects (Mao et al., 2019; Shukla and Singh, 2007; White, 2007). Numerous studies based on clinical trials and animal models showed that constituents of ginger play a significant role in disease prevention via modulation of genetic and metabolic activities. Phytocompounds in ginger including 6-, 8-, 10-gingerol, 6-shogaol, 6-hydroshogaol, and oleoresin elicit various pharmacological effects, not limited to antioxidation, antitumor/anticancer, anti-inflammatory, antihyperglycemic, antihypertensive, anticholesterolemic, antibiotic/antimicrobial, neuroprotective, antiulcer/gastroprotective, antiemetic, hepatoprotective, and antiplatelet aggregation (Chan et al., 2008; El-Ghorab et al., 2010; Höferl et al., 2015; Li et al., 2022; Mao et al., 2019; Sanwal et al., 2010; Shirin and Jamuna, 2010b). Many studies (in vitro, in vivo, and cell lines) contributed to the establishment of these safety profiles, though some of these potentials are yet to be explored (Chan et al., 2008; El-Ghorab et al., 2010; Höferl et al., 2015; Li et al., 2022; Mao et al., 2019; Sanwal et al., 2010; Shirin and Jamuna, 2010b).

## Chapter 2

# USE OF THE HALFWAY CULTIVATION TECHNIQUE OF GINGER (*Zingiber officinale*) IN FIELD SOILS UNDER PROTECTED OR OPEN CULTURE UNDER DIFFERENT IRRIGATION LEVELS AT TWO LOCATIONS IN DELAWARE


## Abstract

Ginger *(Zingiber officinale*) is a medicinal spice native to the tropical rainforests of Southeast Asia. It is widely used for culinary and medicinal purposes. Ginger is grown for almost 10-12 months for its mature storage version. However, when cultivated halfway (4-6 months) for its immature (baby) version, it can be sold as a fresh spice.

Five production trials were conducted in Newark and Georgetown, Delaware (DE) from February to November 2022 to assess the production potential in this region of the Mid-Atlantic United States. Yellow ginger rhizomes were sprouted and grown in growth chambers for 10 weeks, then transplanted under high tunnel, rain shelter, mulched open field, and bare-ground open field systems. Trials included different soils (clay loam soils and loamy sand soils), coupled with different irrigation frequencies (80%, 60%, 40%, and 20% minimum depletion before replenishment) during cultivation. Plant growth and development parameters were monitored monthly for 16 weeks followed by a final harvest; Statistical analysis was used to assess irrigation treatment differences.

Ginger growth and development (tillering, leaf number, chlorophyll content, fresh and dry biomass, and final yield) was proportional to irrigation levels. Plant height was highly influenced by the production environment (open field or protected culture) irrigation treatment had minimal effect on the stem diameter of the plants, leaf length,

and leaf width. Yield potential ranged from 19.2–30.2 tons $ha^{-1}$ (0.58 – 0.91 kg $plant^{-1}$) in high irrigation frequency irrigation treatments. Water usage for the most productive location and irrigation treatment (Newark-high tunnel) required 665 L $kg^{-1}$ of rhizomes, while the rain shelters with drip irrigation required 432.5 L $kg^{-1}$ of rhizomes. Low irrigation treatments in the open field averted significant water stress due to frequent precipitation received during the growing season.

**Keywords**

Ginger, baby ginger, immature ginger, halfway cultivation technique,

**Abbreviations**

| | | | |
|---|---|---|---|
| cm – centimeter | ft – feet/foot | ha – hectares | IL – Illinois |
| kg – kilogram | m – meter | NC – North Carolina | |
| ppm – parts per million | sq – square | USA – United states of America | |
| x – times | % - percentage | $^0$C – degree Celcius | |

## Introduction

This study reduces ginger's cropping cycle from fully matured ginger to immature (baby) ginger by half which demands half the inputs. The full potential of Zingiberaceae family members is attained during both physiological maturity for cardamom. (Leela et al., 2008) and during immature stages for turmeric and ginger (Ernst and Durbin, 2019). Based on the existing claims, it is assumed that the ginger plant also attains its full potential half-way through its traditional cropping cycle.

Ginger is an important food and cash crop requiring significant resources during cultivation for its heavy feeding and longer cultivation nature. (Maigari Ibrahim, 2018). The global production potential of ginger is threatened due to diminishing natural

resources (Chang and Criley, 1993). As a food crop, ginger is used for culinary purposes for its properties as a spice. As a cash crop it is transformed into value added products (powders, flakes, teas, confections, essential oils, concentrates, flavors) or further processed for its phytocompounds with medicinal benefits.

Halfway cultivation has been termed “baby ginger” in the United States. Virginia State University found that ginger could be grown in high tunnels and harvested as baby ginger (Rafie et al. 2012). Other trials in the Northeast and Mid-Atlantic States have also shown the potential to grow baby ginger in high tunnels and greenhouses (Chawla et al., 2021; Hayden, 2006).

The objective of this study was to determine the effects of protected and open field cultivation systems and different irrigation treatments on baby ginger growth and development. Cultivation systems include high tunnel, rain shelter, open field with plastic mulch, and bare open field while irrigation was applied on a high frequency 80%, medium frequency 60%, medium-low frequency 40% and low frequency 20% basis.

Through this study, information on the sustainable usage of water resources and productivity was sought. Cutting the production time in half reduces resource usage while increasing output potential. This enables growers to run a successful 4 – 6 month cropping cycle of baby ginger per annum while relying on rainfed agriculture as for the case of most tropical countries (Adamgbe and Ujoh, 2013) ; Rattis *et al.*, 2021), or in temperate regions during 5 – 6 warm months (Ford *et al.*, 2022).

## Materials and methods

### Locations and facilities

Experiments in this multi-location trial were conducted in different parts of the state of Delaware in the Mid-Atlantic region of the USA). The experiment involved

usage of a tunnel, a rain shelter (covered with Clear IRAC Greenhouse Plastic Sheeting - 6 Mil - (40' x 100') - 4 Year UV Resistant Infrared Anti-Condensate Greenhouse Covering Thermal Greenhouse Plastic 6 mil), a mulched open field (using with black embossed 1.2 mil plastic mulch, from Rain-flow Irrigations, 929 Reading Rd. East Earl, Pennsylvania 17519) and a bare open field. The production and research facilities are at the University of Delaware, campuses of Newark (39.6780° N, 75.7506° W, 137 m asl) and Georgetown (38.72180 N, 75.47760, 16 m asl), The experiments lasted from February 2022 to February 2023.

Delanco soil and Rosedale soil dominated the experimental sites in the US. Delanco soils are found in Newark, Delaware; they are fine-loamy, mixed, semi-active, mesic aquic hapludults which consist of very deep moderately well drained and poorly drained soils. Permeability is moderately slow in the solum and moderate in the substratum. Runoff is slow to medium, and they suit cultivation of general crops. (Larsen *et al.*, 2014). Rosedale soils, loamy, siliceous, semi active, mesic Arenic Hapludults prevalent in Georgetown, Delaware; they are loamy sand or sand soils that are deep, well drained with high saturated hydraulic conductivity in the surface and subsoil. This soil is well drained without flooding or ponding frequency and duration and with a negligible or very low surface runoff index. Saturation hydraulic conductivity is high/very high in the surface, high in the subsoil and moderate in the substratum and low shrink-swell potential. Mostly these soils are ideal for cultivated crops. (Goble *et al.*, 2010).This thesis presents data from USA Delaware trials only. Tanzanian trials will be added to reports upon completion.

Layout and design

The experiments were inside the tunnels, rain shelters and open fields using their prevalent soils. The experimental design in the tunnel and bare open field was Latin square design and a randomized complete block design (RCBD) in rain shelter and mulched open field experiments.

Plant material and propagation

Experimental seedlings were initiated from disease free, organically grown, matured yellow ginger rhizomes, sourced from Peru. Rhizomes were split into sets (propagules) weighing 45 – 65 g with at least 2 – 3 visible nodes (eyes) then surface sterilized using 10 % ZeroTol HC (from BioSafe Systems 22 Meadow Street, East Hartford, CT 06108 containing 5.34% Hydrogen peroxide and 1.36% Peroxyacetic acid) for 15 minutes. Curing of the rhizomes followed by placing them to air dry and heal the wounds in a shaded area for 3 days at room temperature. The next step was potting in a 10.16 × 10.16 $cm^2$ pots using Pro-mix TM growing media (from Premier Technology Limited, 1, avenue Premier, Campus Premier Tech, Rivière-du-Loup (Québec), Canada G5R 6C1, containing sphagnum peat moss 85 %, coco coir fiber 5%, perlite 5%, ground limestone 3%, and wetting agent 2%). We incubated the potted rhizomes in the growth chamber (Chamber #4 -Conviron walk in model # TCR-240 96 ft./sq. of shelf space 59-Watt fluorescent and 40-watt incandescent lights Temperature, light and humidity control) potted rhizomes at 28 $^0$C, 60 % RH, and 14 hours of light. Raising seedlings took an average of two months, with irrigation done twice – thrice a week, and fertigation done on a bi-weekly interval post sprouting using a 12-4-16 NPK fertilizer (JR PETERS INC 6656 Grant Wat, Allentown, PA 18106) and Epsom salt (Magnesium sulphate from JR PETERS INC) at dissolution rate of 1.05 and 0.28 g $L^{-1}$ (0.14- and 0.038-ounces $gal^{-1}$) respectively. Air fans circulated air inside the

chambers to ensure even distribution of temperature and humidity. Transplants were grown to a height of 30 – 50 cm (1 – 1.5 ft) with 2 – 3 tillers.

Planting and Hilling

All experimental sites had 16 experimental units, for the high tunnel (9×22 m) and two rain shelters (9×15 m), we established 27 plants per experimental unit and 22 plants each for mulched open field (4 × 30 m) and bare open field (9 × 22 m). The planting holes were 30 cm deep to completely hold the rootzone of the seedlings and for the mulched open field we cut 15 cm diameter holes for seedlings pseudo stems, which increased with respect to ginger tillering. We raised beds to 30 cm for the Newark tunnel, 45 cm for the Newark open field, 20 cm for Georgetown open field and none for Georgetown shelters. For all the experimental sites, we performed hilling once a month by pulling the soil onto the base of ginger plants to enhance the aesthetic quality of rhizomes by covering the vertically developing ones.

Soil amendments and Fertilization

Georgetown sites had 0.5 % organic matter and a pH of 6.9. Fertility index values were P = 163 (very high), K = 25 (low), Ca = 110 (very high) and Mg = 25 (low). In Georgetown, plots were amended with compost (Bioenergy Devco, Seaford, Delaware) at a rate of 1.8 kg $m^2$ (compost analysis 2-1-0.3 N-P-K as is) with estimated release of 32-35-54 kg $ha^{-1}$ N-P-K. Soils in Georgetown were also fertilized with 20-20-20 N- P2O5-K2O (Jacks' professional water-soluble fertilizer from JR PETERS) at the rate of 40 g $plant^{-1}$ administered through drip irrigation monthly for three consecutive months. This provided 170-170-170 kg $ha^{-1}$ N-P2O5-K2O.

The clay-based soils in Newark had sufficient fertility not to require any additional fertilizer amendments. Soils had 4.9% organic matter in the ridges with an

estimated N release of 160 kg ha $^{-1}$. pH was 5.8. Fertility index values were P = 310 (very high), K = 95 (high), Ca = 123 (high), and Mg 144 (very high). Mid-season tissue tests showed sufficient levels of all mineral nutrients in the ginger plants.

Irrigation Treatments

Minimum moisture levels before replenishment were the irrigation treatment levels. They included high irrigation frequency 80% (soil moisture bandwidth ranged from 100 – 80%), medium irrigation frequency 60% (soil moisture bandwidth ranged from 100 – 60%), medium-low irrigation frequency 40% (soil moisture bandwidth ranged from 100 – 40% and it served as the standard) and low irrigation frequency or 20% (soil moisture bandwidth ranged from 100 – 20%). The bandwidth was directly proportional to drought stress and inversely proportional to irrigation frequency. The Tunnel and bare open fields were hand watered using hose and wand, and drip tube or tape delivered irrigation water to the rain shelters (1/4" drip tubing 6 inch spacing from DripWorks, 190 Sanhedrin Circle Willits, CA 95490), and mulched open field (T-tape .45 gpm 12-inch emitter spacing from Rain-flow irrigations, 929 Reading Rd. East Earl, Pennsylvania 17519).

## Data collection and analysis

All collected data falls under three categories of non-destructive, destructive, and associated data (irrigation treatments, soil moisture data, and weather data). The collection interval of destructive and non-destructive was once per month (30, 60, 90, and 120 days after transplanting DAP) involving three and four plants, respectively. The four plants for non-destructive data were permanently marked for consistent data collection. Both destructive and non-destructive data involved phenological observations and counts of tillers and leaves, linear measurements of plant height,

main stem width using vernier calipers (NEIKO 01407A Electronic Digital Caliper), $5^{th}$ leaf length, $5^{th}$ leaf width, and chlorophyll quantifications (chlorophyll meter SPAD-502Plus, Konica Minolta sensing Americans, Inc. New Jersey, U.S.A and MC-100 chlorophyll concentration meter, 721 West 1800 North, Logan, UT 84321, United States of America. Destructive measurements had added data collected from the three uprooted plants per experimental unit which included fresh and dry biomass, and categorization of rhizome fingers, with yield data obtained at the end of the cultivation phase (rhizome fresh and dry weights). Plant parts were dried at 65 C in an oven to obtain dry weights. Associated data include location-specific irrigation dates, amount of water applied, soil moisture levels and weather data. Irrigation treatments were applied according to soil moisture levels determined by the gravimetric method (sampling soils and determining water percentage using ovens), reflectometry method (using a TDR meter from Fondriest Environmental, 2091 Exchange Court, Fairborn, OH 45324, USA, that indirectly measures soil water content based on the travel time of a high frequency electromagnetic pulse through the soil) and tensiometers ("Jet-Fill Tensiometer Model 2725 ARL, 12. Digital data loggers (WatchDog A-Series Loggers, Spectrum Technologies, 3600 Thayer Court, Aurora, IL 60504) and weather stations (http://www.deos.udel.edu/data/agirrigation_retrieval.php) Delaware environmental observing system recorded weather data at a specified time interval.

The data was subjected to analysis of variance (ANOVA) by using JMP® version 16.1 (100 SAS Campus Drive, Cary, NC 27513, USA) to determine the significance of the main effects (irrigation treatment, location, and sampling period) and interactions. ANCOVA (Analysis of Covariance) was used to remove and reduce the impact of noise from dependent variables amongst the different means the means

were separated and then compared using the Tukey's HSD test at 5% probability. Orthogonal polynomial contrasts were used to determine linear and quadratic effects associated with irrigation treatments.

## Results and Discussion

Tests of significance from the Analysis of Variance (ANOVA) for main irrigation treatment effects are presented in Tables 1, 2, and 3 for parameters measured by test location.

Table 2.1: ANOVA tests of treatment (irrigation) effects on plant height, tiller numbers, stem diameter, leaf number, leaf length and width, and chlorophyll concentration by location.

| Location | Plant height (cm) | Tiller (no.) | Stem diameter (mm) | leaf (no.) | leaf length (cm) | leaf width (cm) | Chlorophyll concentration |
|---|---|---|---|---|---|---|---|
| Newark Field | <.001 | <.001 | <.012 | <.001 | <.034 | 0.281 | <.001 |
| Newark Tunnel | <.001 | <.001 | <.001 | <.001 | <.001 | 0.006 | <.001 |
| Georgetown Rain Shelter P1 | <.001 | <.001 | 0.637 | <.021 | <.001 | 0.514 | <.001 |
| Georgetown Rain Shelter P2 | <.001 | <.001 | 0.038 | <.001 | 0.003 | 0.665 | <.001 |
| Georgetown Field | <.001 | <.001 | <.001 | <.001 | 0.601 | 0.812 | <.001 |

Table 2.2: ANOVA tests of treatment (irrigation) effects on leaf, pseudo stem, and baby rhizome fresh and dry weight by location.

| Location | Leaf dry weight | Leaf fresh weight | Pseudo-stem dry weight | Pseudo-stem fresh weight | Baby rhizome fresh weight | Baby Rhizome dry weight |
|---|---|---|---|---|---|---|
| Newark Field | 0.004 | <.001 | <.001 | <.001 | 0.568 | <.001 |
| Newark Tunnel | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 |
| Georgetown Rain Shelter Planting 1 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 |
| Georgetown Rain Shelter Planting 2 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 |
| Georgetown Field | 0.004 | <.001 | <.001 | <.001 | 0.644 | <.001 |

Table 2.3: ANOVA tests of treatment (irrigation) effects on root fresh and dry weight, primary, secondary, tertiary, and quaternary fingers, and final yield by location.

| Location | Roots fresh weight | Roots dry weight | Primary Fingers | Secondary Fingers | Tertiary Fingers | Quaternary Fingers | Yield |
|---|---|---|---|---|---|---|---|
| Newark Field | 0.029 | .003 | <.001 | 0.030 | 0.066 | <.001 | <0.001 |
| Newark Tunnel | <.001 | <.001 | <.001 | 0.648 | <.001 | <.001 | <0.001 |
| Georgetown Rain Shelter Planting 1 | <.001 | <.001 | <.001 | 0.549 | <.001 | 0.002 | <0.001 |
| Georgetown Rain Shelter Planting 2 | <.001 | .002 | <.001 | 0.110 | 0.036 | 0.022 | <0.001 |
| Georgetown Field | 0.712 | <.001 | 0.074 | 0.970 | <.001 | <.001 | <0.001 |

Plant height and tiller numbers

Irrigation treatment had a significant effect on plant height for destructive data, (Table 2.1). Newark tunnel had significantly taller plants compared to the other sites whereas the Newark field site had the shortest plants (Table 2.4). Georgetown rain shelter and field plants had similar heights. Irrigation treatment 80% resulted in the tallest plants in all but one sampling in the Newark tunnel. At the final sampling period heights ranged from 39.0 cm (Newark field) to 137.2 cm (Newark Tunnel). Plant height increased with an increase in irrigation in the Newark tunnel, Georgetown rain shelter, and Georgetown field and was significantly linear. Quadratic tests were also significant as plant height leveled off after the 60% water replenishment was reached in later sampling dates (Table 4). Plant height did not differ in the Newark field location with treatment. Growth rates as measured by height over time were significantly higher in the Georgetown tunnel compared to other sites (Table 2.4). These results were mirrored in the non-destructive measurements (results not shown).

Irrigation treatment had a significant effect on the extent of tillering per plant in destructive measurements (Table 2.1). Throughout the sampling period, Newark tunnel had the average highest number of tillers, per location basis compared to the lowest number of tillers recorded in Georgetown, RS PD2 (Table 2.4). Treatment 80% in Newark tunnel had the highest score of tillers (24.7), significantly different from the least irrigated 20% (7.6). Tiller numbers increased with an increase in irrigation in the Newark tunnel, and Georgetown rain shelter was significantly linear. Quadratic tests were also significant as tiller number leveled off after the 60% water replenishment was reached in later sampling dates (Table 2.4). In both open field sites, tiller numbers were not affected by irrigation treatment. (Table 2.4) Tiller numbers ranged from 10.1 in the Georgetown RS PD2 test to 26.3 in the Newark field test.

Again, these results were mirrored in the nondestructive measurements (data not shown). Shade avoidance response triggered higher height response within tunnels and rain shelter as compared to open fields despite treatment effect probably due to low Red to Far red-light ratio. Ginger plants produce an enzyme that speeds up production of a plant growth hormone (auxin) when shaded which causes the plants to grow faster and taller; ginger's shade avoidance response is associated with increased tillering leading to increased crown density and volume (Cao et al., 2021). Morelli and Ruberti (2000) reported observations of increased elongation in Arabidopsis when subjected under low light intensities through phytochrome-mediated photomorphogenic responses. Ahaiwe (2009) found that the fertility status of the soil partly influences height in ginger plants. Abundant resources in open fields such as water during rainy seasons and fertilizers for the case of nutrient dense soils, stimulated the extent of tillering. The Newark open field has a close water table and fertile soil which accounts for higher tillering. Wilson and Ovid, (1993) found a similar response of increased tillering in shaded ginger. Maximum tillering is expected during vegetative growth phase 2 – 4 months, then shifts with rhizome development.

Stem Diameter

The Newark tunnel had significant stem diameter value differences recorded across its irrigation treatments while there was minimal to no significant effect on stem diameter among irrigation treatments in Newark open field (Table 2.1). Stem diameter increased with an increase in irrigation in the Newark tunnel and Georgetown field. Minimal or no effects of irrigation treatment were seen in the Georgetown rain shelter on stem diameter.

Table 2.4: The effect of irrigation, and days after planting (DAP) on the height and tillering of ginger by location. Delaware Trials, 2022.

| Location/Irrigation[1] | 30 DAP[3] | | 60 DAP | | 90 DAP | | 120 DAP | |
|---|---|---|---|---|---|---|---|---|
| | Height (cm) | Tillers (no) | Height (cm) | Tillers (no) | Height (cm) | Tillers (no) | Height (cm) | Tillers (no) |
| Newark Tunnel | | | | | | | | |
| 20[2] | 32.9 d[6] | 2.8 c | 48.7 d | 4.2 c | 52.9 c | 5.5 c | 70 b | 7.6 c |
| 40 | 39.1 c | 4.7 b | 54.4 c | 7.7 b | 64.2 b | 13.6 b | 129 a | 20.6 b |
| 60 | 46.6 b | 6.4 a | 61.8 b | 9.4 a | 73.3 a | 18.3 a | 137 a | 24.5 a |
| 80 | 52.0 a | 6.7 a | 67.2 a | 9.7 a | 75.9 a | 18.3 a | 132 a | 24.7 a |
| Linear[4] | *** | *** | *** | *** | *** | *** | *** | *** |
| Quadratic[5] | *** | *** | *** | *** | *** | *** | *** | *** |
| Newark Field | | | | | | | | |
| 20 | 16.1 a | 6.9 ab | 32.0 a | 14.1ab | 39.3a | 19.5 ab | 39.0 b | 24.5 a |
| 40 | 16.1 a | 8.1 a | 26.5 b | 15.8a | 36.0ab | 21.3 a | 36.0 b | 26.3 a |
| 60 | 13.5 a | 7.2 ab | 26.6 b | 14.5ab | 33.9 b | 21.1 ab | 38.5 b | 26.0 a |
| 80 | 15.1 a | 5.9 b | 27.3ab | 11.8b | 39.1 a | 17.3 b | 42.9 a | 23.1 a |
| Linear | NS | NS | * | NS | NS | NS | ** | NS |
| Quadratic | * | * | NS | NS | NS | NS | ** | NS |
| Gtown RS PD1 | | | | | | | | |
| 20 | 37.0 c | 6.6 b | 40.7 c | 7.6 b | 44.5 c | 9.0 c | 48 c | 10.5 b |
| 40 | 34.9 c | 6.1 b | 38.3 c | 7.4 b | 55.7 b | 12.5 a | 60 b | 14.6 a |
| 60 | 52.3 b | 8.2 a | 56.6 b | 9.1 a | 61.1 a | 10.6 bc | 66 ab | 12.0 b |
| 80 | 57.9 a | 8.6 a | 61.4 a | 9.5 a | 65.1 a | 10.9 ab | 68 a | 12.5 ab |
| Linear | *** | *** | *** | *** | *** | NS | *** | NS |
| Quadratic | *** | *** | *** | *** | *** | NS | *** | NS |
| Gtown RS PD2 | | | | | | | | |
| 20 | 34.0 b | 6.8 c | 37.7 c | 7.8 c | 41.5 c | 8.8 c | 45.4 c | 10.1 c |
| 40 | 34.3 b | 5.3 d | 45.1 b | 7.4 c | 53.6 b | 9.6 c | 57.4 b | 11.0 c |
| 60 | 49.9 a | 10.3 b | 53.6 a | 11.3 b | 57.5 ab | 13.0 b | 61.4 ab | 14.5 b |
| 80 | 52.6 a | 12.3 a | 56.4 a | 14.3 a | 60.2 a | 16.5 a | 64.1 a | 18.9 a |
| Linear | *** | *** | *** | *** | *** | *** | *** | *** |
| Quadratic | *** | *** | *** | *** | *** | *** | *** | *** |
| Georgetown Field | | | | | | | | |
| 20 | 42.4 b | 6.3 a | 46.7 b | 9.6 a | 50.9ab | 13.1 a | 55.1ab | 16.8 a |
| 40 | 42.3 b | 7.3 a | 44.4 b | 9.3 a | 46.5 b | 11.6 a | 48.5 b | 13.9 a |
| 60 | 54.2 a | 6.0 a | 57.1 a | 8.4 a | 59.9 a | 10.8 a | 62.7 a | 12.8 a |
| 80 | 51.8 a | 6.5 a | 56.2 a | 10.1 a | 60.6 a | 13.3 a | 65.0 a | 16.7 a |
| Linear | ** | NS | ** | NS | ** | NS | ** | NS |
| Quadratic | *** | NS | *** | NS | ** | NS | ** | NS |

[1] Location and protection. RS = Rain Shelter, PD = Planting Date, Gtown = Georgetown; [2] Soil moisture level depleted to in percent of Field Capacity until irrigated back to field capacity
[3]DAP = Days after Planting. [4],[5] Orthogonal contrasts. Irrigation treatment effects on plant height are significantly linear or quadratic at the *0.05 level, **0.01 level, *** 0.001 level, or are not significant NS [6]Mean separation by Tukey's HSD. Means followed by the same letter are not significantly different at the 0.05 level

Leaf number and chlorophyll concentration

Irrigation treatment and had significant influence on leaf number (Table 2.1). Leaf numbers increased with irrigation frequency and days after planting (Table 2.5). Orthogonal tests of linear and quadratic effects were significant throughout for Georgetown RS PD2, and only for the first three data collections for Newark tunnel, Newark open field, and Georgetown RS PD1 (Table 6). Georgetown field had significantly linear and quadratic contrasts throughout the course of data collection (Table 6).

Chlorophyll concentration in ginger plants' leaves responded to irrigation treatment (Table 2.1). There was a steady increase in chlorophyll concentration in the tunnel and rain shelters as it moved from 30 to 120 days after planting and from low irrigation frequency to high irrigation frequency unlike Newark and Georgetown open field (Table 2.5). There were significant linear and quadratic contrasts in shelters and tunnels as compared to both open fields.

Chlorophyll readings increased with increasing irrigation in the Newark tunnel, Newark field 120 DAP, Georgetown RS PD 1, and Georgetown PD 2 (except 120 DAP) and were significantly linear and quadratic. Chlorophyll readings ranged from 12.1 to 22,1 at 120 DAP.

Drought stress significantly reduces the quantum efficiency of photosystem II (Fv/Fm), the non-cyclic electron transfer efficiency of photosystem II (ϕPSII), and photochemical quenching (qP), while simultaneously increasing non photochemical quenching (NPQ) (Lv et al., 2020). Xu et al., (2003) found that chlorophyll content in ginger leaves decreased with increasing drought stress but increased under shade setup.

Table 2.5: The effect of irrigation and days after planting (DAP) on the leaf no. and chlorophyll concentration of ginger by location. Delaware Trials, 2022.

| Location/Irrigation[1] | 30 DAP[3] | | 60 DAP | | 90 DAP | | 120 DAP | |
|---|---|---|---|---|---|---|---|---|
| | Leaf (no) | Chloro-phyll. | Leaf (no) | Chloro-phyll | Leaf (no) | Chloro-phyll. | Leaf (no) | Chloro-phyll |
| Newark Tunnel | | | | | | | | |
| 20[2] | 19 d[6] | 9.3 c | 34 c | 11.3 c | 81 c | 13.0 c | 94 b | 15.4 c |
| 40 | 26 c | 11.1 c | 41 c | 12.4 c | 89 bc | 15.8 b | 104 ab | 18.1 b |
| 60 | 43 b | 14.8 b | 58 b | 16.2 b | 106 a | 19.3 a | 105 a | 20.4 a |
| 80 | 62 a | 18.2 a | 77 a | 19.6 a | 98 ab | 18.5 a | 102 ab | 20.5 a |
| Linear[4] | *** | *** | *** | *** | *** | *** | NS | *** |
| Quadratic[5] | *** | *** | *** | *** | *** | *** | NS | *** |
| Newark Field | | | | | | | | |
| 20 | 40 ab | 11.1 b | 70 b | 19.4 b | 94 ab | 17.6 b | 102 a | 13.1 b |
| 40 | 46 a | 13.9 a | 87 a | 19.4 b | 101 a | 21.3 a | 102 a | 13.2 b |
| 60 | 37ab | 13.9 a | 63 b | 14.7 c | 80 c | 14.4 c | 96 a | 14.9 b |
| 80 | 33 a | 12.9 ab | 65 b | 23.0 a | 83 bc | 21.9 a | 98 a | 21.8 a |
| Linear | ** | NS | * | NS | ** | NS | NS | *** |
| Quadratic | ** | NS | ** | NS | *** | NS | NS | *** |
| Gtown RS PD1 | | | | | | | | |
| 20 | 19 a | 15.4 b | 20 a | 17.0 b | 21 a | 18.7 b | 22 a | 18.8 b |
| 40 | 17 a | 15.7 b | 19 a | 17.7 b | 20 a | 19.7 b | 21 a | 20.7 ab |
| 60 | 18 a | 16.4 b | 19 a | 18.3 b | 20 a | 20.3ab | 22 a | 21.6 a |
| 80 | 19 a | 18.7 a | 19 a | 20.4 a | 19 a | 21.8 a | 21 a | 22.1 a |
| Linear | NS | *** | NS | *** | NS | *** | NS | *** |
| Quadratic | NS | *** | NS | *** | NS | ** | NS | ** |
| Gtown RS PD2 | | | | | | | | |
| 20 | 46 c | 15.6 b | 46 c | 17.5 b | 47 c | 19.4 b | 48 c | 21.2 a |
| 40 | 44 c | 15.9 b | 51 bc | 17.2 b | 60 b | 18.6 b | 60 b | 20.0 a |
| 60 | 56 b | 17.8 a | 58 b | 19.2ab | 60 b | 20.5 ab | 62 b | 20.9 a |
| 80 | 70 a | 18.7 a | 72 a | 20.2 a | 73 a | 21.6 a | 75 a | 21.7 a |
| Linear | *** | *** | *** | *** | *** | ** | *** | NS |
| Quadratic | *** | *** | *** | *** | *** | ** | *** | NS |
| Georgetown Field | | | | | | | | |
| 20 | 38 b | 13.2 a | 39 b | 12.9 b | 40 c | 12.2 a | 42 c | 12.1 b |
| 40 | 35 b | 13.3 a | 36 b | 13.3 b | 49 bc | 13.2 a | 51 bc | 13.2 b |
| 60 | 58 a | 12.8 a | 59 a | 14.8ab | 61 a | 13.8 a | 65 a | 15.8 a |
| b80 | 50 a | 14.4 a | 51 a | 15.8 a | 55 ab | 13.2 a | 55 ab | 13.5 b |
| Linear | *** | NS | *** | ** | *** | NS | *** | ** |
| Quadratic | *** | NS | *** | ** | *** | NS | *** | ** |

[1] Location and protection. RS = Rain Shelter, PD = Planting Date; [2] Soil moisture level depleted to in percent of Field Capacity until irrigated back to field capacity

[3]DAP = Days after Planting [4,5] Orthogonal contrasts. Irrigation treatment effects on plant height are significantly linear or quadratic at the *0.05 level, **0.01 level, *** 0.001 level, or are not significant NS. [6]Mean separation by Tukey's HSD. Means followed by the same letter are not significantly different at the 0.05 level.

Soil nitrogen influences leaf number during crop growth. Leaf numbers account for the extent of transpiration, directly proportional to plant's size.(Fender et al., 2011) identified soil moisture, nitrogen availability and water vapor saturation deficit as external drivers for the number of leaves produced in beech saplings. Nitrogen becomes readily available for plants absorption in high soil moistures, as for the case of both T2 and Newark open fields. Environmental parameters influence leaf numbers in ginger plants, (Ahaiwe, 2009) noticed a lack of irrigation treatment effect in leaf number post improvisation of organic fertilizer amendments but concluded recording the highest leaf number from the highest fertility irrigation treatment. (Flores *et al.*, 2021) reported that night interruptions with artificial lights increased the number of leaves in ginger.

Nutrient availability and environmental stress such as drought, salinity, cold, heat and others influence chlorophyll concentration per area as an indicator of photosynthetic capacity of plants. Plants grown in areas with abundant soil moisture, or which received moderate high irrigation frequency (T2) had higher chlorophyll quantity. (Ghasemzadeh *et al.*, 2010) linked higher chlorophyll content in ginger with lower light levels, which prevailed in tunnels and rain shelter during cultivation, different from open fields.

Leaf fresh and dry weight

Leaf fresh and dry weight were significantly influenced by irrigation treatment (Table 2.2). The 80% treatment in Newark tunnel had the highest fresh and dry weight (g) at 120 DAP compared to other irrigation treatments in Newark field, Georgetown RS 1 and 2, and Georgetown open field (Table 2.6). Leaf weights increased with an increase in irrigation in the Newark tunnel and Georgetown RS PD2 and were

significantly linear and quadratic. Irrigation treatments in other sites had variable effects on leaf weight. Leaf fresh weight ranged from 18 g to 125 g 120 DAP. Leaf dry weights were proportionally higher in the Newark field than in other sites.

Leaves are the most important organs for plants to transfer solar energy to biological energy through photosynthesis. Leaf fresh weight relates to foliar water content and biomass, used when scaling relationships with leaf area.(Xu *et al.*, 2003) discussed that water stress decreased the chlorophyll contents, stomata density, and stomata size of ginger leaves which could account for lower weight observed in water stressed irrigation treatments, while increasing the chlorophyll contents and stomata size of the upper cuticle of ginger leaves. Leaf dry weight is a precious measurement of biomass eliminating fluctuations caused by water content. Leaf dry weight through leaf dry mass per unit area (LMA) represents the photosynthetic capacity, implying a hypothesis that foliar water mass (leaf fresh weight minus leaf dry weight) is proportional to leaf dry weight during leaf growth. Leaf weight measures plants' response to photosynthetic capacity, nutrition, and environmental conditions.

Pseudo-stem fresh and dry weight

Pseudo stem fresh and dry weight was highly influenced by irrigation treatment (Table 2.2).

There was an increase in pseudo-stem weights in all 3 protected sites with an increase in irrigation and the effects were significantly linear and quadratic. The 2 field sites had more variable responses.

Table 2.6: The effect of irrigation, and days after planting (DAP) on leaf fresh and dry weight (g) of ginger by location. Delaware Trials, 2022.

| Location/Irrigation[1] | 30 DAP[3] | | 60 DAP | | 90 DAP | | 120 DAP | |
|---|---|---|---|---|---|---|---|---|
| | Fresh wt.(g) | Dry wt.(g) | Fresh wt. (g) | Dry wt.(g) | Fresh wt.(g) | Dry wt.(g) | Fresh wt.(g) | Dry wt.(g) |
| Newark Tunnel | | | | | | | | |
| 20[2] | 12.9 c[6] | 0.7 c | 20.0 c | 1.1 c | 27.2 d | 1.6 d | 31.8 d | 1.9 d |
| 40 | 27.4 b | 1.6 b | 34.5 b | 2.0 b | 61.4 c | 3.6 c | 78.8 c | 4.7 c |
| 60 | 30.7 b | 1.8 b | 40.1 b | 2.3 b | 100.2 b | 6.0 b | 108.0 b | 6.6 b |
| 80 | 60.9 a | 3.6 a | 79.7 a | 4.8 a | 123.1 a | 8.0 a | 124.5 a | 8.1 a |
| Linear[4] | *** | *** | *** | *** | *** | *** | *** | *** |
| Quadratic[5] | *** | *** | *** | *** | *** | *** | *** | *** |
| Newark Field | | | | | | | | |
| 20 | 8.2 a | 2.3 a | 17.1 a | 4.9 a | 25.6 a | 7.4 a | 34.1 a | 3.9 a |
| 40 | 7.8 a | 2.4 a | 15.6 ab | 4.8 a | 23.4 ab | 7.3 a | 31.2 ab | 2.7 a |
| 60 | 5.7 a | 2.1 a | 11.7 b | 4.2 a | 17.6 b | 6.4 a | 23.5 b | 2.5 a |
| 80 | 7.2 a | 2.1 a | 14.3ab | 4.1 a | 21.5 ab | 6.2 a | 28.7 ab | 3.2 a |
| Linear | NS | NS | * | NS | * | NS | * | NS |
| Quadratic | * | NS | * | NS | * | NS | * | NS |
| Georgetown RS PD1 | | | | | | | | |
| 20 | 13.6 b | 0.9 c | 15.1 b | 1.2 b | 16.7 c | 1.4 c | 18.3 c | 1.5 c |
| 40 | 17.2 ab | 1.5 ab | 18.9 a | 1.6 a | 27.7 a | 2.4 a | 30.0 a | 2.3 a |
| 60 | 19.2 a | 1.7 c | 20.9 a | 1.6 ab | 22.6 b | 1.9 b | 24.4 b | 2.0 ab |
| 80 | 15.8 ab | 1.3 ab | 17.5 ab | 1.5 ab | 19.2 bc | 1.7 bc | 21.0 bc | 1.9 b |
| Linear | NS | ** | * | NS | NS | NS | NS | NS |
| Quadratic | * | ** | * | NS | NS | NS | NS | NS |
| Georgetown RS PD2 | | | | | | | | |
| 20 | 18.2 b | 1.5 c | 19.4 b | 1.6 b | 20.5 b | 1.9 b | 21.7 b | 1.7 c |
| 40 | 14.7 b | 1.2 c | 18.8 b | 1.5 b | 23.2 b | 1.8 b | 24.9 b | 2.0 c |
| 60 | 27.2 a | 2.6 a | 28.9 a | 2.3 a | 30.6 a | 2.6 a | 32.4 a | 2.9 a |
| 80 | 25.0 a | 2.1 b | 26.6 a | 2.2 a | 28.3 a | 2.4 a | 29.9 a | 2.5 b |
| Linear | *** | *** | *** | *** | *** | *** | *** | *** |
| Quadratic | *** | *** | *** | *** | *** | *** | *** | *** |
| Georgetown Field | | | | | | | | |
| 20 | 7.6 ab | 0.9 b | 18.2 a | 2.5 a | 29.8 a | 3.9 a | 41.4 a | 5.4 a |
| 40 | 6.9 b | 0.8 b | 15.0 a | 1.4 b | 24.1 a | 2.8 b | 33.2 a | 4.3 a |
| 60 | 9.3 a | 1.3 a | 18.7 a | 2.2 a | 28.8 a | 3.2 ab | 38.9 a | 5.0 a |
| 80 | 8.4 ab | 0.9 b | 19.2 a | 2.1 a | 30.0 a | 3.4 ab | 40.6 a | 5.4 a |
| Linear | NS | NS | NS | NS | NS | NS | NS | NS |
| Quadratic | ** | ** | * | NS | NS | NS | NS | NS |

[1] Location and protection. RS = Rain Shelter, PD = Planting Date; [2] Soil moisture level depleted to in percent of Field Capacity until irrigated back to field capacity

[3]DAP = Days after Planting

[4,5] Orthogonal contrasts. Irrigation treatment effects on plant height are significantly linear or quadratic at the *0.05 level, **0.01 level, *** 0.001 level, or are not significant NS.

[6]Mean separation by Tukey's HSD. Means followed by the same letter are not significantly different at the 0.05 level.

The formation of pseudo-stems involves tightly parking the erect leaf sheaths, coiled together then forming the erect organ which holds the leaves upright and aids effortless inter-organ conduction of resources. Pseudo-stems' fresh weight is a function of their height, and girth which are collectively influenced by nutrition and prevailing environmental conditions.

Pseudo-stems' dry weight is a function of its fresh biomass accumulated during growth and development. Higher leaf weight translates to higher growth and increased biomass accumulation around the sheets as in the case of Newark open fields and 80% irrigation treatments.

Matured (mother) rhizomes fresh and dry weight**.**

Only location (0.0001) and days after planting (0.0037) had a significant effect on the fresh and dry weight of mother rhizome, there was no irrigation treatment effect influencing the mother rhizome's fresh weight (data not shown).

The matured rhizomes functioned as seed pieces used to initiate the growth of new ginger plantlets. The plantlets exploited the reservoirs in the rhizomes as they sprouted until they were independent by developing their own roots. The fertile clayed soils in Newark open field provided the new plantlets with enough resources to increase their growth rate after transplanting, thus the rhizomes remained unexploited, as with the case of 80% irrigation which had abundant resources.

Higher dry weight of mother rhizomes in Newark open fields translates to higher resource conservation potential within the rhizomes, acquired from the resource dense growing environment thus the new plantlets did not over exhaust reserved resources from the mother rhizomes.

Baby rhizome fresh and dry weight

Baby rhizome fresh and dry weight was highly influenced by d irrigation treatment (Table 2.2). There was 20 – 30 times increase in fresh weight moving from 30 days after planting to 120 days after planting in all locations (Table 2.7).

There was an increase in immature rhizome weights in all 3 protected sites with an increase in irrigation and effects were significantly linear and quadratic. The 2 field sites had more variable responses. Dry weights 120 DAP in both open field tests were significantly lower in the 80% irrigation treatment. Rhizome fresh weights ranged from 64 g to 526 g 120 DAP and rhizome dry weights ranged from 6 g to 77 g. Rhizome dry weights were proportionally highest in the Georgetown field site when compared to fresh rhizome weights (Table 2.7).

Rhizomes play a functional role of storing carbohydrates and nutrients in plants, they supply oxygen to the roots, and stabilize the plant in its environment. Ideally, rhizomes are used to store starches, proteins, and other food reserves to enable plants to perennate or survive an annual unfavorable season underground. Ginger rhizome development in Newark clay soils superseded Georgetown's sandy soils. High irrigation frequencies 80% boosted rhizome formation compared to drought-stressed irrigation treatments 20%.

Succulency level (water content) in the developing rhizomes was high (90 – 97) % when plants were younger at 2 – 3 months but decreased with maturations (75 – 85) % when plants reach 4 – 5 months. As rhizomes grow and age, the water content declines and is replaced by fibers, and other bio-compounds.

Table 2.7: The effect of irrigation, and days after planting (DAP) on baby rhizome fresh and dry weight of ginger by location. Delaware Trials, 2022.

| Location/Irrigation[1] | 30 DAP[3] | | 60 DAP | | 90 DAP | | 120 DAP | |
|---|---|---|---|---|---|---|---|---|
| | Fresh wt.(g) | Dry wt.(g) | Fresh wt.(g) | Dry wt.(g) | Fresh wt.(g) | Dry wt.(g) | Fresh wt.(g) | Dry wt.(g) |
| Newark Tunnel | | | | | | | | |
| 20[2] | 10.0 c[6] | 0.5 c | 31.2 c | 1.8 c | 53.9 c | 3.2 c | 64.4 d | 3.8 d |
| 40 | 36.6 b | 2.1 b | 56.3 b | 3.3 b | 104.7 c | 6.3 c | 142.2 c | 8.6 c |
| 60 | 37.5 b | 2.2 b | 59.8 b | 3.6 b | 199.4 b | 12.1 b | 236.2 b | 14.3 b |
| 80 | 121.4 a | 7.3 a | 166.0 a | 10.0 a | 429.8 a | 26.1 a | 506.0 a | 30.8 a |
| Linear[4] | *** | *** | *** | *** | *** | *** | *** | *** |
| Quadratic[5] | *** | *** | *** | *** | *** | *** | *** | *** |
| Newark Field | | | | | | | | |
| 20 | 24.6 a | 1.7 a | 140.7 a | 21.1 a | 307.3 a | 47.6 a | 422.3 b | 77.4 a |
| 40 | 22.5 a | 1.6 a | 133.9 a | 17.9ab | 290.4 a | 37.4 b | 479.3 a | 68.8 ab |
| 60 | 21.8 a | 1.7 a | 132.6 a | 15.1 b | 287.0 a | 38.8ab | 450.1 ab | 73.5ab |
| 80 | 21.0 a | 1.5 a | 131.1 a | 21.1 a | 283.3 a | 34.0 b | 466.5 ab | 58.2 b |
| Linear | NS | NS | NS | NS | NS | NS | NS | * |
| Quadratic | NS | NS | NS | NS | NS | * | NS | NS |
| Gtown RS PD1 | | | | | | | | |
| 20 | 38.6 b | 3.3 b | 64.1 b | 4.9 b | 72.8 d | 6.2 c | 76.0 c | 6.3 d |
| 40 | 7.2 c | 0.6 c | 12.3 c | 0.8 c | 311.1 a | 28.1 a | 516.3 a | 44.6 a |
| 60 | 59.5 a | 5.3 a | 97.0 a | 7.8 a | 138.0 c | 13.7 b | 247.6 b | 20.9 c |
| 80 | 56.5 a | 4.9 a | 95.2 a | 8.1 a | 283.9 b | 25.9 a | 497.0 a | 39.7 b |
| Linear | *** | *** | *** | *** | *** | *** | *** | *** |
| Quadratic | *** | *** | *** | *** | ** | ** | *** | *** |
| Gtown RS PD2 | | | | | | | | |
| 20 | 39.8 b | 3.0 b | 69.4 b | 7.0 a | 73.1 | 6.3 d | 70.8 c | 6.1 c |
| 40 | 6.7 c | 0.4 c | 56.6 b | 4.8 b | 269.1 | 22.4 b | 463.9 a | 43.8 a |
| 60 | 64.2 a | 4.9 a | 97.9 a | 8.6 a | 145.5 | 12.1 c | 222.9 b | 17.9 b |
| 80 | 61.8 a | 5.3 a | 98.2 a | 8.5 a | 294.1 | 24.5 a | 495.3 a | 41.5 a |
| Linear | *** | *** | *** | *** | *** | *** | *** | *** |
| Quadratic | *** | *** | *** | *** | *** | *** | *** | *** |
| Georgetown Field | | | | | | | | |
| 20 | 20.6 ab | 2.3 ab | 47.8 a | 8.6 a | 75.0 a | 15.1 a | 102.2 a | 21.5 a |
| 40 | 19.7 b | 2.1 b | 45.7 a | 7.7 ab | 71.7 a | 14.2 a | 97.7 a | 20.8 a |
| 60 | 26.6 a | 2.8 a | 49.9 a | 8.2 ab | 73.1 a | 14.1 a | 96.4 a | 20.6 a |
| 80 | 24.4 ab | 2.1 b | 48.6 a | 6.0 b | 72.9 a | 10.4 a | 97.1 a | 14.7 a |
| Linear | * | NS | NS | * | NS | * | NS | * |
| Quadratic | ** | NS | NS | NS | NS | NS | NS | NS |

[1] Location and protection. RS = Rain Shelter, PD = Planting Date; [Gtown]=Georgetown, [2] Soil moisture level depleted to in percent of Field Capacity until irrigated back to field capacity[3]DAP = Days after Planting

[4],[5] Orthogonal contrasts. Irrigation treatment effects on plant height are significantly linear or quadratic at the *0.05 level, **0.01 level, *** <0.001 level, or are not significant NS. [6]Mean separation by Tukey's HSD. Means followed by the same letter are not significantly different at the 0.05 level.

Root fresh and dry weight

Irrigation treatment had highly significant effects on root fresh and dry weights (Table 2.3). Root weights followed similar trends to other growth measurements with the protected sites responding to irrigation treatments and field sites showing little response.

Roots anchor the plant and provide physical support as well as absorption of resources from the soil (water and dissolved minerals) and conduction to the stem. Root fresh weight varies significantly as affected by temperature, humidity, and time from extraction.

The presence of lavish growth conditions or scarce resources stimulates roots dry weight. Lavish conditions trigger plants to grow in accordance with their biology and genetic make-up. Scarce conditions stimulate roots to overstretch in search of resources, thus high dry weight.

Primary, secondary, tertiary, and quaternary fingers

Primary, secondary, tertiary, and quaternary fingers results are presented in Location and irrigation treatment had the highest influence on the score of primary, secondary, and tertiary fingers (Table 2.3). There was a linear and quadratic response for primary fingers in the Newark Tunnel and Georgetown RS PD1. Primary fingers increased with increasing irrigation. Secondary fingers did not vary across irrigation treatments.

Primary rhizomes (fingers) develop directly from the mother rhizomes and their development denotes the initial rhizome development immediately after crop establishment. They bear more than 50% of the total roots and age faster compared to other finger categories. Secondary fingers anchor on the primary fingers and are the

extension of primary rhizome growth. They hold a fraction of the remaining roots and most of the pseudo-stems.

Tertiary finger numbers increased with increasing irrigation in the Newark Tunnel, Georgetown RS PD1 and Georgetown field (Table 2.3) and were significantly linear and quadratic. The highest tertiary fingers counts were found in the Newark tunnel and Georgetown field. Irrigation treatment had limited effect on quaternary finger numbers. Highest numbers of quaternary fingers were found at the Newark field site.

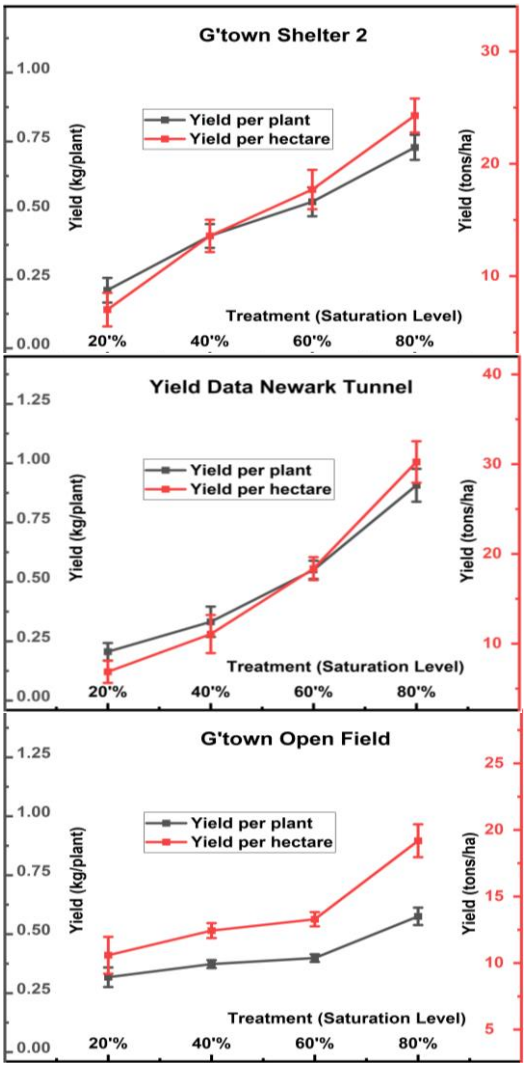
Tertiary fingers mark the beginning of the final exponential expansion of rhizomes, they barely have roots or shoots and make up most of the rhizome fraction when matured. During tertiary finger development, shoots and leaves cease to grow, allocating all resources for rapid rhizome expansion (Nair, 2019). Tertiary fingers have a reddish and whitish/yellowish color with high aesthetic gratification of marketable value when uprooted.

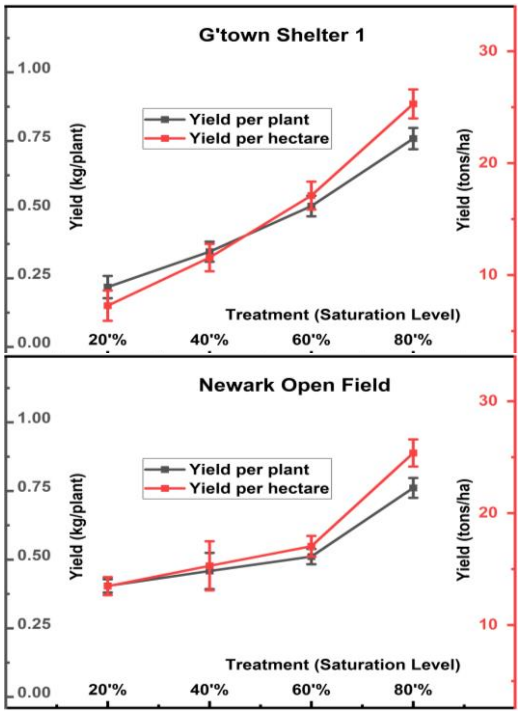
Quaternary fingers denote extended development of rhizomes. They typically begin developing on the $6^{th}$ month of cultivation, or five months provided there are abundant resources. The fingers are normally hindered by scarcity of resources and are the among the youngest category of rhizomes during harvest.

Yield data

Plots were harvested 135 days after planting. Irrigation treatment and had highly significant effects on yield per plant (Table 2.8). The Newark tunnel had a higher yield per plant, compared to the least productive experimental location at Georgetown open field. The multi-location yield potential ranged from 19.19 -- 30.24 tons $ha^{-1}$ exclusively from high irrigation frequency irrigation treatment (80%). The 80%

treatment had 2.7 x higher yield per plant than the 20% treatment There was an average increment of ≥ 1.3 x yield decrease as irrigation diminished in the following manner 80% > 60% > 40% > 20%. The Newark tunnel had both the highest yield per plant (0.91 kg/plant) obtained from 80% and the lowest recorded yield per plant (0.21 kg/plant) from 20% irrigation treatment. (Figure 2.1, Table 2.8).




**Summary of Fit**

| | |
|---|---|
| RSquare | 0.868469 |
| RSquare Adj | 0.826818 |
| Root Mean Square Error | 0.085939 |
| Mean of Response | 0.475594 |
| Observations (or Sum Wgts) | 80 |

**Effect Tests**

| Source | Nparm | DF | Sum of Squares | F Ratio | Prob > F |
|---|---|---|---|---|---|
| Location | 4 | 4 | 0.1244433 | 4.2124 | 0.0045* |
| Treatment | 3 | 3 | 2.4826845 | 112.0508 | <.0001* |
| Location*Treatment | 12 | 12 | 0.3188022 | 3.5971 | 0.0005* |

Figure 2.1: Yield response with respect to location and irrigation treatment. Delaware trials, 2022

Table 2.8. The effect of irrigation treatment on yield of baby ginger, Delaware trials 2022.

| Location | Average Yield (kg) 80% | Average Yield (kg) 60% | Average Yield (kg) 40% | Average Yield (kg) 20% |
|---|---|---|---|---|
| Newark Field | 0.76 a[1] | 0.51 b | 0.45 b | 0.40 b |
| Newark Tunnel | 0.91 a | 0.55 b | 0.33 bc | 0.21 c |
| Georgetown field | 0.57 a | 0.40 b | 0.37 b | 0.32 b |
| Georgetown RSPD 1 | 0.76 a | 0.51 b | 0.34 c | 0.21 c |
| Georgetown RSPD2 | 0.73 a | 0.53 b | 0.41 b | 0.21 c |

[1]Mean separation by Tukey's HSD at the 0.05 level. Means in the same row followed by the same letter are not significantly different.

Table 2.9: Linear and quadratic effects on the influence of soil-moisture levels on the yield of ginger per given location and $R^2$ values from the linear regression of yield on irrigation by location.

| Statistic | Newark Tunnel | Newark Field | Georgetown RS PD1 | Georgetown RS PD 2 | Georgetown Field |
|---|---|---|---|---|---|
| Linear Contrast | *** | *** | *** | *** | *** |
| Quadratic contrast | *** | ** | *** | *** | ** |
| R2 | 0.88 | 0.78 | 0.90 | 0.84 | 0.77 |

Orthogonal contrast for yields were significantly linear and quadratic at all sites (Table 2.9). The Newark sites and Georgetown Field site showed a marked curvilinear response with the largest increase in yield occurring from the 60-80% irrigation rates. This was less evident at the Georgetown Rain Shelter. $R^2$ values from linear regressions were 0.77 and 0.78 at field sites and 0.84, 0.88, and 0.89 at protected sites.

Ginger yield is among the important determinants of the commodity's end product (Kizhakkayil and Sasikumar, 2011), others being quality traits (such as essential oil, fiber and oleoresin contents) along with volatile and non-volatile

constituents. There was partial shading of plants in the tunnel and according to (Lv *et al.*, 2020), Shading significantly increased the expression of proteins related to the light harvesting complex, even under medium drought stress; thus plants were more productive especially when added high irrigation frequency treatmen80%). (Wilson and Ovid, 1993) obtained similar high yield response in shaded ginger plants. Contrastingly, (Xu et a*l.*, 2003) concluded that under normal water content, ginger grew better, and yield was higher in natural sunlight, while under water stress, ginger grew better and yield was higher in shading. With (Ahaiwe, 2009), fertility status of the soil resulted into higher yield. Balancing conditions in the production environment is vital to guarantee maximum yields; weed suppression had a significant high yield on ginger in an experiment by (Thankamani et al., 2016) on effect of mulches on weed suppression and yield of ginger. The total cultivation time in the field has a tremendous influence on the final yield; (Sideman, 2018) experienced a significant yield reduction (twice) from a two months' early harvest plan in baby ginger.

Weather data

There was sufficient warmth from May to October for ginger growth (Figure 2.2) meaning that within the field there are 6 months suitable for field production. Within the tunnels there is a seasonal extension of about 2 more months enabling up to 2 cycles in the tunnel whereas only one cycle is possible in Delaware in the open field. There was uniform distribution of rainfall throughout the year enabling farmers to produce ginger in open fields with either minimal irrigation or without irrigation supplements (although supplemental irrigation produced the highest yields). Temperatures within the tunnel increased due to the amplification effects of plastic covering creating a very ideal condition for ginger growth and development. Ginger

performs best under high humidity levels which normally prevails within the Mid-Atlantic region. Soil temperatures attained a minimum stable threshold within the same warm months.

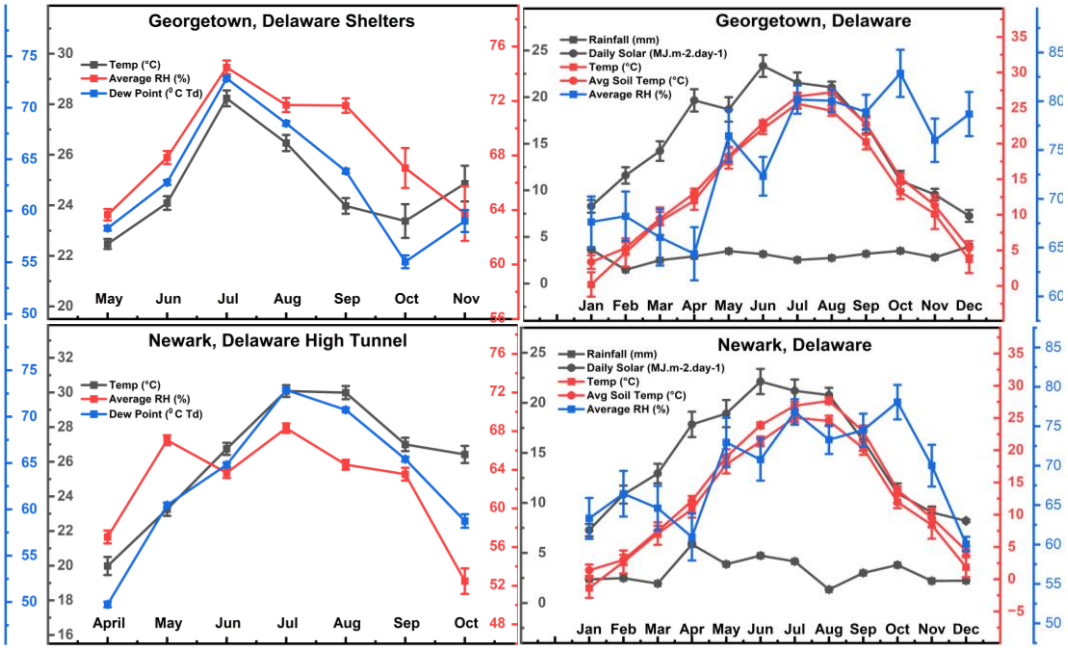



Figure 2.2. Prevailing weather conditions during the experimental duration, Delaware trials 2022.

## Conclusions

This research shows the potential for production of baby ginger in protected and unprotected culture under Delaware growing conditions at economically viable levels. All sites had a return of over 1:10 planted to harvested ginger. High levels of irrigation were needed to maximize yields.

## Acknowledgments

We would like to acknowledge the University of Delaware through the Department of Plant and Soil Sciences.

## Chapter 3.

## SUCCESSFUL GREENHOUSE CULTIVATION OF RHIZOMATOUS CROP GINGER (*Zingiber officinale*) IN HYDROPONICS AND SOILLESS MEDIA


### Abstract

Local baby ginger (*Zingiber officinale*) production enables fresh ginger availability with a reduced carbon footprint, adds economic sales for farmers and increases diversity within farms. Baby ginger are immature forms of ordinary ginger, requiring a 4–6-month cultivation cycle from the 8-12-month traditional cycle. Ginger is a heavy mineral nutrient feeder and requires hot and humid conditions for profitable growth and development. These conditions can be provided in protected greenhouse culture.

Multiple production trials were conducted in Fischer greenhouse laboratory complex at Newark, Delaware (DE) from February 2022 to February 2023 to assess the production potential in greenhouse culture. Ginger plants were grown in growth chambers for 12 weeks from organically sourced yellow ginger mother rhizomes. A section of plants was then transplanted and grown in randomized complete block design using soilless systems (modified hydroponics Kratky system and compost mixed with rice husks) and with different irrigation frequencies (T1-100%, T2-80%, T3-60%, T4-40%, and T5-20% minimum depletion before replenishments) during cultivation, while the other sections of plants were subjected to different pH, and electrical conductivity (EC) treatments.

Plant growth was assessed monthly for data collection, and then harvested at 5 months for the irrigation and hydroponic study and 3 months of monitoring and performance in varying pH and EC studies. Statistical analysis was performed on collected data. Irrigation frequency was directly proportional to ginger growth and

development (including tillering, leaf number, chlorophyll content, fresh and dry biomass, rhizome finger categorization, and final yield). Yield potential ranged from 3.5 – 43.9 tons $ha^{-1}$ with regards to irrigation frequency treatments. Ginger plants tolerated high EC of 4, low pH of 3 and high pH of 10, however extreme pH was detrimental to yield. Optimum EC was 3.0 and optimal pH was 6. Irrigation treatment did not significantly affect the stem diameter of the plants, leaf length and width in most of the cases. The modified hydroponics closed system (T1) had significant water conservation, 1 kg of ginger required 76.4 L of water compared to 310 L in a soilless open irrigation system (80%) under the same greenhouse conditions.

**Keywords**

Ginger, baby ginger, immature ginger, rhizomatous crop, hydroponics, Kratky system, soilless

**Abbreviations**

| | | |
|---|---|---|
| ANOVA – Analysis of variance | asl – above sea level | EC – Electrical conductivity |
| etc. - et cetera | ft – foot/feet | g – grams |
| IL – Illinois | INC – incorporation | L – liter |
| LED – light emitting diodes | mg – milligram | N – nitrogen |
| N – north | NPK – nitrogen phosphorus potassium | |
| PA – Pennsylvania | pH – potential of Hydrogen | |
| RCBD – randomized complete block design | | sq – square. |

W – west $^{0}$C – degree centigrade % - percentage # - number

## Introduction

Ginger is a perennial crop, often grown in tropical or sub-tropical regions annually for its edible rhizome, which grows and develops underground along the root collars. Ginger has different production seasons globally based on location and horticultural culture used. The height of ginger plants ranges from 60 - 120 cm under commercial settings (Suhaimi et al., 2012). Ginger is asexually propagated from a portion of the mature rhizome known as mother finger, sets or propagules.

Improving crop cultivation strategies by embracing ultramodern techniques corresponding to intensified production and sustainability is fundamental to nutritiously feeding the ever – increasing human population and earning more income for farmers to intimately sustain their households, provide raw materials for industrial manufactories (Diao et al., 2010) and contribute to economic growth (Whitaker and Coyler, 2021). Intensification strategies are also needed to account for diminishing arable lands which are transformed into settlement areas together with unstable climatic conditions which pose additional threat to agricultural production (Martinez-Feria and Basso, 2020).

Depletion of water as a natural resource is of global concern. Depletion results from overexploitation of water reserves more than its replenishment rate, divergence of water into agricultural farms, and overuse of feeder streams. The water quality in unreplenished reservoirs continually diminishes due to accumulation of more salts, rendering it unfit for agricultural use in long run (Cañedo-Argüelles et al., 2019; Cunillera-Montcusí et al., 2022). The World's major rivers and freshwater lakes often

have immensely reduced by volume over time (Abiodun et al., 2019; Martin et al., 2020). If overexploitation continues, we will encounter severe shortages of fresh water for agriculture soon. Arid and semi-arid regions without enough rainfalls will continue to overexploit their scarce water reservoirs unless relevant measures are taken; even so, arid regions will run out of water before the rest of the regions (Bozorg-Haddad et al., 2020).

The technology of ginger cultivation ranges from simple basic open field production, blended intermittent technologies, semi-advanced using high tunnels and highly sophisticated systems of controlled environment agriculture using indoor growing facilities, greenhouses, soilless media and hydroponics systems (Flores et al., 2021; Freyre et al., 2019; Marsh et al., 2021). Advanced agricultural production technologies come with added costs but the quality and quantity of their output is worthy especially for short season and high value crops (Kanika and Kumar, 2020).

Irrigation regime stands for the level of irrigation water applied to the field, ranging from 0 % to more than 100 % and irrigation frequency stands for the repetition of regimes. Irrigation regime includes full irrigation to 100%, deficit irrigation to 0-99% or even over irrigation 120%. Irrigation regimes and irrigation scheduling determines the frequency, amount and duration of watering available for crops *i.e.,* irrigation system (Gatabazi et al., 2019b). Frequency can be once, twice, thrice, or more per week. Ginger requires an estimate of 1420 mm of rainfall water for its entire crop cycle, increasing water supply increased yield of rhizome and essential oil content, but lowers the flavonoids, phenolic contents and antioxidation capacity (Gatabazi et al., 2022). The use of overhead irrigation protects the crop against sunburn by creating a microclimate around crops. Ginger loves high humidity and

moisture, but with unstable climates, it is difficult to sustain high soils-water potential by fully relaying on rain. Under ginger cultivation, the major constraints on yield and quality include water availability and plant nutrients (Gatabazi et al., 2019b; Meneghelli et al., 2020). It's highly ambiguous on how water affects the quality of ginger as there have been contradictory claims and conclusions on effects of soil moisture in different crops (Gatabazi *et al.*, 2022; Jabborova *et al.*, 2021; Keskin *et al.*, 2010; Onder *et al.*, 2005). Currently, there is a high rain fluctuation due to climate change across the world. Ginger irrigation under commercial setting is applicable in large producing countries including India, China, Nigeria, Indonesia, Nepal, and others. Water stress affects crops growth stages and physiological processes; sensitive growth stages being germination stage, rhizome initiation and rhizome development (Kandiannan, 2014). Overall there is a research gap on how different soil moisture levels affects ginger development (Gatabazi et al., 2019b).

Protected cultivation enhances off or extended season production of ginger. The use of hydroponics and aquaponics has also been integrated into ginger cultivation systems. Improved technology intensifies production, inducing higher quality and quantity output per area, enabling producers to mitigate dynamic production factors *i.e.* irrigation, water use and fertigation, pests and pathogens (Hayden, 2006; Hayden et al., 2004). Soilless and hydroponics crop production are continually emerging technologies allowing production without actual soils, and eliminate soil related production challenges (Hussain et al., 2014), improving resource sustainability and usability (Putra and Yuliando, 2015). Soilless and hydroponics crop production requires the addition of minimal mineral fertilizers to meet plants' nutritional demand. For soilless production, the fertilization program required is 400

mg $L^{-1}$ of N coupled with other nutrients (Verma et al., 2019b). 1.25 g $L^{-1}$ of NPK 12-4-16 is mixed with 0.34 g $L^{-1}$ of Magnesium sulphate which promotes ginger growth.

Hydroponics is mostly suited for short season crops completing their growth cycle within three months, with other systems used to produce determinate crops such as tomatoes, cucumbers, and sweet peppers. Ginger's long production duration and the underground location of its valuable plant part, hinders it from becoming a suitable candidate for hydroponics production, especially pure water culture (Hussain et al., 2014). Modifying the production facilities allows successful production of ginger crops under soilless cultures and increase the crop turnover with time and space (Nichols, 2012). During production, protected cultivation through greenhouses, high tunnels, screen houses, rain shelters, or indoor farms provides protection to crops from adverse environmental conditions of extreme temperatures, solar radiations, hailstorms, heavy rain and so forth (Nordey et al., 2017a, 2020c). The presence of such barrier between the crop and external environment creates microclimates that affects plant growth, development and yield (Knewtson et al., 2010; Nordey et al., 2020d), biotic stress of disease incidences and insect population dynamics (Lamont Jr., 2009; Nordey et al., 2020c, 2020d; Syed, 2006), allowing monitoring and management practices such as irrigation, lighting, and nutrition. Crops grown under protection have superior quality and higher productivity (Nordey et al., 2020d, 2020c) in several regions with extensive cropping seasons (Carey et al., 2009). In India, China, and Nepal ginger is being produced in pure water culture systems.

Water as a resource is becoming increasingly scarce worldwide (Okhravi *et al.*, 2019). Studies on crop water use efficiency and ample crop water requirements in relation to crop's sensitive growth stages, and productivity are paramount. Modern

technology, research and innovation allows significant increase of crop production and productivity by improving irrigation systems, production technology and infrastructure (Koutsos and Menexes, 2019; Yan et al., 2019). Soilless and hydroponics food production are among novel approaches toward sustainability and conservational usage of natural resources that can be applied to ginger production.

The overall objective of this study was to determine the optimum greenhouse condition of growth for rhizomatous plant ginger. The specific objectives were first, to determine the water use efficiency of immature (baby) ginger grown under a hydroponics closed system and soilless open irrigation systems and second, to test different pH and EC levels of nutrient solution at which ginger plant can develop well.

Greenhouses are often used to grow profitable crops *i.e.*, crops with actual high value such as flowers, crops with multiple annual turnover such as leafy greens or fruiting crops with multiple harvests such as tomatoes, peppers, and cucumbers. The 8 – 12-month mature ginger does not fit into in any of the mentioned categories, however, the 3 – 6-month baby ginger bears some qualifying attributes under modified production systems. The ability to produce baby ginger in greenhouses guarantees year-round production, especially in regions with extended off seasons such as temperate regions but also facilitates local production, cutting back the transportation carbon footprints. Soilless production avails interferences from soil born pests and diseases.

Testing different pH and electrical conductivity (EC) levels which ginger can grow, develop and yield is fundamental to reduce the need for constant pH and EC regulation during large scale production. Ginger's resilience to extreme environments reduces the likelihood of crop failure or poor performance during cultivation. Extreme

EC and pH are associated with reduced plant nutrient absorption ability in their growing environments.

## Materials and methods

### Location

All greenhouse trials were conducted in the United States of America (Delaware state). The experiments involved usage of growth chamber and greenhouse. All research facilities are in University of Delaware main campus-Newark (39.6780° N, 75.7506° W, 448 ft asl). The experiments were conducted from February 2022 to February 2023.

### Layout and design

For greenhouse growing experiment, the experimental design was randomized complete block design (RCBD) with five treatments and four replications, thus 20 experimental units. EC and pH were under the same experimental design (RCBD) and had 5 treatments and 4 replications, thus 20 experimental units each. For soilless culture, plants were grown in plastic bin 60 cm x 40 cm x 18 cm filled with a 50:50 blend of rice husks and compost. The hydroponic system was pot in bucket with reservoir, pot filled with sharp sand.

### Plant material and propagation

Disease free, organically grown, mature yellow ginger rhizomes imported from Peru served as the initial planting material. We then split the mother rhizomes into sets (propagules) weighing 45 – 60 g with at least 2 – 3 visible nodes (eyes). The sets were surface sterilized using 10% ZeroTol HC (from BioSafe Systems 22 Meadow Street, East Hartford, CT 06108 containing 5.34% Hydrogen peroxide and 1.36%

Peroxyacetic acid) for 15 minutes, then cured for 3 days at room temperature. Potting proceeded in 10.16 × 10.16 square cm pots using pro-mix growing media (from Premier Technology Limited, 1, avenue Premier, Campus Premier Tech, Rivière-du-Loup (Québec), Canada G5R 6C1; containing sphagnum peat moss 85%, coco coir fiber 5%, perlite 5%, ground limestone 3%, and wetting agent 2%). These were then incubated in growth chamber (Chamber #6 - Conviron walk in model # C- 10 10 M 96 ft./sq. shelve space Lumigrow Lumibar L.E.D. lights Temperature, light and humidity control) set at 28 $^{0}$C, 60 % RH, and 14 hours for temperature, humidity, and photoperiod, respectively. Raising seedlings took an average of two months, irrigation was done twice – three times a week, and fertigation bi-weekly using a 12-4-16 NPK fertilizer (JR PETERS INC 6656 Grant Wat, Allentown, PA 18106) and Epsom salt (Magnesium sulphate from JR PETERS INC) at dissolution rate of 1.05 and 0.29 g $L^{-1,}$ respectively. Air fans were used to circulate air inside the chambers. Desired seedlings were 30 – 50 cm (1 – 1.5 ft) tall with 2-3 tillers.

Treatments

For greenhouse growing experiments, treatments were soilless moisture levels based on allowable minimum moisture level before replenishments, and included hydroponics/modified Kratky system or 100% (medium moisture kept at 100%), high irrigation frequency or 80% (medium moisture bandwidth ranged from 100 – 80%), medium irrigation frequency or 60% (medium moisture bandwidth ranged from 100 – 60%), medium-low irrigation frequency or 40% (medium moisture bandwidth ranged from 100 – 40% and it served as control) and low irrigation frequency or 20% (medium moisture bandwidth ranged from 100 – 20%).

EC treatments were 0.5, 1, 2, 4 and 6; experimental setup for EC treatments involved the fertilizer combinations of part A (NPK 12-4-16) and part B (Magnesium sulphate/Epounces)) dissolved in 3.785 L (1 gallon) of reserve osmosis water at a weight (grams) rate of; 1. EC of 0.5 ± 0.1 (1.2 g (0.041675 ounces) and 0.32 g (0.0113 ounces)), 2. EC of 1 ± 0.1 (2.4 g (0.08335 ounces) and 0.64 g (0.0226 ounces)), 3. EC of 2 ± 0.1 (4.73 g (0.1667 ounces) and 1.3 g (0.0452 ounces)), 4. EC of 4 ± 0.1 (9.45 g (0.3334 ounces) and 1.28 g (0.0904 ounces)), 5. EC of 6 ± 0.1 (18.9 g (0.6668 ounces) and 5.13 g (0.1808 ounces)); EC of 2 ± 0.1 served as control.

For the pH treatments, the experimental setup involved the fertilizer combinations of part A (NPK 12-4-16) and part B (Magnesium sulfate/Epsom salt) dissolved in 3.785 L (1 gallon) of reserve osmosis water at a rate of 4.73 g (0.1667 ounces) and 1.3 g (0.0452 ounces) respectively, then Phosphoric acid and potassium carbonate were used to adjust the pH to desired ranges. Target pH values were 1. pH of 2 ± 0.1, 2. pH of 4 ± 0.1, 3. pH of 6 ± 0.1, 4. pH of 8 ± 0.1, and 5. pH of 10 ± 0.1; pH of 6 ± 0.1 served as control.

## Data collection and analysis

For greenhouse growing experiments, there were three major categories of data collected: 1. non-destructive data, 2. destructive data, 3. associated data of irrigation, media moisture levels, and indoor climate. Non-destructive data for greenhouse growing experiments was collected once per month in 4 plants per experimental unit, permanently marked for phenological observations and counts of tillers and leaves number, linear measurements of plant height, main stem width, $5^{th}$ leaf length, $5^{th}$ leaf width, and chlorophyll quantifications. Destructive measurements were collected once

per month in 1 plant uprooted per experimental unit: relevant data being fresh and dried biomass, chlorophyll quantification (Chlorophyll meter, MC 100, Apogee instruments Inc., 721 West 1800 North Logan, UT 84321 U.S.A), leaf and tillers counts, linear measurements of plant height, plant stem width, $5^{th}$ leaf length, $5^{th}$ leaf width; and categorization of rhizome fingers and final yield data. Irrigation dates and amount of water applied were recorded; media moisture levels were monitored through gravimetric (weighing dried media in trays, deducing the amount of water present, equivalent to amount of weight when saturated. Weather data was obtained from weather stations (Delaware Environmental Observing System, http://www.deos.udel.edu/data/agirrigation_retrieval.php), light meters (LightScout DLI 100 from spectrum technologies, Spectrum Technologies, 3600 Thayer Court, Aurora, IL 60504), digital data loggers (WatchDog A-Series Loggers, Spectrum Technologies, 3600 Thayer Court, Aurora, IL 60504) which recorded temperature and humidity every 30 minutes.

Data collection for pH and EC experiments was on a weekly basis, involving adjustments of nutrient solution's pH, and EC, coupled with monthly data collection of vegetative growth: leaf number, shoot/tiller number, plant height, plant stem width, leaf chlorophyll concentration and physiological abnormalities. The final biomass data was obtained by uprooting the entire plant and weighing the plant parts, and the associated data of weather parameters *i.e.*, temperature, humidity, and light quantity within the growing period was obtained.

All the data was subjected to analysis of variance by using JMP® version 16.1 (100 SAS Campus Drive, Cary, NC 27513, USA). ANOVA (analysis of variance) was used to determine the significance of main effects and interactions. ANCOVA was

used to remove and reduce the impact of noise from dependent variables amongst the different means. The means were separated and then compared using the Tukey's HSD test at 5% probability. Orthogonal contrasts were used to determine linear and quadratic relationships where appropriate. Regressions among the parameters were constructed using JMP®.

## Results and Discussion

### Experiment I (greenhouse production)

Tests of significance from the Analysis of Variance (ANOVA) for main effects and interactions are presented in Tables 1, 2, and 3 for parameters measured.

Table 3.1: ANOVA tests of the effect of irrigation/hydroponic treatments on plant height, tillers, stem diameter, leaf number, leaf length and width and chlorophyll content by season.

| | Plant height (cm) | Tillers (no.) | Stem Diameter (mm) | Leaf (no.) | Leaf Length (cm) | Leaf width (cm) | Chlorophyll Concentration μmol $m^{-2}$ |
|---|---|---|---|---|---|---|---|
| Season 1 | <.001 | <.001 | 0.012 | <.001 | 0.049 | 0.936 | <.001 |
| Season 2 | <.001 | <.001 | 0.101 | <.001 | 0.074 | 0.578 | <.001 |

Table 3.2: ANOVA tests of the effects of irrigation and hydroponic treatments on leaf (L), pseudo stem (Ps), and baby rhizome (Br) fresh and dry weights by season.

| | L fresh weight (g) | L Dry Weight (g) | Ps Fresh weight (g) | Ps Dry weight (g) | Br Fresh Weight (g) | Br Dry Weight (g) |
|---|---|---|---|---|---|---|
| Season 1 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 |
| Season 2 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 |

Table 3.3 Table: ANOVA tests of irrigation and hydroponic treatments on root fresh and dry weight and primary secondary, tertiary, and quaternary finger numbers by season.

| | Root Fresh Weight (g) | Root Dry Weight (g) | 1º Fingers (no.) | 2º Fingers (no.) | 3º Fingers (no.) | 4º Fingers (no.) | Yield data (kg) |
|---|---|---|---|---|---|---|---|
| Season 1 | <.001 | <.001 | 0.073 | 0.049 | <.001 | <.001 | <.001 |
| Season 2 | <.001 | <.001 | 0.613 | <.001 | <.001 | <.001 | <.001 |

Plant height and Tiller Numbers

Irrigation and hydroponic treatments were significant for both plant height and tiller number (Table 3.1).

Plants were taller in season 2 than in season 1. In season 1 there was a significantly linear response of height to irrigation level at all DAP. Height at 120 DAP were 14.7, 35.0, 38.2, 40.0, and 51.5 cm from irrigation levels of 20, 40, 60, 80 and 100, respectively. In season 2 there was also a significantly linear response to

irrigation level in 30, 60, and 120 DAP. At 120 days height ranged from 35.3 to 190.7 cm from low to high water level.

Tiller numbers were greater in season 2 than in season 1. Tiller numbers did not differ by treatment in Season 1 until 90 and 120 DAP where a linear increase was seen with water availability ranging from 3.2 to 15.2 from 20 to 100 % water treatments. In Season 2 tiller number followed a similar trend ranging from 6.5 to 33.0.

Table 3.4: The effect of irrigation, and days after planting (DAP) on the height and tillers number of ginger grown in Fischer greenhouse by season. Delaware Trials, 2022.

| Season/Irrigation[1] | 30 DAP[3] | | 60 DAP | | 90 DAP | | 120 DAP | |
|---|---|---|---|---|---|---|---|---|
| Season 1 | Height (cm) | Tillers (no) | Height (cm) | Tillers (no) | Height (cm) | Tillers (no) | Height (cm) | Tillers (no) |
| 20[2] | 21.4 b[6] | 4.0 a | 32.0 a | 5.0 a | 27.8 c | 3.3b | 14.8 cb | 3.35 d |
| 40 | 24.3 b | 4.3 a | 34.9 a | 5.8 a | 32.5 bc | 5.8 ab | 35.0 b | 6.5 cd |
| 60 | 25.5 ab | 5.5 a | 33.9 a | 7.3 a | 33.0 abc | 6.8 ab | 38.3 b | 9.0 bc |
| 80 | 27.2 ab | 5.3 a | 34.0 a | 7.0 a | 39.3 ab | 6.5ab | 40.0 b | 10.0 b |
| 100 | 35.4 a | 5.9 a | 44.8 a | 7.4 a | 41.3 a | 9.5 a | 51.5 a | 15.3 a |
| Linear[4] | ** | NS | * | NS | *** | ** | *** | *** |
| Quadratic[5] | NS | NS | NS | NS | NS | NS | ** | * |
| | | | | | | | | |
| Season 2 | | | | | | | | |
| 20[2] | 32.2 b | 4.5 b | 29.6 c | 4.8 cd | 32.5 c | 5.8 cd | 35.4 d | 6.5 c |
| 40 | 37.4 b | 3.3 b | 40.2 c | 3.5 d | 49.4 c | 4.5 d | 58.5 d | 5.5 c |
| 60 | 63.5 a | 9.0 ab | 71.2 b | 11.5 bc | 89.6 b | 14.3 bc | 108.0 c | 17.3 b |
| 80 | 64.1 a | 12.8 a | 80.9 b | 16.3 ab | 108.5 b | 20.5 ab | 113.0 b | 24.3 ab |
| 100 | 76.1 a | 13.8 a | 105.8 a | 20.0 a | 118.3 a | 26.3 a | 129.7 a | 33.0 a |
| Linear[4] | *** | *** | *** | *** | NS | NS | *** | NS |
| Quadratic[5] | * | NS | * | NS | * | NS | * | NS |

[1] Irrigation frequency and season, PD = Planting Date; 2 Soil moisture level depleted to in percent of Field Capacity until irrigated back to field capacity or grown hydroponically (100) [3]DAP = Days after Planting.,[5] Orthogonal contrasts. Irrigation treatment effects on plant height are significantly linear or quadratic at the *0.05 level, **0.01 level, ***0.001 level, or are not

significant NS.[6]Mean separation by Tukey's HSD. Means followed by the same letter are not significantly different at the 0.05 level.

from low (20%) to high (100%) water, respectively. Height is genetically controlled, in some plants, height-related traits including plant height and internode number are tightly linked with biomass, planting density, and yield in the field (Zhou et al., 2018). Plant height is similarly affected by nutrient availability, nutrients are readily available in dissolved states, thus requiring water in the growing media. This explains the superior performance of treatments with high water saturation levels. Sufficiency of nitrogen positively affects plant height while chromium at toxic levels has a negative impact (Osco et al., 2020).

Leaf number and Chlorophyll concentration

Season, treatment, days after planting, and all their interaction had significant effects on leaf numbers and chlorophyll concentration, with exceptions of the two-way interaction between season and days after planting, and the three-way interaction for leaf number (Table 1). Lower chlorophyll concentration values were recorded under lower irrigation frequency treatments throughout the course of sampling in both seasons. On the 120 DAP, the chlorophyll concentration was 6, 10, 14, 18, and 29: 6, 12, 17,19, and 25 for 20%, 40%, 60%, 80%, and 100% irrigation treatments in seasons 1 and 2 respectively (Table 3.5). There was an increase in chlorophyll concentration with an increase in water availability in the two seasons and the response was significantly linear and quadratic (Table 5). Leaf number had a linear relationship with increasing irrigation frequency; at the final data collection (120 DAP), leaf number ranged from 37 – 174 in season 1 and 37 – 354 in season 2 (Table 3.5).

Our data indicate that water-induced stress significantly affected leaf number in ginger. Moisture stress leads to increased stomatal resistance, increased stomatal diameter, and fewer developing leaves (Tibbitts and Bottenberg, 1976) Both (Tollenaar and Hunter, 1983) argued that temperature and photoperiod are the two environmental variables that were known to affect leaf number, (Kiniry, 2015) later advanced and supported their claims.

Measurement of chlorophyll concentration in plants is an in-depth determination of photosynthesis efficiency and health of plants (Yin et al., 2021a). Chlorophyll concentration in ginger is readily affected by extent of salinity in the growing environment (Mostajeran et al., 2014; Yin et al., 2021a); foliar spraying of elicitor compounds (Ghasemzadeh and Jaafar, 2013) (Sivaranjani et al., 2022),

Drought stress significantly reduces the quantum efficiency of photosystems, and photochemical quenching, while simultaneously increasing non-photochemical quenching (Lv et al., 2020). High chlorophyll concentration translates to higher photosynthetic rate capacity, which positively influences total soluble carbohydrates and total phenolics within ginger plants (Ghasemzadeh and Jaafar, 2013). Nutrient availability and environmental stresses such as drought, salinity, cold and heat among others affect leaf chlorophyll content (Palta, 1990). Beneficial microbes such as *Bacillus endophyticus* and arbuscular mycorrhizal fungi significantly increase chlorophyll content in ginger when used during cultivation (Jabborova et al., 2022)

Table 3.5: The effect of irrigation, and days after planting (DAP) on leaf number and chlorophyll concentration of ginger grown in Fischer greenhouse. Delaware Trials, 2022.

| Season/Irrigation[1] | 30 DAP[3] | | 60 DAP | | 90 DAP | | 120 DAP | |
|---|---|---|---|---|---|---|---|---|
| Season 1 | Leaf (no) | Chloro-phyll | Leaf (no) | Chloro-phyll | Leaf (no) | Chloro-phyll | Leaf (no) | Chloro-phyll |
| 20 | 34 c | 9.5 c | 45 c | 14.5 b | 37 b | 10.7 c | 37 d | 5.6 d |
| 40 | 28 c | 10.8 bc | 69 b | 12.2 c | 80 ab | 11.2 c | 72 c | 10.0 cd |
| 60 | 49 b | 11.5 b | 75 ab | 15.5 b | 97 ab | 15.1 b | 107 b | 13.6 bc |
| 80 | 41 b | 11.0 b | 81 ab | 16.1 b | 114 a | 17.8 b | 128 b | 18.1 b |
| 100 | 62 a | 14.1 a | 82 a | 23.0 a | 120 a | 27.9 a | 174 a | 28.8 a |
| Linear | NS | * | * | *** | NS | *** | *** | *** |
| Quadratic | NS | NS | NS | NS | NS | NS | * | * |
| | | | | | | | | |
| Season 2 | | | | | | | | |
| 20 | 26 c | 5.9 e | 29 c | 5.4 e | 34 c | 5.1 e | 37 c | 6.0 d |
| 40 | 24 c | 10.7 d | 31 c | 12.2 d | 39 ac | 11.5 d | 46 c | 12.1 c |
| 60 | 112 b | 16.6 c | 132 b | 17.6 c | 154 b | 17.0 c | 175 b | 16.9 b |
| 80 | 112 b | 19.1 b | 148 b | 19.8 b | 186 b | 19.9 b | 224 b | 18.6 b |
| 100 | 184 a | 25.2 a | 240 a | 24.4 a | 297 a | 24.6 a | 354 a | 24.5 a |
| Linear | *** | *** | *** | *** | *** | *** | *** | *** |
| Quadratic | NS | *** | NS | *** | NS | *** | NS | ** |

[1] Irrigation frequency and season, PD = Planting Date; 2 Soil moisture level depleted to in percent of Field Capacity until irrigated back to field capacity or grown hydroponically (100)
[3]DAP = Days after Planting
[4,5] Orthogonal contrasts. Irrigation treatment effects on plant height are significantly linear or quadratic at the *0.05 level, **0.01 level, ***0.001 level, or are not significant NS.
[6]Mean separation by Tukey's HSD. Means followed by the same letter are not significantly different at the 0.05 level.

Fifth leaf length and width

Leaf length and leaf width were only influenced by seasonal effects (Table 3.1). Leaf size is attributed to several environmental factors, nutrition deficiencies of calcium limit complete development of the leaves. (Garrido et al., 2014) explained how salt stress induces physiological, phytochemical, and structural changes of leaves. There is genotypic variation in plants' leaf area, partially influenced by geographical location. Members in family Zingiberaceae have leaf width traits adjoined with traits

for weights, number of primary rhizomes or rhizome length at both genotypic and phenotypic levels, these traits are ambiguously yielding attributing with a positive and significant correlation at genotypic level (Gupta et al., 2016)

Stem diameter

For stem diameter, significant influences came from the seasonal effect (Table 3.1). There was a minimal effect on stem diameter attributed from irrigation treatment effect in season 1, season 2 did not have any significant differences.

Change in pseudo stem width appraises crop growth, it's a function of leaf numbers and is used as a growth index in some crops (Holder and Gumbs, 1982). Higher pseudo stem diameters guarantee rigidity and ability to withstand external pressure without logging or breaking. Compost and bio fertilizers (phosphorein – effective microorganisms - *Minia azoteine* and their combinations) application are reported to influence stem diameter in pseudo stem crops (Abdou et al., 2020)

Leaf fresh and dry weight

Leaf fresh and dry weight was influenced by season, irrigation frequency treatment, days after planting, and all the two-way interactions from the factor variables except treatment interacting with days after planting for leaf dry weight (Table 2). Leaf weights increased with increasing water in both seasons and were significantly linear (Table 8). Overall, season 2 had higher leaf weights in grams (62 – 392) compared to season 1 (30 – 136) at the final sampling date (120 DAP).

Leaves are plants factories, harnessing sunlight, and fixing Carbon dioxide into carbohydrates. Availability of water influences overall plant development including

leaf formation. Light quality affects plant leaf's fresh weight (Zhang et al., 2015), similarly with the cultivar or varietal differences (Yoder and Davis, 2020), fertilization use especially, slow-release ammonium- and potassium-loaded zeolite fertilizer (Li et al., 2013), prolonging ultraviolet-A irradiation throughout the growth cycle (Gao et al., 2022).

Apart from irrigation frequencies, other factors that influence leaf dry matter in ginger includes high carbon dioxide concentrations (Ghasemzadeh and Jaafar, 2011) and interactive effect of salicylic acid which affects total dry weight (Ghasemzadeh and and Jaafar, 2013)

Table 3.6: The effect of irrigation, and days after planting (DAP) on leaf fresh and dry weight of ginger grown in Fischer greenhouse. Delaware Trials, 2022.

| Season/Irrigation[1] | 30 DAP[3] | | 60 DAP | | 90 DAP | | 120 DAP | |
|---|---|---|---|---|---|---|---|---|
| Season 1 | Leaf Fresh weight (g) | Leaf Dry weight (g) | Leaf Fresh weight (g) | Leaf Dry weight (g) | Leaf Fresh weight (g) | Leaf Dry weight (g) | Leaf Fresh weight (g) | Leaf Dry weight (g) |
| 20[2] | 22.2 c | 1.0 bc | 25.8 b | 1.1 b | 23.0 d | 1.0 b | 29.8 d | 1.2 d |
| 40 | 21.8 c | 0.9 c | 42.4 ab | 1.8 ab | 42.6 c | 1.8 b | 57.3 c | 2.4 c |
| 60 | 34.2 b | 1.4 b | 50.8 a | 2.1 a | 56.3 b | 2.4 ab | 73.8 bc | 3.1 bc |
| 80 | 28.0 b | 1.2 b | 50.8 a | 2.1 a | 63.5 b | 2.7 ab | 92.8 b | 3.9 b |
| 100 | 44.1 a | 1.8 a | 59.0 a | 2.4 a | 90.0 a | 3.8 a | 136.0 a | 5.7 a |
| Linear[4] | NS | NS | ** | ** | ** | ** | *** | *** |
| Quadratic[5] | NS | NS | NS | NS | NS | NS | NS | NS |
| | | | | | | | | |
| Season 2 | | | | | | | | |
| 20[2] | 11.2 c | 1.0 c | 38.3 d | 2.9 e | 60.3 c | 4.5 c | 61.6 d | 4.7 c |
| 40 | 9.3 c | 0.5 c | 65.1 c | 4.2 d | 57.7 c | 3.7 c | 67.8 d | 4.4 c |
| 60 | 77.0 ab | 4.9 b | 169.2 b | 11.1 bc | 261.1 ab | 16.9 b | 196.0 c | 13.2 b |
| 80 | 65.6 b | 4.3 b | 207.6 a | 14.2 b | 210.3 b | 14.1 b | 234.1 b | 15.9 b |
| 100 | 152.8 a | 11.6 a | 274.4 a | 20.0 a | 330.8 a | 25.0 a | 391.8 a | 29.9 a |
| Linear | *** | *** | *** | *** | *** | *** | *** | *** |
| Quadratic | NS | NS | NS | NS | NS | NS | NS | NS |

[1] Irrigation frequency and season, PD = Planting Date; 2 Soil moisture level depleted to in percent of Field Capacity until irrigated back to field capacity or grown hydroponically (100)
[3]DAP = Days after Planting
[4,5] Orthogonal contrasts. Irrigation treatment effects on plant height are significantly linear or quadratic at the *0.05 level, **0.01 level, ***0.001 level, or are not significant NS.
[6]Mean separation by Tukey's HSD. Means followed by the same letter are not significantly different at the 0.05 level.

Pseudo stem fresh and dry weight

Pseudo stem fresh and dry weight were significantly affected by irrigation and hydroponic treatment (Table 3.2). There was a large fresh weight difference with respect to irrigation treatments throughout all sampling dates, with higher weights coming from high irrigation frequency treatments. Fresh pseudo stem weight (g) on the final sampling date (120 DAP) ranged from 68 – 289 for season 1 and 31 to 400 for season 2. All linear

contrasts were significant for seasons 1 and 2 (weight increased linearly with increasing water) with a few exceptions, but none of the quadratic contrasts were significant.

Water is a key factor in plant growth and development, growing the environment plays a crucial role in the quality development of other pseudo stems in crops. Saran et al., (2019) presented how different shade-net intensities affect asparagus stem development, favoring the no to low shade treatment, unlike ginger which is a shade-loving crop.

Mother rhizome fresh and dry weight

100% and 80% water treatments conserved the weight of mother rhizomes compared to the rest the of treatments which had different drought stress levels.

The mother rhizomes are plant materials used to initiate a new generation of plants; they contain reservoirs to trigger the spouting of new tillers. Once a tiller is formed, it quickly produces its own roots immediately and becomes independent from its mother rhizome although remains attached together. The mother rhizomes' dry weight resembled that of an ordinary matured ginger since neither deposition made into the rhizomes, nor severe depletion of its reserves. New plantlets become readily independent after root setting, which is the initial developmental stage.

Baby rhizome fresh and dry weight

The development of baby rhizomes was significantly affected by irrigation and hydroponic treatment (Table 3.2). During the development of baby rhizomes, weight increase, and irrigation frequency were directly proportional. Greater weights (g) were observed in season 2 (>640) as compared to season 1 (401) during the last sampling

date (120 DAP). In seasons1 and 2, under lower irrigation frequency treatment (20%) the weight (g) increased from 30 to 41 and 34 to 71, while under the highest irrigation frequency (100%) the weight increased from 82 to 401, and 57 to 641 respectively (Table 3.7).

Ginger is a heavy feeder and addition of fertilizers leads to significant yield increase (Zhang et al., 2017), these fertilizers become available for plant uptake in dissolved states, thus yield, and plant development is proportional to irrigation frequency. Under moderate, short term drought stress, ginger plants generate calcium-dependent protein kinase genes as a stress fighting mechanism (Vivek et al., 2013) Gatabazi et al. (2019b) derived a relationship between varieties, and soil moisture levels, elucidating the potential impact of irrigation regimes on fresh rhizome yield, he further elaborated the significance of commercial ginger varieties to withstand different irrigation regimes over traditional varieties.

Root fresh and dry weight

Root fresh and dry weight were significantly affected by hydroponic and irrigation treatments (Table 3.3). There was a significantly linear increase in the root weight with water availability in Season 2; In season 1, a quadratic relationship was found as root weights peaked at the 80% treatment (Data not shown). Final root fresh weight was 112 and 163 in high irrigation frequency (100%) as compared to 4 and 17 from lowest irrigation frequency (20%) for season 1 and 2, respectively.

Table 3.7: The effect of irrigation, and days after planting (DAP) on baby rhizomes fresh and dry wt. (g) of ginger grown in Fischer greenhouse. Delaware Trials, 2022.

| Season/Irrigation[1] | 30 DAP[3] | | 60 DAP | | 90 DAP | | 120 DAP | |
|---|---|---|---|---|---|---|---|---|
| Season 1 | Fresh weight (g) | Dry weight (g) | Fresh weight (g) | Dry weight (g) | Fresh weight (g) | Dry weight (g) | Fresh weight (g) | Dry weight (g) |
| 20 | 26.9 a | 1.1 a | 34.8 c | 1.4 c | 37.3 c | 1.5 c | 41.8 e | 1.7 e |
| 40 | 33.9 a | 1.4 a | 54.0 bc | 2.3 bc | 63.3 bc | 2.6 bc | 105.3 d | 4.4 d |
| 60 | 55.7 a | 2.3 a | 107.5 a | 4.5 a | 122 abc | 5.1 abc | 153.8 c | 6.5 c |
| 80 | 58.9 a | 2.5 a | 96.8 a | 4.1 a | 178 ab | 7.5 ab | 308.3 b | 13.0 b |
| 100 | 82.1 a | 3.4 a | 96.5 ab | 4.1 ab | 205.8 a | 8.7 a | 400.8 a | 17.0 a |
| Linear | * | ** | ** | ** | ** | ** | *** | *** |
| Quadratic | NS | NS | ** | ** | NS | NS | * | * |
| | | | | | | | | |
| Season 2 | | | | | | | | |
| 20 | 57.0 c | 5.2 c | 34.1 d | 2.9 c | 58.8 d | 5.0 cd | 71.1 d | 6.1 d |
| 40 | 58.7 c | 5.9 c | 40.6 d | 2.8 c | 64.7 d | 4.3 d | 76.7 d | 5.1 cd |
| 60 | 59.4 c | 3.9 bc | 111.7 c | 9.6 bc | 161.1 c | 13.9 c | 185.8 c | 16.0 c |
| 80 | 61.2 b | 3.6 ab | 220.3b | 17.3 b | 342.4 b | 26.7 b | 403.5 b | 31.5 b |
| 100 | 56.9 a | 3.9 a | 371.7 a | 25.5 a | 551.5 a | 37.9 a | 641.4 a | 44.1 a |
| Linear | *** | *** | *** | *** | *** | *** | *** | *** |
| Quadratic | NS | * | * | NS | NS | NS | * | NS |

[1] Irrigation frequency and season, PD = Planting Date; 2 Soil moisture level depleted to in percent of Field Capacity until irrigated back to field capacity or grown hydroponically (100)
[3]DAP = Days after Planting
[4,5] Orthogonal contrasts. Irrigation treatment effects on plant height are significantly linear or quadratic at the *0.05 level, **0.01 level, ***0.001 level, or are not significant NS.
[6]Mean separation by Tukey's HSD. Means followed by the same letter are not significantly different at the 0.05 level.

Root development and dry weight dependents on nutrient resources in the growing media. Khosh Kholgh Sima et al., (2012) did an experiment of the interactive effects of salinity and phosphorus nutrition on plants' root responses and found that high phosphorus levels in growing media had a negative relationship with the sodium content in plants but were positive with roots' dry weight.

Number of primary, secondary, tertiary, and quaternary fingers

The influence of hydroponic and irrigation treatments was variable across seasons. Seasons and irrigation treatments influenced primary, tertiary, quaternary, and quinary finger ranks, irrigation treatment influenced all finger ranks except primary fingers (Table 3.3). Under season 2, highly significant linear and quadratic contrasts were observed throughout the study and finger numbers increased as water availability increased.

Primary finger development is the initial step in ginger growth after planting and is affected by several factors such as soil moisture, fertility status, and others. Experiments by (Singh et al., 2012) showed triacontanol applications significantly affected the number of primary fingers per plant at harvest (240 days after planting). Secondary fingers being part of initial rhizomes development, they require enough water and fertility resources to balance their growth and development demand. Triacontanol affects the secondary rhizomes through increased uptake of nutrients, rate of photosynthesis and translocation of photosynthates and other metabolites to the sinks, ultimately, leading to the enhanced yield of rhizomes per plant (Singh et al., 2012). Genetic variability, and heritability affects both primary and secondary fingers of ginger rhizomes (Behura, 2001). Umar et al. (2017) conducted an experiment on effects of nitrogen and potassium on growth and yield of mango ginger, resulting in significant effect of tertiary fingers among other responses. The onset of quaternary finger indicates the readiness for harvest of the baby ginger, it is described as the ultimate developmental stage in annual ginger cultivation (Nair, 2019).

Table 3.8: Average water use (L) per plant during the cultivation season of April to August 2022.

| Growth stage | 100% | 80% | 60% | 40% | 20% |
|---|---|---|---|---|---|
| Seedlings | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 |
| Month 1 | 12.8 | 75.7 | 75.7 | 75.7 | 75.7 |
| Month 2 | 16.0 | 45.4 | 15.1 | 7.6 | 3.8 |
| Month 3 | 19.4 | 60.6 | 22.7 | 13.0 | 5.8 |
| Month 4 | 15.0 | 68.1 | 26.5 | 11.4 | 6.1 |
| Month 5 | 9.4 | 56.8 | 18.9 | 9.8 | 4.5 |
| Total | 76.40 | 310.37 | 162.76 | 121.27 | 99.62 |

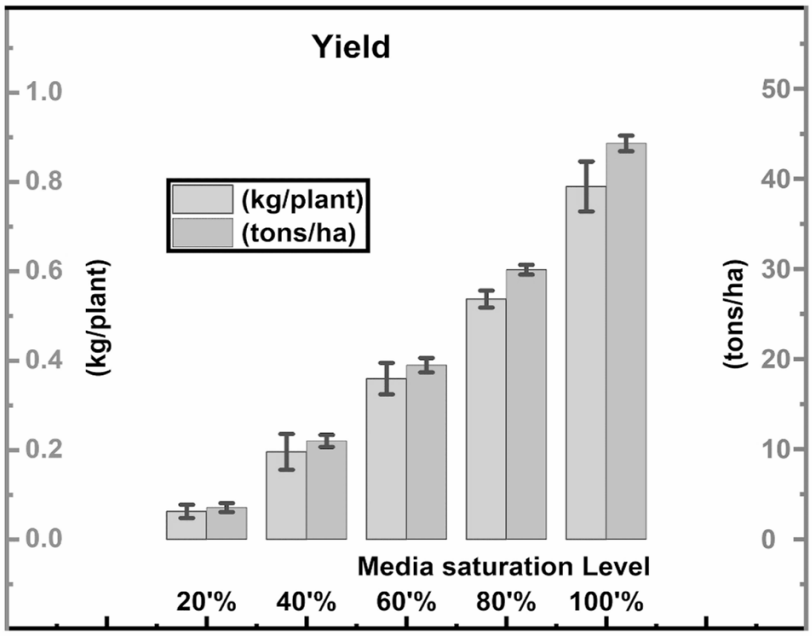



Figure 3.1: Yield of ginger grown in the Fischer greenhouse laboratory complex under different water-saturation levels, University of Delaware, 2022 Each error bar is constructed using 1 standard error from the mean. Linear and quadratic contrasts were significant for yield by irrigation treatment at the 0.001 level.

Water Use

Water use is presented in Table 3.8 for season 1. The hydroponic (100%) treatment was much more efficient in using water than the treatments using growing media because almost all the water was transpired and there was no surface evaporation.

Yield Results from Greenhouse Production Experiments

There was a highly significant effect of irrigation treatment on yield both seasons (Table 3.3). Yield responses were significantly curvilinear with almost no production at 20% and a significant increase occurring from 80 to 100% (Figure 3.1). Yields were 43.9-, 29.9-, 19.3-, 10.9- and 3.5-tons $ha^{-1}$ in 100, 80, 60, 40, and 20% irrigation treatments, respectively. This response was largely attributed to the water availability effect as nutrient levels were controlled.

Temperature, light and nutrition are among important environmental factors controlling greenhouse production (Seginer *et al.*, 1991; Stagnari *et al.*, 2015). Greenhouse production systems for ginger can increase production by at least 30% compared to traditional cultivation in open areas. Greenhouses would be necessary for ginger production in cold environments.

Experiment II (pH and EC)

Dried leaves are a sign of stress and low and high pH had greater dry leaf numbers. As EC increased dried leaf numbers also increased (Table 3.9). Fresh leaf number was greatest at a pH of 6 and EC of 2 (Table 3.9).

Table 3.9: The effect of different pH and EC levels, 120 days after planting on the height and tillering of ginger. Delaware Trials, 2022.

| | Height (cm) | Tiller (no.) | Dried leaf (no.) | Fresh leaf (no) | Chlorophyll Reading[3] |
|---|---|---|---|---|---|
| pH experiment[1] | | | | | |
| 2 | 49.1 | 13.3 | 13.3 | 41.7 | 15.7 |
| 4 | 81.6 | 4.0 | 4.0 | 60.7 | 25.0 |
| 6 | 82.8 | 2.7 | 2.7 | 85.0 | 28.4 |
| 8 | 60.9 | 10.0 | 10.0 | 62.3 | 21.2 |
| 10 | 51.1 | 10.7 | 10.7 | 46.3 | 17.6 |
| Ro Water[3] | 47.7 | 6.0 | 36.0 | 33.3 | 18.0 |
| Linear[4] | NS | *** | NS | NS | NS |
| Quadratic[5] | *** | *** | *** | *** | ** |
| | | | | | |
| EC experiment[2] | | | | | |
| Ro Water (EC 0) | 39.3 | 7.0 | 7.0 | 22.7 | 15.7 |
| 0.5 | 41.3 | 2.0 | 2.0 | 28.0 | 19.0 |
| 1 | 71.3 | 0.3 | 0.3 | 58.0 | 25.3 |
| 2 | 84.7 | 3.0 | 3.0 | 97.7 | 29.3 |
| 4 | 68.3 | 10.7 | 10.7 | 57.7 | 26.0 |
| 6 | 45.7 | 18.3 | 18.3 | 31.0 | 22.7 |
| | | | | | |
| Linear | NS | NS | ** | ** | NS |
| Quadratic | ** | ** | *** | *** | ** |

[1] pH values of nutrient solution, [2] Electrical Conductivity of nutrient solution, [3]Chlorophyll meter units,[4,5] Orthogonal contrasts: parameter values in different EC, pH and fertilizer types are significantly linear or quadratic at the *0.05 level, **0.01 level, ***<0.001 level, or are not significant NS.

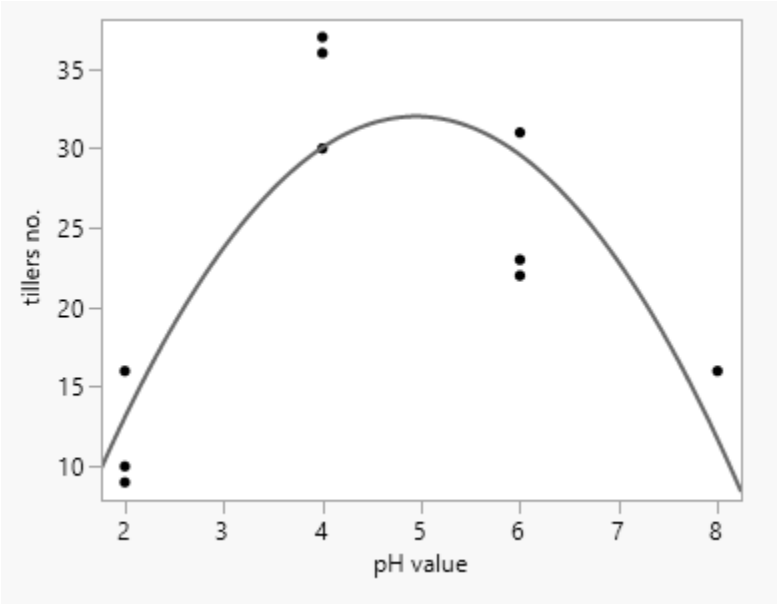



Figure 3.2: Quadratic regression of pH on tillers number, p = 0.008, R2=0.74, equation: tillers no. = 20.863636 + 2.3863636*pH value - 2.1780303*(pH value-4.4)^2.

Final tiller counts were highest at a pH between 4 and 5 and at an EC of 3 (Figures 3.2 and 3.3). Quadratic regressions had R2 values of 0.74 for pH and 0.82 for EC and both had highly significant quadratic contrasts.

Plant height was greatest at an EC of 3 and pH between 5 and 6. Both EC and pH had significant quadratic response curves (Figures 3.4 and 3.5).

Chlorophyll readings were highest at a pH of 6 and EC of 3 (Figures 3.6 and 3.7) and the response curves followed a quadratic response.

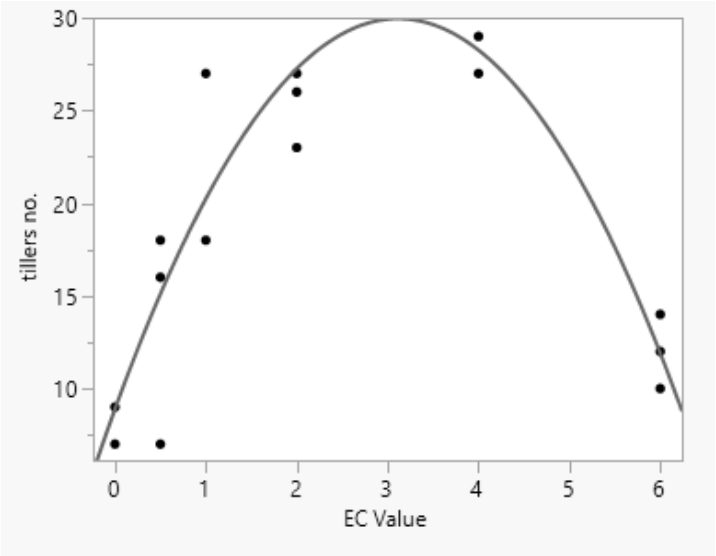



Figure 3.3. Quadratic regression of EC on tillers number, p>0.001, R2=.82. Equation: tillers no. = 19.873037 + 3.7594142*EC Value - 2.1701822*(EC Value-2.25)^2.

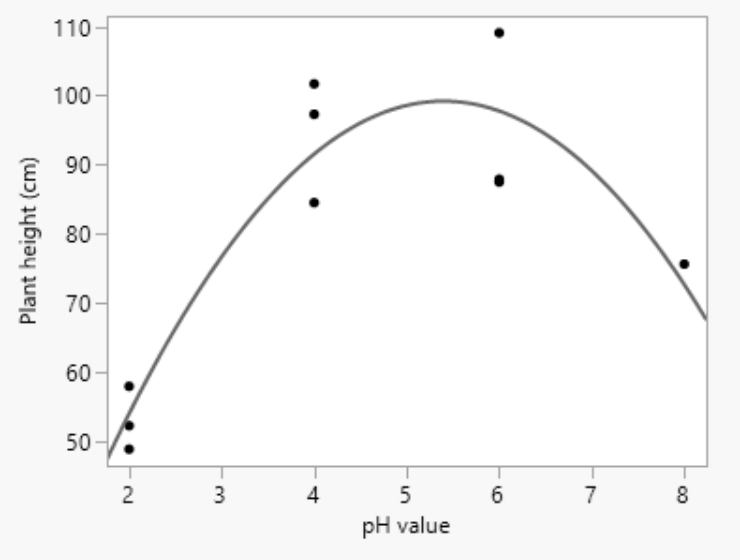



Figure 3.4: Quadratic regression of pH on plant height, p=0.001, R2=0.86, Equation: Plant height (cm) = 60.890667 + 7.8216667*pH value - 3.9208333*(pH value-4.4)^2.

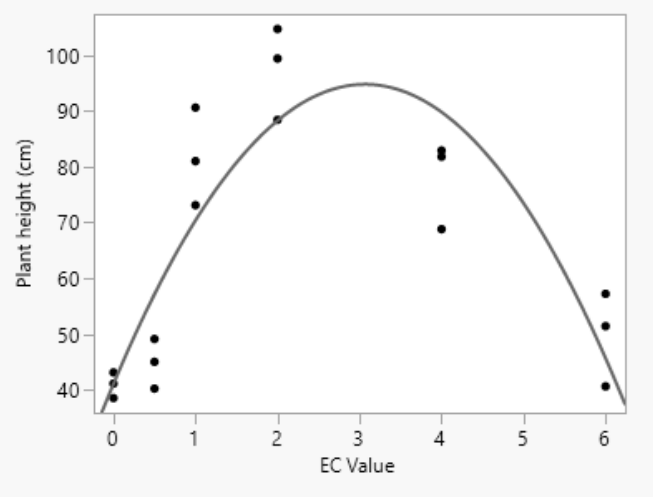



Figure 3.5: Quadratic regression of EC on plant height, p<0.001, R2=0.75, Equation: Plant height (cm) = 69.959229 + 9.3340337*EC Value - 5.7103193*(EC Value-2.25)^2

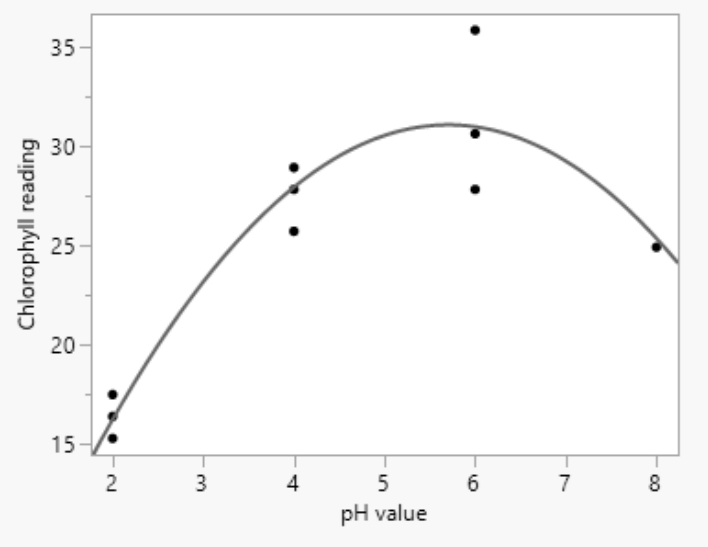



Figure 3.6: Quadratic regression of pH on chlorophyll reading, p<0.001, R2=0.90, Equation: Chlorophyll reading = 16.842667 + 2.8116667*pH value - 1.0791667*(pH value-4.4)^2.

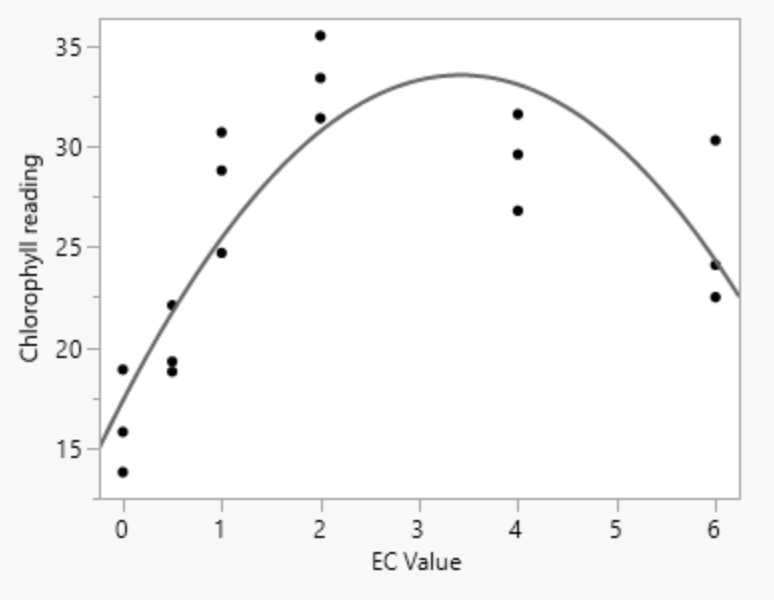



Figure 3.7: Quadratic regression of EC on chlorophyll reading $p<0.001$, $R2=0.72$, Equation: Chlorophyll reading = 24.36404 + 3.2382857*EC Value - 1.3842268*(EC Value-2.25)^2

Soil pH influences interactive processes and properties which are fundamental to the soil's nutrient cycling, plant nutrition, soil remediation (Neina, 2019). Under normal soil conditions, low pH increases the mobility of micronutrients up to toxic levels or become less soluble and unavailable for the plant's uptake under high pH. These complex interactions between mineral nutrients, soil colloids and plant roots differ between plants and growing environments. Hydroponics exclude the interaction of plants roots and soils resulting from pure water culture or when blended with

soilless media. Most of the plant's interaction under different pH levels in hydroponics have not been explored. Ginger withstood extreme pH (2-10) and EC (0.5 – 6) conditions during cultivation with consequences on the overall yield. This ability is partly inherent and partly due to the ability to quickly overcome soil challenges. High EC interferes osmosis and active nutrient absorption leading to salt stress and burning of the leaf edges as the initial stage, leading to plant death once the stress advances. (Yin et al., 2021) suggested that low pH first improves photosynthesis efficiency, and second nutrient acquisition; his experiment involved different saline levels combined with low pH. Ginger has hyper performance when subjected to both low pH and saline environment (Yin et al., 2020). The phenological development and yield increased as EC of nutrient solution increased from 0.5 to 4 dSm-1, due to increase in nutrient concentrations. Ginger had uninterrupted development at lower EC (0.5) since we changed the nutrient solution every 4 weeks, thus absorbed the required nutrients even if they were available at lower concentrations. Similarly, yield decreased as the EC of nutrient solution increased from 4 to 6 dSm-1 because of increasing water-salt stress, which also affected root growth and distribution into the nutrient solution.

Yield data for pH and EC experiments.

Table 3.10: The effect of pH, EC, and days after planting (DAP) on the yield of ginger. Delaware Trials, 2022.

| | EC experiment | | | pH experiment | |
|---|---|---|---|---|---|
| EC experiment[1] | Yield (kg/plant) | Yield (tons/ha) | pH experiment[2] | Yield (kg/plant) | Yield (tons/ha) |
| 0.5 | 206.3 de | 8.3 de | 2 | 205.7 c | 8.2 c |
| 1 | 332.7 bc | 13.3 bc | 4 | 422.7 a | 16.9 a |
| 2 | 469.3 a | 18.8 a | 6 | 467.0 a | 18.7 a |
| 4 | 391.7 ab | 15.7 ab | 8 | 346.7 ab | 13.9 ab |
| 6 | 247.7 cd | 9.9 cd | 10 | 221.3 bc | 8.9 bc |
| RO Water[3] | 123.0 e | 4.9 e | RO Water | 182.7 c | 7.3 c |
| Linear[4] | ** | ** | Linear | NS | NS |
| Quadratic[5] | *** | *** | Quadratic | ** | *** |

[1] pH values of nutrient solution, [2] Electrical Conductivity of nutrient solution, [3]Reverse Osmosis Water EC 0

[4,5] Orthogonal contrasts. Yield in different EC, pH experiments are significantly linear or quadratic at the *0.05 level, **0.01 level, ***0.001 level, or are not significant NS.

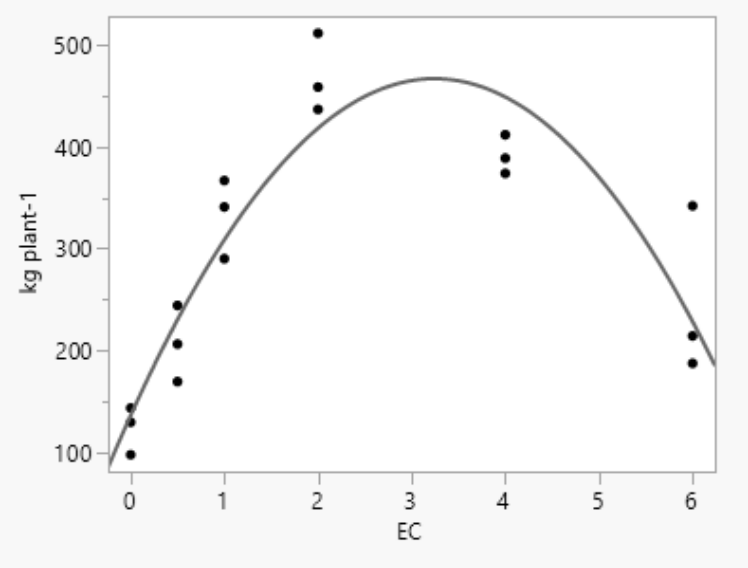


Figure 3.8: Quadratic regression of EC on yield (kg per plant), p>0.001, $R^2$ = 0.82, Equation: kg plant-1 = 295.24538 + 62.61997*EC - 31.485588*(EC-2.25) ^2.

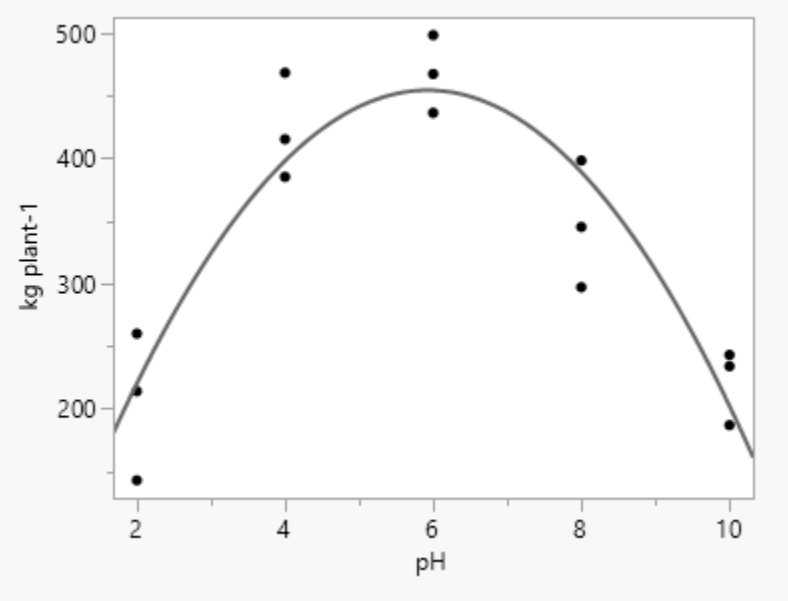



Figure 3.9: Quadratic regression of pH on yield (kg per plant), p>0.001, $R^2$ = 0.84 Equation: kg plant-1 = 467.4 - 2.2333333*pH - 15.166667*(pH-6) ^2.

Yields were significantly quadratic in the EC experiment with an optimum EC of 3 (Table 3.10, Figure 3.8. Within the EC experiment, yields (t ha $^{-1}$) were 18.77 in EC 2, 15.67 in EC 4, 13.31 in EC 1, 9.91 in EC 6, 8.25 in EC 0.5, and 4.92 in reverse osmosis water (EC 0). Yields in the pH experiment were significantly quadratic with an optimum of pH 6 (Table 3.10, Figure 3.9). Within the pH experiment, yields (t ha $^{-1}$) were 18.68 in pH 6, 16.91 in pH 4, 13.87 in pH 8, 8.85 in pH 10, 8.23 in pH 2, and 7.31 in reserve osmosis water. These results are in line with (Eltez *et al.*, 2002) who

obtained similar results when testing different EC values (2-5) in tomatoes and found that highest total yields came from lower EC of 2 rather than 4 or 5.

## Conclusions

Experiments showed the potential for baby ginger as an alternative greenhouse crop in soilless culture and in static hydroponics. There is sufficient heat in the greenhouse above $20^0$C, enabling good ginger growth in spring, summer, and fall. From the EC and pH experiments, we can conclude that the salinity threshold of ginger is 4 $dSm^{-1}$ with maximum performance at EC 3 $dSm^{-1}$ and acidic/alkaline range for ginger is pH 2 – 10 with maximum performance at pH 6.

## Acknowledgments

We would like to sincerely acknowledge the University of Delaware through the Department of Plant and Soil Sciences.

## Chapter 4

## THE EFFECTS OF GROWING CONDITIONS AND STORAGE METHODS ON THE QUALITY OF BABY GINGER (*Zingiber officinale*)


### Abstract

Ginger (*Zingiber officinale*) is a potent medicinal spice native to the tropical rainforests of Southeast Asia. Ginger is grown for 10-12 months for its mature rhizomes which are shelf-life stable. Its potency increases in immature (baby) rhizomes cultivated and harvested prematurely (3-6 months). As a baby version, the entire plant is edible thus increasing consumption sustainability. The major limitation of baby ginger cultivation and utilization is the short storage life of immature rhizomes. In the first study, trials conducted from a 4-5-month field cultivation cycle assessed were used to the determine concentrations of phytocompounds across the entire plant in terms of total phenolic contents (TPC) and anti-oxidation capacity DPPH -2,2-diphenyl-1-picrylhydrazyl assay. In a second study, shelf-life extension of baby rhizomes was studied with treatments being temperature and humidity combinations ($4^0$C, $10^0$C, 50% RH, 95% RH, and room conditions), washing techniques (no-wash, water, peroxyacetic acid, and hydrogen peroxide), parking styles (Ziplock bags, vacuum-sealed bags, bins, and sand incorporations), and addition of absorbent polymers. The parameters assessed included phytocompound concentration of the entire plant, physical and quality attributes of stored ginger, as well as storage pathogens. Statistical analysis was performed through JMP software. Results from the entire plant analysis stipulate immature rhizomes have 1.5, 3, 5, and 5.7 times higher TPC and DPPH compared to matured rhizomes, leaves, pseudo-stems, and roots respectively on a dry weight basis, showing the advantage of immature rhizomes and potential for entire plant consumption, thus sustainability. Ginger utilization scales

from 44% to more than 95% utilization when there is a transition from consuming only the rhizomes to the entire plant. Fresh ginger and value-added products increase potential product diversity in the markets. Results from manipulating the storage environment of baby rhizomes favored $4^0$C and 95% RH to conserve the weight of tender immature rhizomes, maintaining density, maintaining higher TPC, and having the lowest pathogen score. Peroxyacetic acid had a limited effect on ginger storage. Vacuum-sealed and Ziplock bags had a positive effect on weight conservation, while bins and sand triggered increased rhizome density, higher TPC, and lowered pathogen scores. The addition of absorbent polymers had no effect on either weight change or pathogen score, decreased density, and TPC content. Combinations giving the longest average storage time include $4^0$C and 95% RH storage environment (41 days), washing with water (38 days), and usage of empty bins or sand incorporation (38 days), regardless of the addition of polymers. Dominant storage pathogens of ginger were *Globisporangium spinosum, Rhizoctonia bicornis, Pythium ultimum, Fusarium oxysporum*, and *Pythium irregulare* becoming more persistent under higher storage temperatures and humidities.

**Keywords**

Ginger, baby ginger, immature ginger, phytocompounds, TPC, DPPH,

**Abbreviations**

asl – above sea level
B – billion
DPPH - 2,2-diphenyl-1-picrylhydrazyl
etc. – et cetera
ft – foot/feet
GME – the antioxidative activity of methanolic

kg – kilogram M – million N – north OH – Ohio TPC – total phenolic content USA – United States of America VSU – Virginia State University W – west $ - US dollar 0 C– degree centigrade % - Percentage

## Introduction

Ginger is a multipurpose crop exploited for its spicy nature and/or medicinal potential (Maizura et al., 2011). Due to raised health concerns, it is an alternative source of anti-oxidant and anti-inflammation compounds compared to their synthetic counterparts (Shahrajabian et al., 2020). Ginger is a remedy for numerous ailments including gastrointestinal disorders, respiratory disorders, mental health issues, and blood circulatory system disorders (Irfan et al., 2019). Ginger's antioxidation property is derived from its ability to capture free radicles through the donation of hydrogen atoms or electrons to ameliorate dysfunction (Zhou et al., 2018). Ginger is among the top-ranked medicinal crops which strengthen body systems by modulating immune responses, and working against chronic non-communicable diseases (Srinivasan, 2017). Its potential and demand are increasing in both fresh and dried state The longer shelf-life of disease-free matured rhizomes allows for widespread medicinal use (Kaushal et al., 2017; Moreira et al., 2013; Sharma and Sharma, 2019). The medicinal value of ginger peaks when it is still immature and declines with maturation.

Recently, the rate of non-communicable diseases has escalated presumably due to unhealthy lifestyles, technology advancement and other associated factors (Branca et al., 2019). Frequent consumption of medicinal crops such as ginger is a way to

address this trend. Fortunately, there are numerous studies pinpointing the health potential of ginger consumption (Chrubasik et al., 2005; Dissanayake et al., 2020; Irfan et al., 2019; Shahrajabian et al., 2019, 2020; Shirin and Jamuna, 2010a; Srinivasan, 2017; Terry et al., 2011). More than 80% of world's population consumes organic medicines in one way or another (Sahoo et al., 2010), thus its necessary to increase nutritious and potential options such as the immature (baby) ginger.

Ginger rhizomes at 6 months or less from establishment have a higher water content and are less pungent. Tenderness reduces after 7 months and the aroma, flavor and pungency spike up between 8 and 9 months of age making it ideal for drying. After 9 months the extent of fiber content overshadows phytocompounds (B. Bag, 2018; Balakrishnan, 2016).

Reports on the medicinal potential of ginger spice are numerous (Afzal et al., 2001; Chrubasik et al., 2005; Dissanayake et al., 2020; Irfan et al., 2019; Riaz et al., 2015; Shahrajabian et al., 2019), less for agronomic and horticultural aspects during production. There is limited information available on the response of ginger to irrigation regimes and frequency, which may significantly affect phytocompound quality and quantity attributes.

Future sustainability in agricultural production involves stretching the consumption volume from the total harvested biomass, this includes utilization of leaves, pseudo stems, roots, and other plant parts where applicable. All these plant parts require definite storage techniques.

Microbial degradation and rots of stored ginger includes species from *Penicillin, Fusarium, Aspergillus,* and *Mortierella genera. Penicillium sp.* contaminates a variety of foods, grows in chilly temperatures and spoils refrigerated

foods. These fungi physically degrade ginger through their extracellular feeding nature and production of secondary metabolites *i.e.,* mycotoxins or Aflatoxins. Fusarium spoils foods in stores, their species thrive under very low oxygen levels and are reported to re-contaminate foods treated with ultra-high temperatures. These are all mycotoxins producing fungi and under large scale, they grow in spots challenging sampling for mycotoxins (Coppock *et al.*, 2018; Krasauskas, 2019; Nguyen *et al.*, 2017).

These studies were designed to investigate the potential of entire ginger plant consumption and explore several alternatives of extending the shelf life of immature (baby) rhizomes without affecting its quality. The specific objectives of these studies were 1) to assess phytocompound accumulation in immature (baby) ginger plant parts, cultivated for 4–6 months under different irrigation frequencies and 2) to assess methods of extending the shelf-life of baby ginger while maintaining its quality using different temperature and humidity combinations, washing, and packing styles, and losses from dominant storage pathogens.

This study seeks to confirm the higher potency claims of immature (baby) ginger compared mature ginger. Storage of fresh ginger rhizomes ensures its year-round availability. During storage, active phytocompounds are converted into inactive forms. Nair, (2019) stated gingerols are converted to shogaols under long term storage. Ginger is a natural longer shelf-life crop when harvested matured, disease free, and stored under ambient conditions unlike the immature (baby) ginger, which is highly succulent, thus prone to deterioration. If the immature (baby) ginger rhizomes are disease-free, then ambient temperature, humidity and storage invasive microbes are the most limiting factors.

## Materials and methods

### Location

All experiments were in the United States of America (Delaware and Virginia States). Research facilities used were Fischer greenhouse laboratory complex in the University of Delaware Newark-campus (39.6780° N, 75.7506° W, 448 ft asl) and Research facilities in Virginia State University (37.2384° N, 77.4198° W, 86 ft asl). The experiments commenced were conducted from February 2022 to February 2023. Additionally, storage experiments required usage of incubators and dew chambers from the University of Delaware.

### Design and layout

In the phytocompound analysis study, we systematically collected plant samples established under both RCBD and Latin square field designs described in Chapters 2 and 3. Laboratory analysis proceeded to quantify the amount of phytocompounds present in the entire ginger plant from their growing locations. For the storage study, the experiment followed the randomized complete block design, with three repetitions, replications spaced at 1-month intervals, and each repetition replication had 28 treatments at a particular temperature and humidity combination.

### Plant material

Yellow ginger grown in the field, tunnels, and greenhouses of the University of Delaware served as plant materials for analysis. Analysis was done by both the University of Delaware and Virginia State University.

The storage experiments involved freshly harvested baby ginger rhizomes from a 5–month cultivation cycle in the fields and tunnels of Newark and Georgetown

campus. The experiment consumed a total of 200 kg, washed, and grouped into 0.45 kg bundles.

Treatments and data collection

Phytocompound analysis was performed for the determination of TPC and DPPH concentrations in all ginger plant parts (*i.e.*, leaves, pseudo stems, baby rhizomes, mother rhizomes and roots) grown in different production environments of growing media, moisture levels and levels of protection. The growing media were sand based soils, clay-based soils, compost mixed with rice husk at 1:1, and Kratky hydroponics systems blended with sand. Levels of protection were open fields, high tunnels, and greenhouses. Moisture levels were 100%, 80%, 60%, 40%, and 20% minimum depletion before replenishments, 100% was the hydroponics system and plants stood in nutrient solution. Higher moisture levels numbers mean absence of drought stress, while lower numbers mean drought stress.

Treatments for the storage experiment were different temperatures (4 $^{0}$C, 10 $^{0}$C or room temperature) and humidity combinations (50%, 90% or room humidity); washings and disinfections (wash with water, no wash, was with peroxyacetic acid or hydrogen peroxide); packing styles (Ziplock bags, vacuum sealed bags, empty bins, or placed in bins then covered with sand), and use of polymer adsorbents.

## Laboratory analysis and procedures

Data for plant component analysis involved selection of well-formed plant parts (leaves, pseudo stems, mother rhizomes, baby rhizomes and roots), removing defects and abnormal tissues. Then samples were washed to remove debris, air dried, then chopped into small pieces of 2 mm$^2$. Samples were placed in freeze drier

(Harvestright 95 North Foxboro Drive, Suite 100 North Salt Lake, Utah 84054) for 96 hours to remove all the water, then were ground into fine powder (using coffee grinder, COSORI Coffee Espresso Grinder Electric, Food Grade Stainless Steel Blades, 12 Cups, Black). The powder was kept in mini-zip lock bags in cabinets away from direct sunlight to avoid photoreactions. The powdered samples were then subjected to spectrophotometric quantifications to determine phytocompound concentrations as described below.

Total phenolic content (TPC)

Samples were extracted with 80% ethanol and directly used to evaluate TPC, TPC was measured using Folin and Ciocalteu's (FC) reagent with slight modification to adopt a 96-well microplate version.

A 7% $Na_2CO_3$ solution, 1 mg/mL gallic acid stock solution was prepared in the 80% ethanol, gallic acids working solutions (made from at least four concentrations) for preparing standard curve (0-500 μg/mL), Gallic acid stock I: 10 mg/ml. Gallic acid stock II: 1 mg/ml, FC reagent. Folin-Ciocalteu (FC) Reagent, Sigma; to make a standard curve of Gallic acid in 80% ethanol: 0, 12.5, 25, 50, 100, 200, 400, 500 μg/ml.

In the TPC test we 80 μL of water was added to each well, a 20 μL sample, standard, or solvent (blank), and 20 μL FC reagent was added to each tube, then tubes were shaken for 5 seconds and then allowed to rest at least 1 min, but no longer than 8 minutes, followed by addition of 160 uL 7% $Na_2CO_3$ solution to each well mixed well. Well plates were sealed and kept in dark at ambient temperature for 2 hours. measured

Absorbance was measured at 765 nm using a microplate reader SpectraMax M5 (Molecular Devices, LLC. San Jose, CA).

Total phenolic content was then determined using Gallic acid as a standard curve and the analysis was performed in triplicate, expressing data as milligrams of Gallic acid equivalents (GAE)/g of dried sample as mean ± SD for all experiments.

DPPH

DPPH was evaluated after direct sample extraction with 80% ethanol. A 0.2 mM 2,2-diphenyl-1-picrylhydrazyl (DPPH), working solution was prepared in 80% Ethanol, 50 mM primary stock solution of 6-hydroxy-2,5,7,8-tetramethylchoman-2-carboxylic acid (trolox) was prepared in 80% Ethanol, Trolox working standards were diluted with 80% Ethanol and Clear 96-well plates compatible with absorbance readings were use.

For the DPPH test, 200 µL of the solvent was added to Blank wells, 100 µL of the solvent to control wells, 100 µL of standard and sample solutions to appropriate wells, 100 µL of 0.2 mM DPPH solution to control, standard, and samples wells, then plates were shaken for 5 seconds, and then absorbance was read at 515 nm every minute for 1.5 hours with lids on plates.

## Data collection and analysis

Data collection was on a monthly interval for the storage experiment. Parameters collected included the total number of storage days, weight change, change in moisture content, density change, storage pathogens and associate data of temperature and humidity that prevailed during the experimental duration.

The total number of storage days was determined by subtracting the date of the experimental data collection from the date when the rhizomes were unfit for usage. Weight change was a function of difference between the initial weight of the rhizomes during experimental setup and the weight during each data collection date. For the change in moisture content, small rhizome sections with known weight were dried. Density change data involved comparison of the initial rhizome density recorded during experimental setting to the density within each data collection date using a penetrometer (Geotester pocket penetrometer, Gilson company, 7975 North Central Drive, Lewis Center, OH 43035, USA). Determination of storage pathogens involved culturing infected rhizome sections and subjecting the cultures to molecular analysis. Digital data loggers (WatchDog A-Series Loggers, Spectrum Technologies, 3600 Thayer Court, Aurora, IL 60504) recorded the prevailing temperature and humidity in all treatments during the experimental duration.

## Results and Discussion

### Experiment 1. (Phytocompound analysis of Total Phenolic Content (TPC) and anti-oxidation capacity (DPPH))

Table 4.1: ANOVA tests of  significanc for on the anti-oxidation capacity (DPPH) and Total phenolic content (TPC) within different ginger plant parts

| Source | DPPH | TPC |
|---|---|---|
| Plant Part | <.0001* | <.0001* |

Plant parts differed significantly in DPPH and TPC levels (Table 4.1)

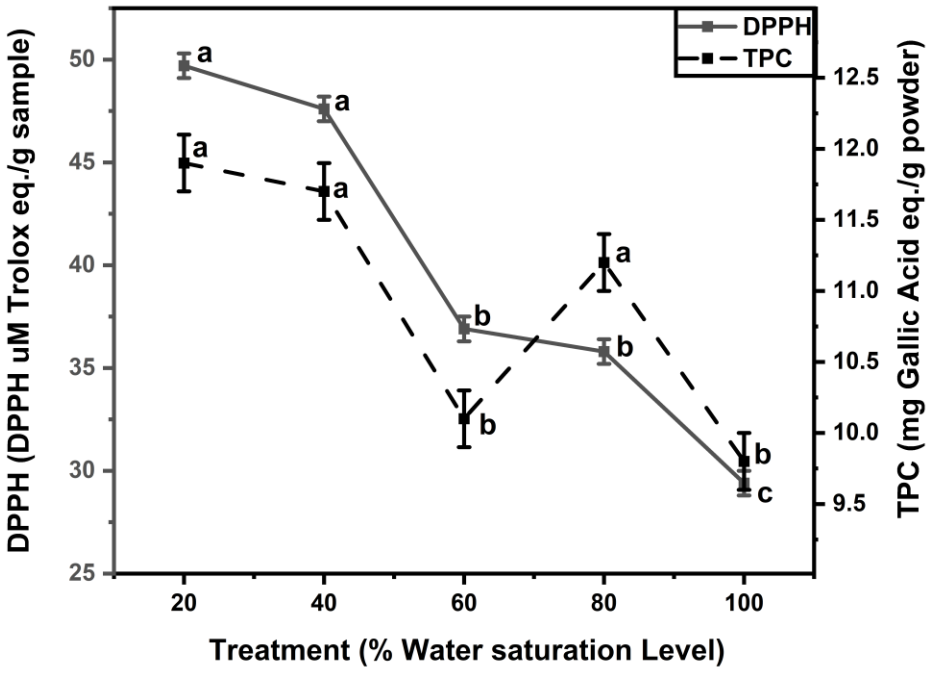



Figure 4.1: TPC (Total Phenolic Content) and DPPH (antioxidant capacity) for all plant parts, Newark greenhouse, Delaware 2022. Means separation by Tukey's HSD at the 0.05 level.

Plant parts had significantly different levels of DPPH and TPC (Table 4.1)

In greenhouse trials, drought stress treatments (20 and 40%) had higher concentrations of TPC (60 and 100%) except 80%. (Figure 4.1). The high order of concentration of DPPH anti-oxidation capacity within ginger plant parts was inversely proportional to water saturation level in the soil (Figure 4.1). Drought stress is responsible for reduced water content in plant tissue thus higher concentrations of phytocompounds as observed in lower irrigation treatment.

General ranking of TPC within ginger plant parts followed the trend of immature (baby) rhizomes > matured rhizomes > leaves > pseudo stems > roots (Table 4.x).

In the hydroponic treatment (100%), 20% and 40% treatments, matured rhizomes had similar TPC and DPPH levels as baby rhizome whereas baby rhizomes had higher TPC and DPPH levels in the 60% and 80% treatments. Within 2-month-old seedlings, TPC and DPPH were highest in matured rhizomes, leaves, young baby rhizomes, and lowest in the roots and pseudo stems. Roots and pseudo stems had the lowest phytocompound concentrations across different irrigation frequency treatments (Tables 4.2, 4.4). Hydroponics treatments had similar concentration patterns as soilless media (compost mixed with rice husk at 1:1). As compared to Newark tunnel plants with clay-based soils, their young seedlings of 2 month had very high concentrations of both TPC and DPPH in baby rhizomes as compared to mature/mother rhizomes. In 80% Newark open field plants TPC and DPPH concentrations were higher in matured/mother rhizomes as compared to baby rhizomes (Tables 4.3, 4.5).

There are numerous aromatic compounds in baby ginger from alcohols, aldehydes, olefines, and esters which constitute to the terpenoids or their derivatives (Luo et al., 2017). Due to the volatility, photoreaction and vulnerable oxidation nature of ginger's phytoconstituents, its nutritional composition is highly dependent on the processing method used, but not for polyphenolic content which is stable regardless (Sangwan et al., 2014). According to Ghasemzadeh and Jaafar, (2013) who conducted an experiment assessing the effect of two CO2 concentrations (400 and 800

Table 4.2: The effect of % water saturation level on the TPC content (TPC mg Gallic Acid eq./g powder) in ginger plant parts grown in the greenhouse.

| Fischer greenhouse | TPC in baby rhizomes | TPC in matured rhizomes | TPC in leaves | Average TPC in pseudo-stems | Average TPC in roots |
|---|---|---|---|---|---|
| 20% Minimal depletion | 18.7 b[1] | 25.1 a | 7.0 c | 2.5 d | 3.4 d |
| 40% Minimal depletion | 20.3 a | 24.4 b | 7.3 c | 2.9 d | 1.8 d |
| 60% Minimal depletion | 21.2 a | 12.2 b | 7.4 c | 4.0 d | 2.9 d |
| 80% Minimal depletion | 23.8 a | 13.4 b | 7.3 c | 7.1 c | 3.5 d |
| 100% Minimal depletion | 13.4 a | 17.3 b | 8.7 c | 4.3 d | 2.1 e |

[1]Mean separation by Tukey's HSD. Means in each row followed by the same letter are not significantly different at the 0.05 level.

Table 4.3. The effect of % water saturation level on the TPC content (TPC mg Gallic Acid eq./g powder) in ginger plant parts grown in the tunnel.

| Newark Tunnel | TPC in baby rhizomes | TPC in matured rhizomes | TPC in leaves | Average TPC in pseudo-stems | Average TPC in roots |
|---|---|---|---|---|---|
| 20% Minimal depletion | 16.7 a[1] | 17.0 a | 9.4 b | 3.0 c | 0.5 c |
| 40% Minimal depletion | 10.7 b | 17.3 a | 8.4 c | 2.4 d | 1.3 d |
| 60% Minimal depletion | 19.1 a | 13.5 b | 8.9 c | 12.0 bc | 2.7 d |
| 80% Minimal depletion | 19.2 a | 17.8 a | 9.1 b | 1.9 c | 4.6 c |

[1]Mean separation by Tukey's HSD. Means in each row followed by the same letter are not significantly different at the 0.05 level.

Table 4.4: The effect of % water saturation level on the DPPH (DPPH uM Trolox eq./g sample) in ginger plant parts grown in the greenhouse.

| Fischer greenhouse | DPPH in baby rhizomes | DPPH in matured rhizomes | DPPH in leaves | DPPH in pseudo-stems | DPPH in roots |
|---|---|---|---|---|---|
| 20% Minimal depletion | 88.0 a[1] | 93.3 a | 28.1 b | 18.3 bc | 14.7 c |
| 40% Minimal depletion | 82.1 a | 94.8 a | 28.1 b | 12.6 bc | 6.2 c |
| 60% Minimal depletion | 71.4 a | 42.5 b | 22.7 c | 20.9 cd | 14.7 d |
| 80% Minimal depletion | 69.3 a | 60.9 a | 18.7 b | 13.1 b | 11.8 b |
| 100% Minimal depletion | 58.1 a | 52.4 ab | 22.9 bc | 13.0 c | 6.4 c |

[1]Mean separation by Tukey's HSD. Means in each row followed by the same letter are not significantly different at the 0.05 level.

Table 4.5: The effect of % water saturation level on the DPPH (DPPH uM Trolox eq./g sample) in ginger plant parts grown in the tunnel.

| Newark Tunnel | DPPH in baby rhizomes | DPPH in matured rhizomes | DPPH in leaves | DPPH in pseudo-stems | DPPH in roots |
|---|---|---|---|---|---|
| 20% Minimal depletion | 99.9 a[1] | 90.0 a | 24.6 b | 16.1 b | 14.0 b |
| 40% Minimal depletion | 82.0 a | 73.3 a | 28.0 ab | 11.6 b | 6.4 b |
| 60% Minimal depletion | 61.7 a | 51.1 a | 22.2 b | 19.0 b | 16.4 b |
| 80% Minimal depletion | 75.8 a | 58.5 a | 16.3 b | 13.3 b | 12.9 b |

[1]Mean separation by Tukey's HSD. Means in each row followed by the same letter are not significantly different at the 0.05 level.

μmol $mol^{-1}$), observed the following trend of total phenolic content within ginger plant parts; rhizomes > stems > leaves. Quality traits (pungency, essential oil, fiber, oleoresins, and others) along with volatile and non-volatile constituents are important determinants of ginger's end product (Kizhakkayil and Sasikumar, 2011b). The quality and concentration of ginger's phytocompounds is also dependent on the drying temperature and method used. In the experiment conducted by Jayashree and Visvanathan, (2011), they obtained maximum essential oil (13.9 mg/g) and oleoresin content (45.2 mg/g) of dry ginger from a whole ginger rhizome dried by either solar tunnel drier or direct sunlight , with a 12.2% loss in essential oil when mechanical drying methods at 60 °C was used.

Newark tunnel with clay based soils, had highest TPC and DPPH concentrations in baby rhizomes as compared to other plant parts in 20%, 60% and 80%, unlike 40%. The order of concentration within plant parts started from baby rhizomes, mature rhizomes and leaves, with roots and pseudo stems having similar concentrations (Table 4.1, 4.2, 4.3, 4.4 and 4.5). Occasionally, 40% did not conform to these trends; phytocompounds concentrations in plant organs ranked from matured/mother rhizomes to baby rhizomes to leaves to pseudo stems and least in roots  Table 4.2, 4.3 and 4.4). In average, phytocompound concentrations were high and similar in mature/mother and immature/baby rhizomes, and low and similar in pseudo stems and roots; Most often leaves' phytoocompound concentrations were midway between rhizomes and other plant parts.

Zhang et al., (2013) found that normal irrigation, under natural sunlight without any shading effect resulted into higher anti-oxidation capacity in ginger leaves; this could be a plants' defense mechanism to over produce such

phytocompounds when stressed with the natural solar radiation. Lengthening photoperiod and night interruptions through applications of artificial lights increased the crude fiber content in ginger rhizomes (Flores et al., 2021). There is a large influence of environmental factors on the content of key compounds in ginger (Kizhakkayil and Sasikumar, 2011).

Experiment 2. Effects on the shelf life of baby ginger.

Temperature and humidity combinations, together with packing styles had a higher significant influence on the weight of baby rhizomes while addition of absorbent polymers and washing and disinfections were not significant (Table 4.6). Temperature and humidity combinations, together with packing styles had a significant influence on the weight of baby rhizomes while addition of absorbent polymers, washing and disinfections were not significant.

Temperature and humidity combinations together with packing styles had a significant influence on the weight of baby rhizomes while addition of absorbent

Table 4.6: ANOVA tests of temperature and relative humidity combinations, washing and disinfections, packing styles and absorbent polymers on the weight, density, total phenolic content, and pathogen score of stored ginger.

| Source | Weight | Density | TPC | Pathogen score |
|---|---|---|---|---|
| Temperature and R.H | <.0001* | 0.0038* | 0.0032* | 0.77 |
| Washing/Disinfections | 0.47 | 0.11 | 0.07 | 0.23 |
| Packing styles | <.0001* | 0.0159* | 0.0020* | 0.0318* |
| Absorbent polymers | 0.38 | 0.66 | 0.74 | 0.77 |

polymers, washing and disinfections did not (Table 4.6). Packing styles had a significant influence on the pathogen score of baby rhizomes while temperature and humidity combinations, addition of absorbent polymers and washing and disinfections had no significant effect on the pathogen score of baby ginger (Table 4.6).

The quality of baby rhizomes cannot be improved after harvesting, but rather be maintained to ensure its extended availability during storage. Pre-harvest determinants of produce quality include quality if planting materials, management,

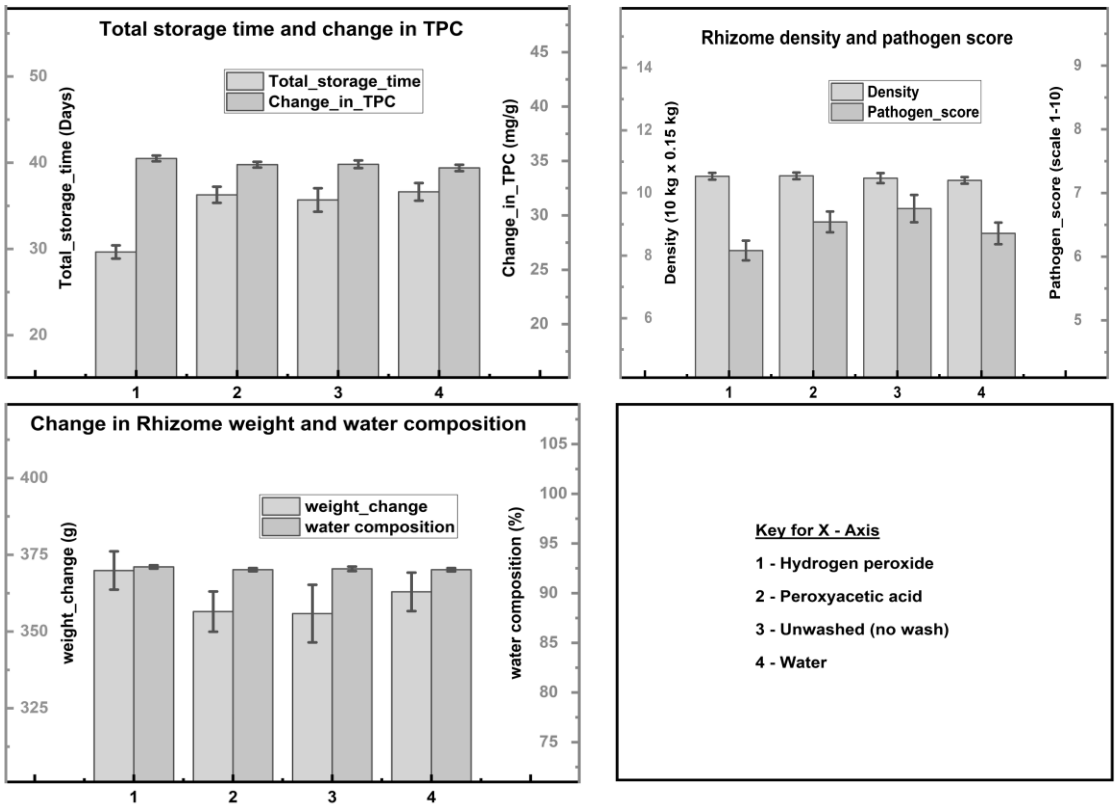



Figure 4.2: Effects of washings and disinfections using hydrogen peroxide, peroxyacetic acid, unwashed/no wash, and wash with water on rhizomes' total storage time, change in TPC content, density, pathogen score, weight change, and water composition.

practices, water supply, type of soil, environmental temperature, and mechanical damage, with packing, handling, and storage conditions of temperature, humidity, air composition affecting the storage life (Prusky, 2011).

In Figure 4.2, the upper left graph shows the effect of washings and disinfections on the total storage time and change in TPC content, the TPC concentration was similar across different washing and disinfections with highest TPC values recorded from hydrogen peroxide and lowest values from peroxyacetic acid. Total storage time was highest when ginger was washed with water, like peroxyacetic acid and unwashed, being lowest in hydrogen peroxide. The upper right graph shows the effect of washings and disinfections on the rhizome density and pathogen score. Similar rhizomes density values were obtained across all washings and disinfections; pathogen scores were highest in unwashed rhizomes and least in hydrogen peroxide. The lower left graph shows the effect of washing and disinfections on change in rhizome weight and water composition. Water composition was relatively similar across the factor variables, while weight change was decelerated in hydrogen peroxide and accelerated in unwashed and hydrogen peroxide.

Generally, washing with water then disinfecting with peroxyacetic acid recorded the heaviest weight of rhizomes as compared to washing with water or unwashed rhizomes. Hydrogen peroxide had the highest conservation of TPC, but with the lowest storage time. The density of rhizomes remained uniform regardless of the disinfection or washing levels, with a slight reduction when washed with water. Peroxyacetic acid had no effect on pathogen score or rhizome density. Peroxyacetic acid did not conserve the weight of baby rhizomes. The percentage in water

composition was highest in rhizomes washed with water and the lowest in both unwashed and washed with peroxyacetic acid.

Because wash with water had similar superior performance, it is preferred over peroxyacetic acid (Pedersen et al., 2013). Hydrogen peroxide is a more stable disinfectant but is best suited for sterilization of non-biological materials. The fast-decaying nature of peroxyacetic acid accounted for pathogen presence within the treated rhizomes (Pedersen et al., 2013). Storing rhizomes without washing confounds the specific weight data after harvest, leads to increased storage weight and volume, and provides conducive environment for storage pests (rodents, insects, and disease pathogens) infestation.

Figure 4.3 shows the effects of storage temperature and relative humidity on storage of baby rhizomes The upper left graph in Figure 4.3 shows the effects of storage temperatures and humidity combinations on the change in rhizome weight and water composition. Water composition was relatively similar across all factor variables. Weight change fluctuated with respect to storage temperature and humidity combinations. Weights were higher under high humidity (95%) in both 4 $^0$C and 10 $^0$C and low in room conditions. 10 $^0$C, 95% RH had slightly higher rhizome weight compared to 4 $^0$C, 95% RH; similarly, 10 $^0$C, 50% RH had slightly higher rhizome weight compared to 4 $^0$C, 50%.

The upper right graph shows the effect of temperature and humidity combinations on rhizome's density and pathogen score. Density was uniform, with both high humidities having a low-density score. Pathogen score was highest at 10 $^0$C, 95% RH and lowest in 4 $^0$C, 95% RH (Figure 4.3).

The lower left table shows the effect of temperature and humidity combinations on the total storage time and change in TPC content. The change in TPC was similar across all factor variables, being albeit lowest in 10 $^0$C, 95% RH.

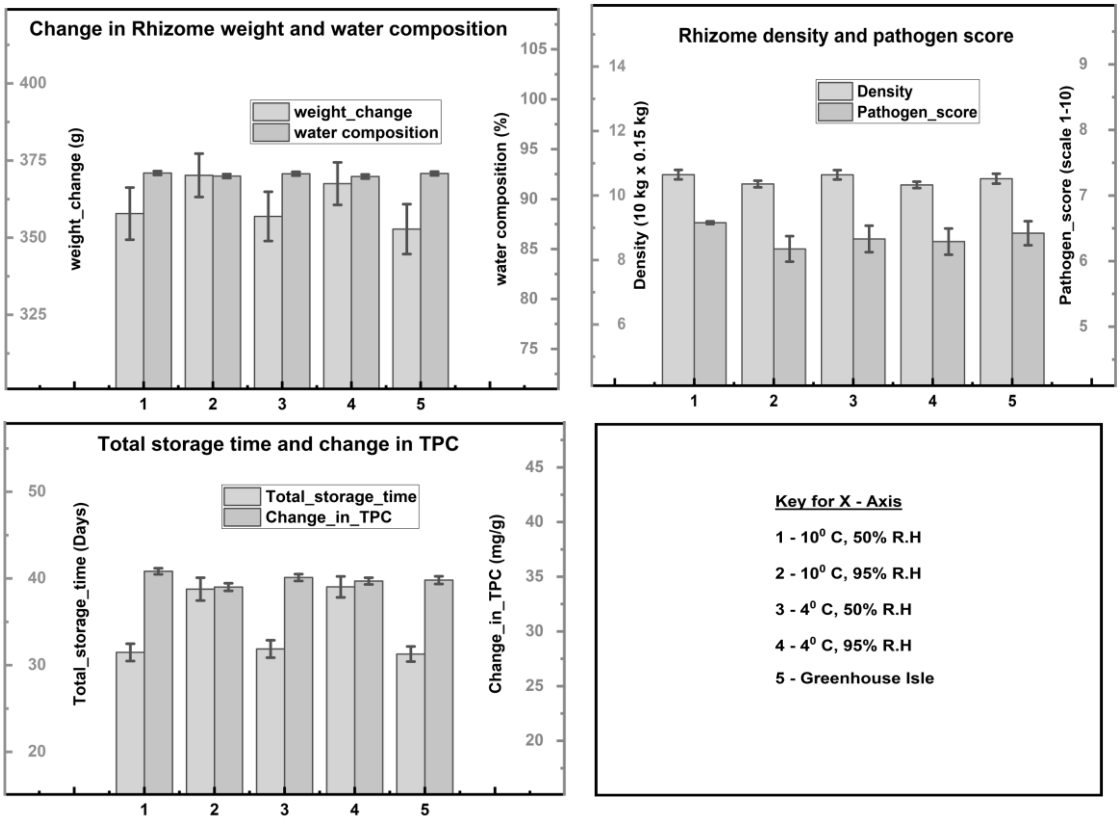



Figure 4.3: Effects of storage temperature (4$^o$C and 10$^o$C), relative humidity (50% and 95%), and room conditions on rhizomes' total storage time, change in TPC content, density, pathogen score, weight change, and water composition.

Total storage time was directly proportional to relative humidity. All high humidity combinations (4 and 10$^0$C by 95% RH) had higher total storage time and vice versa for

low humidity combinations (4 and $10^0$C by 50% RH, and room conditions) (Figure 4.3).

Regardless of temperatures, higher humidities (95%) conserved the weight of baby rhizome as compared to room and lower humidities (50%), with percent water composition remaining relatively uniform across all temperature and humidity combinations. The 4 $^0$ C, 50% RH treatment had the highest rhizome density while 10 $^0$C, 95% RH and 4 $^0$C, 95% RH had the lowest rhizome density. 10 $^0$C, 95% RH treatment had the lowest pathogen score, and the highest score came from 10 $^0$C, 50% RH. The relationship between storage time and relative humidity was directly proportional, lower humidities and room humidities were consequential to the storage time. 10 $^0$C, 95% RH recorded the lowest TPC, while all other treatments were similar.

Metabolic activities of growth of spoilage microorganisms, susceptibility to rhizome rot, wilting and sprouting, action of naturally occurring enzymes, structural changes and chemical reactions associated with ginger rhizomes are temperature dependent (Kaushal et al., 2017). With every 10-fold increase in temperature, metabolic activities double, within a certain temperature range. Lower temperatures such as 4 $^0$ C deactivates enzymatic activities hence delays deterioration of baby rhizomes but as the temperature spikes up, tissue damage results. Retana-Cordero et al., (2021) modelled the effects of temperature on ginger sprouting and found that ginger has active metabolic functioning in the temperature range of 20 to 30 $^0$ C. Matured rhizomes natural store longer and their shelf life is further enhanced with addition of regulators (Lv et al., 2021).

Humidity controls the influx or outflux of water from plant tissues such as the baby rhizome. Higher external humidity blocks the escape of water from the rhizomes, especially in the young and tender rhizomes without a rigid cuticle. High humidity and lower temperatures are among the renowned post-harvest factors for fresh produce (Prusky, 2011). High humidity is additionally consequential to ginger storage as it facilitates disease outbreaks and rapid deterioration of rhizomes through tissue disintegration, thus a balance between humidity and without facilitating disease outbreak is required. High humidity when coupled with fumigants, maintains quality of baby ginger during storage. Jia et al., (2021) extended the shelf life of tender ginger rhizomes for 50 days while maintain firmness, delaying weight loss, reducing decay rate, and enhanced the disease resistance of tender ginger while maintaining the FDA food standard: they combine cold storage, high humidity, and periodic sulfur dioxide fumigation every 15 days.

Absorbent polymers did not improve storage of baby ginger and provided baby rhizomes stored in vacuum sealed and ziplocked bags with enough water-saturated like environment throughout the storage experiment, encouraging colonization of storage pathogens and loss of tissue integrity.

The effects of packing techniques on the storage of baby ginger are shown in Figure 4.4. The graph on the top left corner shows the effect of packing techniques on the total storage time and change in TPC. Change in TPC was uniform across all factor variables while the total storage time was highest in sand, followed by bins, Ziplock bags and least in vacuum-sealed bags (Figure 4.4).

The graph on the top left corner shows the effect of packing techniques on rhizome density and pathogen score. Bins and sand enhanced rhizomes density while

vacuum-sealed bags and Ziplock bags diminished rhizome density. Bins and sand had higher pathogen score probably due to abundant aerobic environment, followed by Ziplock bags and least in vacuum sealed bags (Figure 4.4)

The graph on the bottom left shows the effect of storage techniques on the change in rhizome weight and water composition. Water composition was uniform.

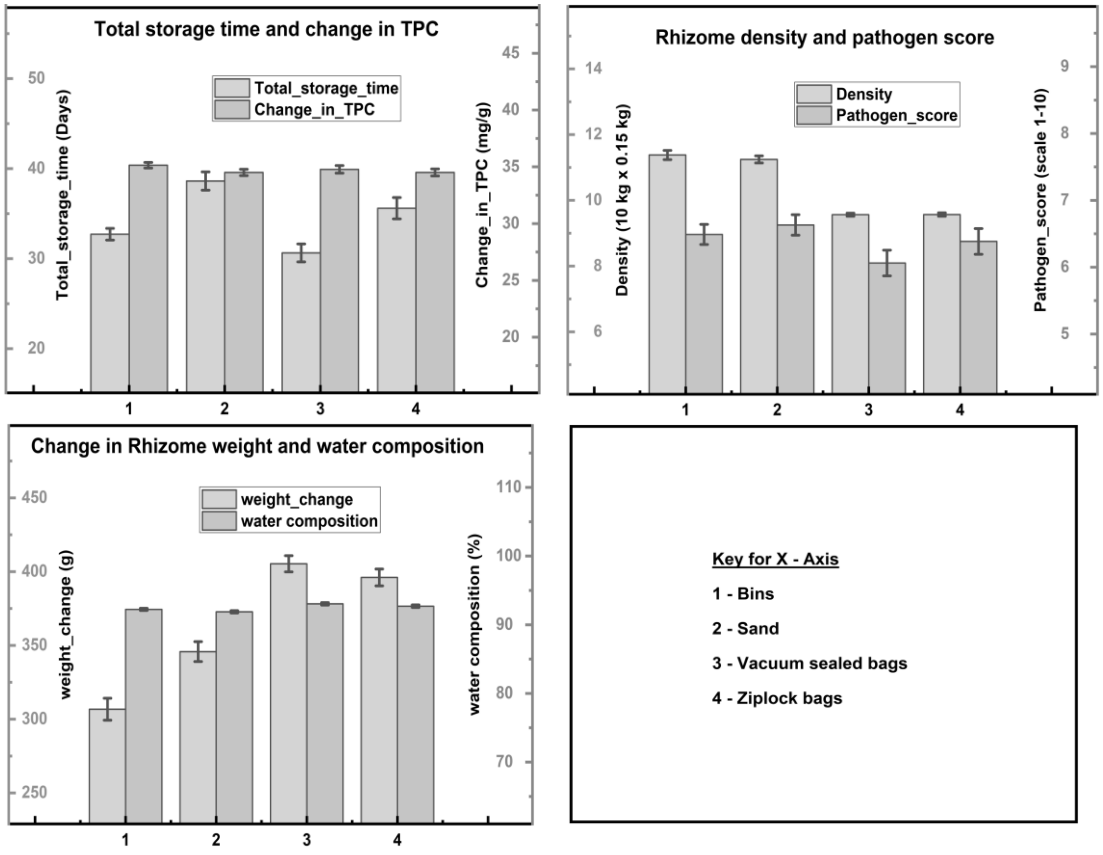



Figure 4.4: Effects of packing techniques using bins, sand, vacuum-sealed bags, and Ziplock bags on the storage of baby ginger.

across all factor variables while rhizome weight conservation was highest in vacuum sealed bags, followed by Ziplock bags. Bins had the lowest weight followed by sand (Figure 4.4).

Overall, Bins as storage vessels had the slightly highest TPC but with the lowest storage time, next to vacuum sealed bags. Usage of sand had the highest storage days (40) different from all other treatments, *i.e.*, Bins (32), vacuum sealed bags (30) and Ziplock bags (36). Bins and sand incorporation had the highest rhizome density, coupled with a higher pathogen score. Ginger in vacuum sealed bags recorded the lowest pathogen score (Figure 4.4).

There was a large weight reduction in bins, followed by sand incorporation. Vacuum sealed and Ziplock bags were excellent for ginger weight conservation. Rhizomes in bins and sand had a slightly lower reduction in moisture composition, but not in vacuum sealed bags or Ziplock bags.

Usage of Ziplock and vacuum sealed bags conserves the moisture of baby ginger. Vacuum sealed bags create an anaerobic storage condition, blocking oxidation process which leads to rapid deterioration. Empty bins and incorporation of baby rhizomes in sand are among affordable and convenient storage techniques for baby ginger when other factors are accounted for. These techniques results in weight loss from gradual water loss leading to maturation of baby rhizomes in 1–2 months under favorable conditions. Liu *et al.*, (2014) manipulated the storage environment of baby ginger using of sand, 20% water, and 3.75% super absorbent polymers, and delayed weight loss and loss of firmness at 12 °C and 90% relative humidity, eventually transforming them into matured ginger after 6 weeks.

Storage pathogens

Through genetic sequencing of infected and cultured ginger tissue, we identified several storage pathogenic and non-pathogenic microbes. Regardless of the washings and disinfections at lower concentrations (1 ppm), pathogens were persistent throughout. Several notable pathogens include *Globisporangium spinosum* a soil-borne pathogen responsible for root-rot and damping off diseases with a substantial yield loss on a variety of vegetables, ornamentals, and field crops; *Rhizoctonia bicornis* persistent as a soil-borne fungus, causing root rots, stem rots, and damping-off. *Pythium ultimum* is an infamous plant pathogen causing damping off and root rot diseases of hundreds of diverse plant hosts. It can grow saprotrophically in soil and plant residue thus longer persistence in the fields. *Pythium irregulars* is a pre- and post-emergence damping off, and root rot disease causing pathogen; they infect the planting materials pre-emergence, leading to discolorations and prevention of successful growth. *Fusarium oxysporum* is a wilt, foot- and root-rot disease causing pathogen with either a neutral, beneficial, or detrimental association with its host. From the tender cuticle and high moisture content of baby rhizomes, Liu *et al.*, (2014) named wilts and rots as their the devastating challenges during storage; they suppressed infection rates of *Mortierella, Fusarium* and *Penicillium* by 60.7%, 54.3%, and 50.3% respectively from their in vivo experiments using cinnamon fumigation at 500 ppm at 12 °C.

## Conclusions

This study suggests that ginger, when harvested pre-maturely, has more total phenolic contents and anti-oxidation capacity compared with traditional, matured

harvesting stage. Phytocompounds detected in other plant parts provide evidence that 95–100% of the ginger plant can be used as a spice. This increases the use potential from what is grown, as rhizomes only constitute about 44% of the total fresh biomass. Consumption of other ginger plant parts (leaves, pseudo stems and roots) increases sustainability of resource usage during production.

Proper storage of baby ginger ensures its longer, fresh availability in the markets, reducing post-harvest losses. When fresh, baby ginger has all its phytocompounds in their active states that are readily used by the human body. Longer storage of baby ginger requires a disease-free environment, with high relative humidity and low temperature. Further studies should be directed towards optimal conditions for baby ginger storage and disclosure of its potential storage pathogens. Additional research should focus on different processing and value addition routes to increase the diversity of marketed ginger products from immature ginger.

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