RESEARCH ARTICLE

Profiling beneficial health contents gingerol and shogoal and assessing plant growth and rhizome yield of ginger cultivars grown in greenhouse

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Ginger (*Zingiber officinale* Rosc.) is a valuable crop used as a spice or fresh herb in culinary dishes and for treating medical issues such as osteoarthritis, neurological diseases, vomiting, and asthma. The demand for ginger in the U.S. is remarkably high. As the number one ginger producer, Hawaii only produces 20% of the demand for ginger in the U.S. The rest of the demand is met by importing from other countries. This study aimed to assess health beneficial contents Gingerol and Shogoal among ginger cultivars and different parts of ginger and evaluate plant growth and rhizome yield of ginger cultivars under greenhouse settings. Ginger cultivars Hawaii Yellow (HY) and Chinese White were tested in 2018, and Big Kahunna (BK), Bubba Blue (BB), Madonna (MD), and Khing Yai (KY) were added in 2019. Health beneficial phytochemicals 6-gingerol, 6-shogaol, 8-gingerol, 8-shogaol, 10-gingerol, and 10-shogaol were measured in 2020 from edible (marketable) rhizome, biological roots, leaf, and root bulbs of all cultivars and were the highest in 6-gingerol edible rhizomes in Big Kahunna (5,946.7 µg/g), Chinese White (5,825.0 µg/g), and Madonna (5,630.0 µg/g) across all cultivars and tissues measured. Ginger cultivars were ranked in order from the highest rhizome yield per plant to the lowest yield for both 2018 and 2019, respectively, as Hawaii Yellow (1,107.2 g) > Kali Ma (731.6 g) > Chinese White (557.1 g) for 2018 and Kali Ma (1,452.0 g) > Madonna (1,186.0 g) > Big Kahunna (868.3 g) > Bubba Blue (561.0 g) > Hawaii Yellow (246.8 g) > Khing Yai (50.0 g) > Chinese White (43.0 g) for 2019. Year-to-year differences in plant growth and rhizome yield suggested genetic variability among cultivars.

Keywords: ginger; *Zingiber officinale* Rosc.; gingerol; shogaol; health.

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Introduction

Renowned for both medicinal and culinary values, ginger (*Zingiber officinale* Rosc.) is a tropical herbaceous plant cultivated primarily for its aromatic, underground tuberous rhizome, and used worldwide both as a spice and a medicinal ingredient [1]. Beyond its traditional role as a spice, ginger has emerged as a subject of scientific interest due to its diverse bioactive compounds and reported therapeutic properties. Native to southern Asia, it has been grown for centuries across Asia, the Caribbean, Central and South America, Australia, and Africa [2, 3]. Although fresh rhizomes remain the most common commercial form, ginger products include dry ginger, powder, oil, and oleoresin [4]. Globally, the Netherlands and the U.S. are major importers [5]. In the U.S., Hawaiian growers supply only about 20% of the total ginger demand, forcing reliance on imports to meet consumer needs [6]. Baby ginger, harvested earlier and prized for its tender, non-fibrous qualities, commands premium prices and has begun attracting growers seeking higher-value niche markets [7, 8]. As a tropical crop, ginger prefers warm, humid conditions, making it well suited for season extension systems such as greenhouses [9, 10]. These controlled environments can protect against adverse weather, extend the growing season, and help maintain optimal humidity and soil conditions [11]. However, limited research exists on ginger cultivar performance under greenhouse conditions, especially regarding health beneficial components Gingerol and Shogoal of ginger cultivars [12].

The ginger rhizome is typically composed of fibrous and fleshy roots. The fleshy portion is harvested along with any usable seed pieces [13]. Propagation occurs vegetatively using small rhizome segments [14]. The chemical composition of ginger includes primarily phenolic compounds, which consist of gingerols and shogaols that produce pungent flavor, antioxidant properties, and medicinal effects [15, 16]. The pungency of fresh rhizomes increases through dehydration to 6-shogaol after post-harvest drying or thermal processing, while the bioactive profile changes [17, 18]. Previous research has shown that these compounds possess anti-inflammatory, antimicrobial, anticancer, and antiemetic properties [19, 20]. The production levels of gingerols and shogaols depend on cultivar genetics and plant age at harvest, growing environment, and post-harvest handling [21]. Chemical composition analysis together with agronomic evaluation serves to identify cultivars that produce high yields and fulfill particular quality and nutraceutical standards.

Optimal growth conditions include partial sun, well-drained soil, temperatures ranging from 19 to 28°C, and relative humidity of 70 - 90% [22]. Harvest timing varies based on the end use, earlier for baby ginger, later for mature, fibrous rhizomes [23]. While ginger continues to gain economic importance, the consistent supply of high-quality, disease-free seed stock and cultivar performance data remains a critical challenge [24]. This research aimed to address these gaps by assessing multiple ginger cultivars in a greenhouse setting to establish recommendations for reliable, high rhizome, gingerol, and shogaol yield production in the United States.

Materials and methods

Transplant production

This research was conducted at the Farm of North Carolina Agricultural and Technical State University (Greensboro, NC, USA), which is in USDA Plant Hardiness Zone 7b. For both 2018 and 2019 growing seasons, ginger transplants were initiated from 20 to 25 g seed pieces each in early March. Ginger seed was purchased from Hawaii Clean Seed, LLC (Pahoa, Hawaii, USA). Each piece contained 1 to 2 growth points (buds). Coconut husk was used as the planting media because it does not compact like traditional soil mix, making it highly porous. It has lignin, which is resistant to bacterial and fungal growth. After 1-2 days of curing, seed ginger pieces were ready to be planted. Every seed tray (10” x 20”) had a thin layer (about 0.5 cm) of coconut husk on the bottom. The cut seed ginger pieces were placed roughly 1 inch apart with about 20 - 25 pieces per tray, depending on seed ginger piece size. The cut seed ginger pieces were covered with husk, thoroughly watered, and clearly labeled. The sprouts from the seed ginger pieces grew for about 2.5 months before being transplanted into pots for the greenhouse trial in late May 2018 and mid-June 2019. During those months, plants were watered daily or whenever it was needed to keep coconut husk moist. Plants were carefully managed to prevent pests and diseases.

Greenhouse trial

Ginger cultivars of Chinese White (CW), Kali Ma (KM), and Hawaii Yellow (HY) for 2018 and CW, KM, HY, Bubba Blue (BB), Madonna (MD), Khing

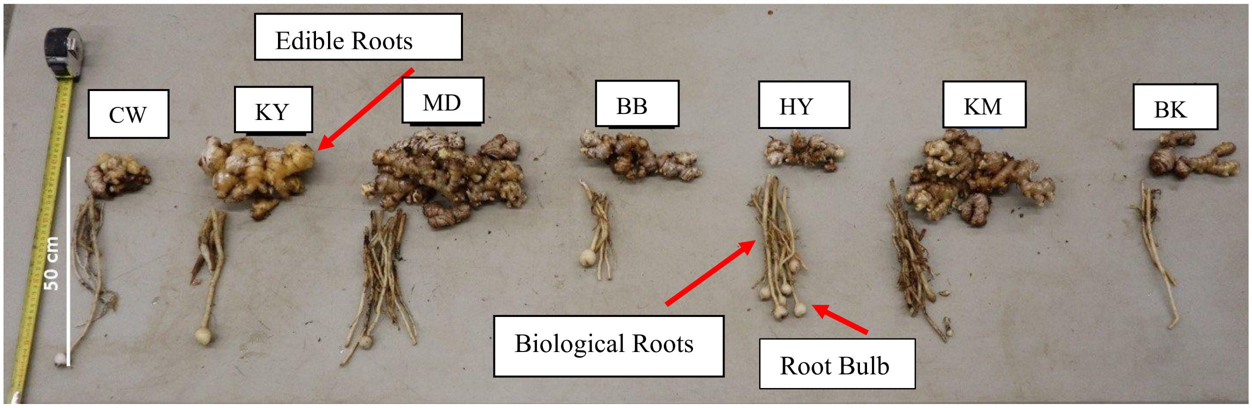

Figure 1. Comparison of cultivars (CW, KY, MD, BB, HY, KM, and BK) of freshly harvested ginger rhizomes from pots with biological and edible roots harvested on December 10, 2019.

Yai (KY), Big Kahunna (BK) for 2019 were grown in separate 10-gallon pots and evaluated for growth and yield. The plant growth and rhizome yield were measured and compared throughout the experiment, as well as overall biological roots (g), edible rhizome (g), seed (g), and total yield (g). The seed ginger was cut and placed in designated pots. One seed ginger was planted per pot on June 11, 2018, with 15 seed ginger pieces per cultivar. In 2019, one seed ginger was planted per pot with 10 seed pieces per cultivar on May 30, 2019. The greenhouse's experimental (potting) design was completely randomized design (CRD). Each pot served as a replication, and all pots were placed on a raised bench. The substrate was a mix of compost and conventional Metro Mix (Sun-Gro Horticulture, Agawam, MA, USA) at a 2:1 ratio. The fertilizer used was Osmocote 14-14-14, a slow-release fertilizer, and was applied at a rate of 111 grams per 10-gallon pot.

Plant growth data

Ginger growth data were collected twice to analyze active growth in a one-month time frame. Data was collected in September and again at the end of October. Plant height (mm), stem diameter (mm), and number of stems per seed ginger piece were measured. A digital dial caliper was used to measure diameter accurately, and a metric tape measure was used to measure plant height.

Harvest and yield data

After 7 months, the ginger rhizomes were harvested manually. Foliage could be used as leverage to pull the rhizome gently out of the soil (Figure 1). Once the ginger rhizomes were pulled out of the growing pots, the green foliage was removed to make the rhizomes easily available for cleaning. The ginger rhizomes were separated by cultivar (individual pots) and were transported to a Horticulture Unit Shop area where they were rinsed to remove any remaining soil. The rhizomes were then ready for further investigation and weighing. After investigation and yield data collection, the rhizomes were stored at room temperature for drying.

Yield data collection and analysis

Yield data included the overall (total) weight of ginger rhizome (g) and the individual weight of the different parts of the rhizome, which included biological root (g), edible rhizome (g), and seed piece (g). The rhizomes were weighed individually based on cultivar using an Ohaus digital scale. Ginger rhizomes were first weighed as a whole piece and then were divided by cutting off the biological roots and locating the seed ginger piece, which could be distinguished by its older appearance and rough texture (skin).

Analysis of 6-gingerol, 6-shogaol, 8-gingerol, 8-shogaol, 10-gingerol, and 10-shogaol with LC-MS/MS electrospray ionization

Analysis of ginger plants was conducted during the 2020 growing season. Plants sampled were grown using the same growing methodology as that used during the 2019 growing season. Mature leaf samples (three months after planting) were collected from the 10th leaf, counting from the base of each plant, with three plants sampled per cultivar. Edible rhizome, biological roots, and root bulb samples were collected post-harvest (six months after planting) from three plants per cultivar. All samples were prepared and placed in -80℃ freezer and then dried in the freeze dryer at -84°C with minimum chamber pressure control at -80℃ for 72 hours. Samples were ground into a fine powder between 200 - 500 um. Powdered samples were then sent to Drumetix Laboratories, LLC (Greensboro, NC, USA) for analysis of 6-gingerol, 6-shogaol, 8-gingerol, 8-shogaol, 10-gingerol, and 10-shogaol. For each sample measured, six samples of 10 - 15 mg of each were carried out with a total of six replicates per cultivar/tissue measured. For every milligram of tissue, 200 uL of methanol was added to extract gingerols and shogaols. After 18-hour extraction at room temperature (23°C), 20 uL of extracted sample was analyzed utilizing LC-MS/MS electrospray.

Data analysis

Data was initially processed and organized for plant growth and yield using Microsoft Excel (Microsoft, Redmond, WA, USA). The Proc mixed model of SAS University Edition Version 9.4 (SAS Institute, Cary, NC, USA) was used for ANOVA and other statistical analyses. Statistical significance was determined at $P \leq 0.05$ and $P \leq 0.01$ levels according to Fisher's Protected Least Significant Difference (LSD). Analysis of gingerol and shogaol contents were conducted using SAS PROC glimmix analyzed at the 0.05 level of significance and Tukey's HSD test to determine the differences of bioactive compound concentrations of ginger cultivars and tissues grown under greenhouse conditions.

Results and discussion

2018 and 2019 plant growth data

During 2018, there were significant differences among ginger cultivars in stem diameter (SD), stem length (SL), and stem number (SN). Hawaii Yellow had the highest SD of 9.1 mm, significantly greater than Chinese White (8.8 mm) and Kali Ma (8.5 mm), while there was no significant difference between Chinese White and Kali Ma. Similarly, Hawaii Yellow had the longest stems of 84.1 cm, significantly longer than Chinese White (76.6 cm) and Kali Ma (79.0 cm), but no significant difference was found between Chinese White and Kali Ma. ANOVA results indicated significant differences in SN ($P <$ 0.0001), whereas SD (P = 0.1398) and SL (P = 0.1161) were not significantly different. Overall, Hawaii Yellow demonstrated superior growth performance in 2018, producing the highest SD, SL, and SN values. In contrast, Chinese White consistently exhibited the lowest growth performance across all parameters. Cultivar differences were also observed in 2019, but the top-performing cultivars changed. Big Kahuna had the thickest stems of 8.8 mm, significantly greater than Chinese White (6.5 mm), Hawaii Yellow (6.2 mm), and Khing Yai (6.4 mm). However, no significant difference was found between Madonna (8.7 mm) and Kali Ma (8.1 mm). The longest stems were observed in Madonna (70.7 cm), which was significantly longer than all other cultivars, while Khing Yai had the shortest stems of 26.9 cm. Regarding SN, Kali Ma had the highest number of stems (12.5), significantly greater than all other cultivars, whereas Chinese White had the lowest number of stems (2.3). ANOVA results confirmed that all growth parameters (SN, SD, and SL) were significantly different among cultivars with P values ranged from < 0.0001 to < 0.0011. Unlike in 2018, Big Kahunna, Madonna, and Kali Ma emerged as top-performing cultivars in 2019, while Chinese White continued to have the lowest growth values across parameters (Table 1).

Overall plant growth performance (2018 *vs*. 2019)

Table 1. Growth average comparisons of ginger stem diameter (SD), stem length (SL), and stem number (SN) in the greenhouse for multiple cultivars by shade level (2018 and 2019).

Time	Cultivar	SD (mm)	SL (cm)	SN
10/8/2018	CW	8.8^{ab}	76.6^{b}	10.2^{b}
	HY	9.1^{a}	84.1^{a}	11.2^{a}
	KM	8.5^{b}	79.0^{ab}	10.1^{b}
	Mean	8.8	80.4	10.6
	Std Dev	2.6	30.4	3.2
	N	396	396	396
8/15/2019	BB	7.9^{b}	56.7^{b}	4.7^{b}
	BK	8.8^{a}	59.2^{b}	7.2^{ab}
	CW	6.5^{b}	46.1^{b}	2.3^{bc}
	HY	6.2^{bc}	38.5^{c}	6.5^{b}
	KM	8.1^{ab}	55.2^{b}	12.5^{a}
	KY	6.4^{bc}	26.9^{c}	4.0^{b}
	MD	8.7^{ab}	70.7^{a}	6.7^{ab}
	Mean	8.2	58.3	7.1
	Std Dev	2.4	27.6	4.3
	N	248	248	248

Notes: Significant difference ($P < 0.05$) between cultivars of the same year was represented by lowercase letters. Means having a letter in common was not significantly different.

The difference in growth performance in 2018 and 2019 indicated that environmental variability and management elements were significant for a cultivar's success. Prior studies suggested that light intensity, temperature changes, and nutrient availability greatly affected plants' growth and development [25, 26]. The relative genetic flexibility of cultivars over several environmental stresses could also account for the positive performance of some cultivars in one year and not in others. Research on plant growth suggested that genotypic plasticity enabled some cultivars to survive and grow more than others under certain stipulated conditions and subsequently exhibited little growth when there were changes in environmental conditions [27]. Moreover, along with the application of specific fertilizers, the soil microbiome's composition had also been shown to affect plant growth and development across many seasons [28]. This evidence pointed to the need to conduct multi-year trials and genotype by environment assessments for a more comprehensive understanding of cultivars for sustainable production [29]. With the use of precision agriculture tools such as controlled environmental studies or remote sensing for monitoring the health of plants, further study may shed more light on this issue of optimal selection of cultivars under changing environmental conditions [30].

2018 and 2019 ginger rhizome yield data

Yield data of 2018 indicated Hawaii Yellow as the highest-yielding cultivar, producing a total yield of 1,107.2 g, which was significantly greater than Kali Ma (731.6 g) and Chinese White (557.1 g). Hawaii Yellow also led in edible yield of 632.9 g, edible + seed weight of 642.7 g, and the number of pieces of 40.2. However, Kali Ma produced the highest biological root weight of 257.8 g, significantly greater than that of Chinese White (16.6 g) and Hawaii Yellow (40.2 g). Chinese White consistently had the lowest yield in all categories. ANOVA results confirmed significant differences in the number of pieces (P = 0.0014), biological root weight (P = 0.0005), edible root weight (P = 0.0416), and total weight (P = 0.0028). However, the weights of seed (P = 0.3977) and edible + seed (P = 0.0737) were not significantly different among cultivars. The results showed that Hawaii Yellow was the dominant cultivar in total yield and edible root production, while Kali Ma performed best in biological root weight. Chinese White had the lowest overall yield with no significant advantage in any measured category. In 2019, Kali Ma emerged as the highest-yielding cultivar, producing a total yield of 1,452.1 g, significantly greater than Hawaii Yellow (267.5 g), Chinese White (43.0 g), Big Kahuna (868.3 g), Khing Yai (70.0 g), and Bubba Blue (561.0 g). Additionally, Kali Ma had the highest biological root weight of 153.2 g, edible root weight of 1,209.7 g, and edible + seed weight of 1,200.1 g. In contrast, Madonna produced the most rhizome pieces of 60.3, significantly greater than Hawaii Yellow (15.0) and Chinese White (6.0) on average. Hawaii Yellow led in seed weight (49.5 g), while Chinese White and Khing Yai had the lowest recorded values in multiple yield categories. As a cultivar,

Table 2. Growth average comparisons and observations for yield parameters in the greenhouse concerning different cultivars (2018 and 2019).

Time	Cultivar	# of Pieces	Bio (g)	Edible (g)	Seed (g)	Edible + seed (g)	Total (g)
2018 greenhouse yield	CW	16.6^{b}	198.8^{b}	332.9^{b}	18.0^{b}	361.0^{b}	557.1^{b}
	HY	40.2^{a}	463.9^{a}	632.9^{a}	26.5^{a}	642.7^{a}	1,107.2^{a}
	KM	32.5^{a}	257.8^{b}	450.2^{b}	26.6^{a}	476.1^{ab}	731.6^{b}
	Mean	31.9	328.7	505.7	25.4	528.5	855.7
	Std Dev	14.7	178.7	249.9	8.7	245.1	372.7
	N	42	42	42	42	42	42
2019 greenhouse yield	BB	35.5^{b}	108.5^{b}	444.9^{b}	8.0^{c}	266.2^{c}	561.0^{b}
	BK	39.7^{b}	106.2^{b}	720.9^{b}	32.6^{b}	752.8^{b}	868.3^{b}
	CW	6.0^{c}	8.0^{c}	21.0^{c}	16.0c	37.0^{c}	43.0^{c}
	HY	15.0^{bc}	56.5^{b}	160.5^{b}	49.5^{b}	210.5^{c}	267.5^{b}
	KM	59.0^{a}	153.2^{a}	1,209.7^{a}	35.5^{b}	1,200.1^{a}	1,452.1^{a}
	KY	3.5^{c}	11.0^{c}	26.5^{c}	32.5^{b}	48.0^{c}	70.0^{c}
	MD	60.3^{a}	143.11^{a}	997.4^{a}	37.0^{b}	1,036.44^{a}	1,185.9^{a}
	Mean	43.8	116.1	752.9	29	728.9	913.8
	Std Dev	28.7	91.5	559.3	17.3	596.1	645.2
	N	44	44	44	44	44	44

Notes: Significant difference ($P < 0.05$) between cultivars of the same year was represented by lowercase letters. Means having a letter in common was not significantly different.

Chinese White did not produce well in this study. Big Kahunna and Bubba Blue did not show consistent trends and had no significant differences. ANOVA results indicated significant differences in the number of pieces ($P = 0.0057$), edible root weight ($P = 0.0004$), seed weight ($P = 0.0002$), edible + seed weight ($P = 0.0002$), and total weight ($P = 0.0004$). However, biological root weight was not significantly different among cultivars ($P = 0.1695$) (Table 2). Overall, Kali Ma was the most productive cultivar in 2019, outperforming all others in multiple yield categories. Although Madonna had the highest number of pieces, it did not have the highest total yield. Hawaii Yellow, which dominated in 2018, had a significantly lower total yield in 2019.

Overall ginger rhizome yield performance (2018 *vs*. 2019)

Rhizome yield performance of ginger cultivars varied significantly between the two years with Hawaii Yellow being the top-performing cultivar in 2018 and Kali Ma producing the highest total yield in 2019. While Kali Ma consistently had the highest biological root weight, its total yield only surpassed other cultivars in 2019. Madonna produced the most rhizome pieces in 2019, whereas Hawaii Yellow led in 2018. Meanwhile, Chinese White remained the lowest-yielding cultivar across both years. Microenvironmental conditions and genetic differences likely influence the rhizome yield fluctuations among ginger cultivars tested. Studies on rhizomatous plants suggested that climate, nutrient availability, and light intensity played key roles in yield variability [31, 32]. The shift in edible seed weight dominance from Chinese White in 2018 to Hawaii Yellow in 2019 indicated that different microenvironmental conditions might have favored distinct reproductive strategies [33]. The lack of a consistently superior cultivar across both years underscored the genotype-environment interaction in ginger yield performance [34]. Factors such as water availability and soil microbiota might also contribute to annual yield differences in rhizome crops [35]. These findings emphasized the need for multi-year cultivar evaluations to identify stable, high-yielding varieties under diverse growing conditions [30]. Despite uniform environmental conditions in a controlled greenhouse setting, ginger cultivars often exhibited varying levels of growth and performance, which could be attributed to a complex interplay of biological, environmental, and management related factors. Among these, key attention might be placed on microenvironments, plant spacing, especially overcrowding, light interception, and overall growth. Plant spacing and density are critical for optimizing light interception and air circulation within a greenhouse. Overcrowding can significantly disrupt these dynamics. Taller or more vigorously growing ginger cultivars might overshadow smaller or slower-growing ones, disproportionately limiting their access to photosynthetically active radiation (PAR). This light penetration reduction impaired photosynthesis, restricting energy production necessary for robust growth and rhizome development. Additionally, dense planting often leads to altered canopy structures, where plants elongate vertically in competition for light. This growth pattern can reduce total leaf area and photosynthetic efficiency [36, 37]. Overcrowding also intensifies competition for essential resources such as water and nutrients, further compounding the performance differences among cultivars, especially those with varying levels of resource use efficiency. Ultimately, these compounded effects can lead to reduced biomass and lower yield in cultivars who are less able to compete under crowded conditions [38, 39].

Although greenhouse environments are designed to provide uniform conditions, subtle microenvironmental variations can still influence plant performance. Differences in airflow and humidity, often determined by proximity to ventilation sources, can affect transpiration rates and disease pressure. Variations in light intensity and distribution may occur due to structural obstructions or the uneven development of plant canopies, resulting in localized shading. Likewise, even with controlled irrigation systems, soil moisture may not be evenly distributed across all pots, impacting root function and nutrient uptake [40, 41]. When combined with the physiological differences among ginger cultivars, these microenvironmental discrepancies could amplify or mitigate the adverse effects of overcrowding and further contribute to variability in growth and yield [42, 43]. Overcrowding on the grow bench during the second year might have resulted in decreased plant growth and yield.

Composition of overall health beneficial phytochemicals gingerol and shogaol by ginger cultivar and tissue type

The health beneficial phytochemicals, Gingerol and Shogaol, in ginger cultivars and tissue types were analyzed and profiled in this research. The noticeable significant differences in gingerol and shogaol contents among ginger cultivars and tissue types were observed. On average, 6-gingerol had the highest overall value for all ginger cultivars and tissue types tested as 1,886.0 µg/g followed by 10-gingerol of 610.6 µg/g, 8-gingerol of 322.2 µg/g, 6-shogaol of 34.8 µg/g, 10-shogaol of 13.2 µg/g, and 8-shogaol of 5.0 µg/g. There was also a significant difference among tissue types overall with edible (marketable) rhizome having the most bioactive compounds on average as 1,369.5 µg/g followed by biological roots of 512.9 µg/g, leaf of 18.5 µg/g, and biological root bulbs of 13.6 µg/g. There was significant difference among the seven ginger cultivars tested on average with ginger cultivar Chinese White having the highest on average for the entire plant of 573.6 µg/g followed by Big Kahunna of 508.7 µg/g, Kali Ma of 494.8 µg/g, Bubba Blue of 492.4 µg/g, Madonna of 477.9 µg/g, Khing Yai of 445.5 µg/g, and Hawaii Yellow of 357.7 µg/g. Gingerols were significantly higher than shogaols across all measurements of ginger cultivar and tissue type. Based on literature, gingerol and shogaol amounts in ginger undergo “reversible dehydration and hydration reactions” to form into one another. Therefore, it is unlikely to have equal amounts of corresponding gingerol or shogaol compounds in ginger samples, regardless of tissue or cultivar. Furthermore, as a general rule, shogaols would only be significantly higher than gingerols if the sample was first dehydrated and/or exposed to heat during the dehydration process [44].

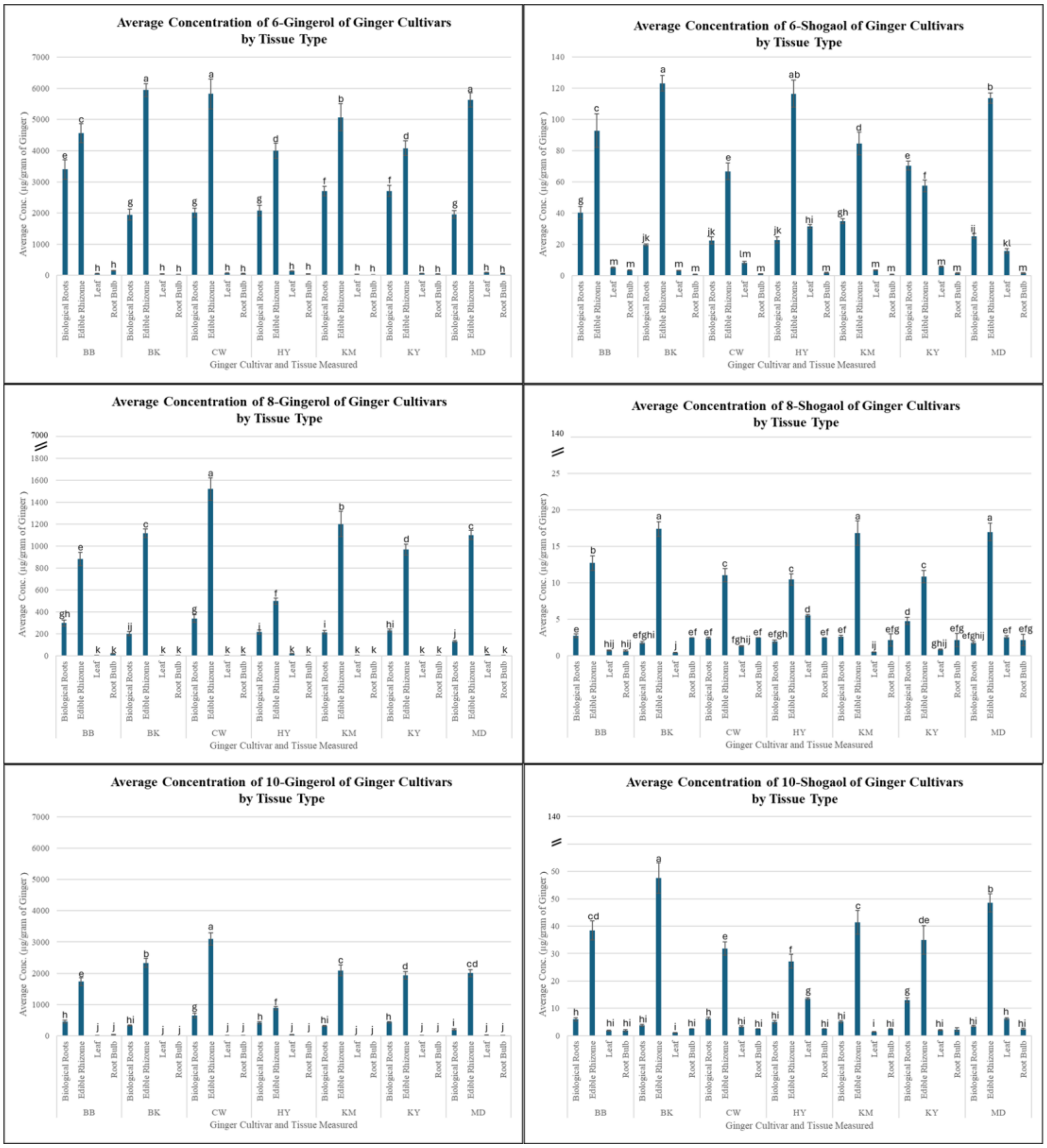

Figure 2. Mean concentration (µg/g of Ginger) +/- Standard Deviation of biochemical compounds by ginger cultivars and tissue type in plants grown under greenhouse settings. Means having a letter in common were not significantly different (*P* > 0.05).

Profiling of health beneficial phytochemicals gingerol and shogaol by ginger cultivar and tissue type

For each of the six biochemical compounds measured, there was significant change in average amounts dependent on the ginger cultivar as well as the type of tissue measured (Figure 2). The highest overall biochemical compound measured, 6-gingerol, was the highest in edible rhizome tissue with ginger cultivars of Big Kahunna (5,946.7 µg/g), Chinese White (5,825.0 µg/g), and Madonna (5,630.0 µg/g) having the highest amounts followed by Kali Ma (5,071.7 µg/g), Bubba Blue (4,565.0 µg/g), and Khing Yai (4,076.7 µg/g) and Hawaii Yellow (4,000.0 µg/g). Biological roots had the second highest contents of 6-gingerol with a noticeable change in ginger cultivars where the highest in edible roots was now the lowest in biological roots and vice versa. In order the highest 6-gingerol content on average was Bubba Blue (3,396.7 µg/g), Khing Yai (2,706.7 µg/g) and Kali

Ma (2,706.7 µg/g), Hawaii Yellow (2,078.3 µg/g), Chinese White (2,011.7 µg/g), Madonna (1,956.7 µg/g), Big Kahunna (1,941.7 µg/g). Leaf and root bulb tissues all had similar amounts across all cultivars ranging from 21.9 – 147.8 µg/g. 6-Shogaol measurements averaged between 0.75 – 123.2 µg/g depending on ginger cultivar and tissue type. The highest amount was found in Big Kahunna edible rhizome (123.2 µg/g), while the lowest one was Kali Ma root bulb (0.75 µg/g).

Both 8-gingerol and 10-gingerol followed the same general trend as 6-gingerol with edible rhizome having the highest across all ginger cultivars and tissue types followed by biological roots with root bulbs and leaf tissue having the same general amounts. The content of 8-gingerol ranged from 1.8 – 1,520 µg/g and 10-gingerol ranged from 3.8 – 3,095.0 µg/g with Kali Ma root bulb being the lowest and Chinese White edible rhizome being the highest. The content of 8-shogaol ranged from 0.4 – 17.4 µg/g and 10-shogaol ranged from 1.1 – 57.6 µg/g with Big Kahunna leaf being the lowest and Big Kahunna edible rhizome being the highest. There has been less research conducted on the amounts of 6-gingerol, 6-shogaol, 8-gingerol, 8-shogaol, 10-gingerol, and 10-shogaol within a ginger plant with most plant growth studies focusing on the production of 6-gingerol as a representative bioactive compound for measurement [45]. However, our results demonstrated that gingerol and shogaol amounts varied greatly between each of these six compounds among ginger cultivars, in this case, *Zingiber officinale* Rosc., and tissue types.

Conclusion

This research demonstrated that ginger cultivation worked as a specialized crop in North Carolina, USA with different cultivars showing distinct performance levels in terms of production and bioactive compounds. The 2018 trial results showed Hawaii Yellow as the top performer, but Kali Ma and Madonna outperformed all other cultivars in the 2019 trial. Kali Ma demonstrated the highest total yield and biological root weight throughout both years, which indicated its potential for root production excellence. Chinese White produced the lowest yields in the 2019 trial, yet maintained high average phytochemical content in 2020, which indicated its value for specialty markets that focused on functional compounds over bulk yield. The 2020 LC-MS/MS profiling showed that Chinese White, Big Kahunna, and Kali Ma produced higher levels of 6-gingerol and related gingerols. However, Hawaii Yellow contained lower bioactive compounds despite its initial strong yield performance. The selection of greenhouse cultivars for North Carolina production requires evaluation of yield performance together with growth characteristics and phytochemical contents. The evaluation process must continue because no single cultivar has achieved top results across all evaluation criteria to determine the best match between genotypes and production and market objectives.

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