Effect of Photoperiod, Propagative Material, and Production Period on Greenhouse-grown Ginger and Turmeric Plants

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Abstract. The objectives were to 1) compare growth and yield of different ginger (*Zingiber officinale*) and turmeric (*Curcuma longa*) propagules grown under two photoperiods (Expt. 1); and 2) evaluate whether their growing season could be extended with night interruption lighting (NI) during the winter (Expt. 2). In Expt. 1, propagules included 1) micro-propagated tissue culture (TC) transplants, 2) second-generation rhizomes harvested from TC transplants (2GR), and 3) seed rhizomes (R). Plants received natural short days (SDs) or NI providing a total photon flux density (TPFD) of $1.3 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Providing NI increased number of new tillers or leaves per plant, rhizome yield (i.e., rhizome fresh weight), and dry mass partitioning to rhizomes in both species. There was no clear trend on SPAD index in response to photoperiod or propagative material. Although TC-derived plants produced more tillers or leaves per plant, 2GR ginger and R turmeric produced a higher rhizome yield. In Expt. 2, seed rhizomes of ginger and turmeric were grown under five treatments with different photoperiods and/or production periods: 1) 20 weeks with NI (20NI), 2) 24 weeks with NI (24NI), 3) 28 weeks with NI (28NI), 4) 14 weeks with NI + 10 weeks under natural SDs (24NISR), and 5) 14 weeks with NI + 14 weeks under natural SDs (28NISR). NI provided a TPFD of $4.5 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Lengthening the production period and providing NI increased rhizome yield and crude fiber content in both species. SPAD index decreased when plants were exposed to natural SDs at the end of the production period (NISR treatments). Results demonstrate the potential to overcome winter dormancy of ginger and turmeric plants with NI, enabling higher rhizome yield under natural SDs.

Spice consumption in the United States is rising, partly because of demand from an increasingly ethnically diverse population (Nguyen et al., 2019; USDA, 2008). Ginger (*Zingiber officinale*) and turmeric (*Curcuma longa*) are popular spices with beverage, edible, and medicinal uses. The active ingredient in their rhizomes (principally gingerol and curcumin) includes phytochemicals with reported digestive, antioxidant, and anti-inflammatory properties (Ayodele et al., 2018; Nelson et al., 2017). Rhizomes can be marketed as fresh,

dried, and processed products, enabling commercialization to diverse target markets.

The United States is the largest importer of ginger and turmeric in the world, importing $\approx 80,000$ tons of ginger rhizomes per year, valued at \$136 million in 2018 (Garay Company, 2018; Statista, 2018). Similarly, the almost 10,000 tons of U.S.-imported turmeric were valued at $\approx \$38$ million in 2017 (Statista, 2019). There is a significant opportunity to produce these rhizomes domestically because of increased interest in local food crops, concerns with the availability and quality inconsistencies of imported products, and uncertainties surrounding international trade disruptions.

Production of these crops in the United States is mainly limited to Hawaii and southeastern states, where they are grown primarily by small-scale growers using conventional or organic production practices (Shannon et al., 2019). Existing protocols for field production of ginger and turmeric have been largely published in Asia (Nair, 2019); therefore, recommendations likely require adaptation for production in the United States because of differences in climate, labor cost, and market opportunities for locally grown products.

To develop a significant commercial ginger and turmeric industry in the continental

United States, environmental limitations that affect plant growth and development must be considered. One of the primary limitations for commercial production of these two tropical crops is their sensitivity to photoperiod. Ginger and turmeric are SD plants that enter dormancy when exposed to natural SDs (<12 h of light), which decreases rhizome yield and increases fiber content (Pandey et al., 1996). Therefore, field-grown rhizomes are generally harvested during the fall or winter, limiting production to specific seasons of the year.

NI lighting with electric lamps could be used as a strategy to control the seasonality of ginger and turmeric plants, as it is a common horticultural technique used by the floriculture industry to manipulate the critical night length of photoperiodic-sensitive species (Thomas and Vince-Prue, 1996). The NI strategy interrupts the dark period with low-intensity light during natural SDs, which can induce flowering of long-day (LD) plants or inhibit flowering of SD plants to promote vegetative growth (Meng and Runkle, 2016; Park et al., 2017). This enables season extension and flowering control in edible crops such as blueberry (*Vaccinium* spp.) and citrus (Bowman and Albrecht, 2021; Spann et al., 2003), and could be an effective strategy to maximize growth and rhizome yield of ginger and turmeric plants (Freyre et al., 2019).

Another important consideration for commercial production of these crops is ensuring availability of high-yielding, clean propagative material. Ginger and turmeric are commonly propagated from “seed rhizomes,” which are regular rhizomes either purchased from commercial sources or preserved by growers from a previous harvest (Ravindran and Babu, 2005). Rhizome preservation for seed material is often considered uneconomical, as growers miss the opportunity to sell high-value, locally grown rhizomes. Furthermore, significant labor and space is required for seed preservation (Nasirujjaman et al., 2005). In addition, rhizome-derived plants are susceptible to various soil-borne diseases that can lead to yield losses (Chenniappan et al., 2020; Guji et al., 2019; Ravindran et al., 2007; Salvi et al., 2002). An alternative to seed rhizome propagation is to use TC transplants, which can ensure uniform and pathogen-free starting material. However, TC transplants are more expensive than seed rhizomes and tend to result in lower yield during the first production cycle (Freyre et al., 2019; Ravindran and Babu, 2005; Salvi et al., 2002; Smith and Hamill, 1996). Second-generation rhizomes harvested from TC transplants could provide the cleanliness advantage of TC transplants and the yield potential of seed rhizomes.

Numerous opportunities exist to refine ginger and turmeric production systems in the United States, but practices related to photoperiod control and propagative material must be developed. Therefore, the objectives of this study were to 1) compare growth and yield of different ginger and turmeric propagules (derived from rhizomes or TC transplants) grown under two photoperiods in a greenhouse environment (Expt. 1); and 2) evaluate

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whether the growing season for these crops could be extended with NI applied to different production periods during the natural SDs of winter (Expt. 2). We hypothesized that rhizome yield would be higher in rhizome-derived plants compared with TC transplants. In addition, we hypothesized that longer production periods with continuous NI would increase plant growth and rhizome yield compared with production under natural SDs.

Materials and Methods

Plant material and growing conditions. In Expt. 1, propagules included the following: 1) micropropagated TC transplants of unknown ginger and turmeric varieties obtained from a commercial transplant supplier (Agri-Starts™ Inc., Apopka, FL); 2) second-generation rhizomes harvested in Jan. 2018 from TC transplants grown for 16 months in a research greenhouse at the University of Florida (UF) in Gainesville, FL (2GR); and 3) seed rhizomes (R) of ‘Bubba Blue’ ginger and ‘Hawaiian Red’ turmeric obtained from a commercial supplier (Hawaii Clean Seed LLC, Pahoa, HI).

On 18 Apr. 2018, 2GR (average weight of 43 and 20 g for ginger and turmeric, respectively) and R (average weight of 41 and 32 g for ginger and turmeric, respectively) were initially planted individually in black plastic trays [21-cm high × 27.8-cm wide × 6.2-cm deep; T.O. Plastics, Inc. Clearwater, MN] filled with sphagnum peatmoss (Klasmann-Deilman, Geeste, Germany) and placed in a growth room for 34 to 48 d under a constant ambient temperature of 25 °C, relative humidity (RH) of 90%, and daily light integral (DLI) of 5.7 mol·m⁻²·d⁻¹ (100 μmol·m⁻²·s⁻¹; 16 h·d⁻¹ photoperiod from 0500 to 2100 HR) provided by cool-white light-emitting diode (LED) fixtures (Model 40803; Green Creative, San Bruno, CA). Air temperature and RH were measured with temperature/RH probes (S-THC-M002; Onset Computer Corp., Bourne, MA) interfaced to a data logger (Onset Computer Corp.). The DLI was calculated by measuring the photosynthetic photon flux density with a quantum sensor (LI-250A; LI-COR Biosciences, Lincoln, NE).

Rhizomes were sprouted from 22 May through 5 June 2018. Uniform rhizomes of 2GR and R with at least one 5-cm shoot were planted into 1-gallon nursery trade containers (2.78 L) (Nursery Supplies Inc., Orange, CA) with a substrate consisting of 75% sphagnum peatmoss and 25% perlite by volume (Fafard®2P; Conrad Fafard, Inc., Agawam, MA) and placed in a polycarbonate greenhouse at UF in Gainesville, FL, under natural days (≈13.5 h·d⁻¹) until 26 June 2018. Uniform TC transplants with at least two shoots were planted on 4 May 2018 following the same procedures mentioned previously. Environmental conditions in the greenhouse were measured with a data logger (WatchDog Weather Tracker 305; Spectrum Technologies, Inc., Plainfield, IL), with day and night air temperature and solar DLI of 25.6 ± 1.9 °C, 24.7 ± 1.8 °C, and 9.6 ± 2.1 mol·m⁻²·d⁻¹ (mean ±

standard deviation), respectively. All plants were subsequently repotted on 27 June 2018 into 5-gallon nursery trade containers (14.5 L) (Nursery Supplies Inc.) filled with 56% pine bark, 31% sphagnum peatmoss, and 13% perlite by volume (Fafard®52 Mix, Conrad Fafard, Inc.). Immediately after transplanting, containers with plants were placed in one of two polycarbonate greenhouse compartments with automated heating and pad-and-fan evaporative cooling located at the UF Plant Science Research and Education Unit in Citra, FL. The experimental design was a split-plot design with photoperiod as the main plot and plant type as the subplot. Within each compartment, containers were arranged in a randomized complete block design with two replicate plants per propagative material per species placed in three separate benches (8 m × 2 m) (blocks).

Plants in one greenhouse compartment received natural days, whereas those in the other compartment were exposed to NI delivered by incandescent lamps providing a total photon flux density (TPFD) between 400 and 800 nm of 1.3 μmol·m⁻²·s⁻¹ from 2200 to 0200 HR starting on 6 July 2018. Air temperature, RH, and DLI were measured with temperature/RH probes and a quantum sensor (S-THC-M002 and S-LIA-M003, respectively; Onset Computer Corp.) interfaced to a data logger (Onset Computer Corp.). Plants under SDs were grown under day and night air temperature, RH, and solar DLI of 26.6 ± 3.1 °C, 21.3 ± 2.6 °C, 82.5 ± 10.5%, and 9.1 ± 3.6 mol·m⁻²·d⁻¹, respectively. Plants under NI were grown under a day and night air temperature, RH, and solar DLI of 26.8 ± 3.9 °C, 21.4 ± 2.1 °C, 78.5 ± 13.6%, and 8.4 ± 3.8 mol·m⁻²·d⁻¹, respectively. Plants were drip-irrigated with tap water and top-dressed with controlled release fertilizer (Osmocote Plus 15–3.9–10, 8- to 9-month release; ICL Specialty Fertilizers, Dublin, OH) at 114 g per container, providing 17.1 g·L⁻¹ N after transplanting. To promote growth of new shoots, plants were mounded on 29 Aug. 2018 with a depth of ≈10 cm using the same substrate described previously. Plants under SDs were harvested on 22 Jan. 2019, whereas those under NI were harvested on 21 Feb. 2019 (≈8 and 9 months after sprouting, respectively).

In Expt. 2, rhizomes of ‘Bubba Blue’ and ‘Madonna’ ginger (Hawaii Clean Seed LLC) and ‘Indira Yellow’ and ‘Hawaiian Red’ turmeric (average weight of 75 g) (Hawaii Clean Seed LLC) were initially planted individually in flat plastic trays (T.O. Plastics, Inc.) filled with a commercial substrate composed of 79% to 87% peatmoss, 10% to 14% perlite, and 3% to 7% vermiculite by volume (PRO-MIX BX Mycorrhizae; Premier Tech Horticulture, Quebec, Canada). Rhizomes were kept in a growth room for 60 d under a constant ambient temperature of 21 °C, 80% RH, and a DLI of 9 mol·m⁻²·d⁻¹ (173 ± 5 μmol·m⁻²·s⁻¹ with a 14-h·d⁻¹ photoperiod from 0600 to 2000 HR) provided by broadband white LED fixtures (RAY66; Fluence Bioengineering, Austin, TX). Before transplanting,

sprouted rhizomes with 5- to 20-cm shoots were selected to be used in the experiment.

On 28 Aug. 2019, sprouted rhizomes were planted into 5-gallon nursery trade containers (14.5 L) (Nursery Supplies Inc.) filled with the same substrate described previously mixed at 50% by volume with composted pine bark. Powdered dolomitic lime (M.K. Minerals, Manhattan, KS) was incorporated before planting at 3 g·L⁻¹. Immediately after transplanting, containers with plants were placed in one of four benches (4.6 m × 1.8 m) inside a polycarbonate greenhouse compartment at UF in Gainesville, FL. Air temperature, RH, and DLI were measured with temperature/RH probes (HMP60-L; Campbell Scientific, Logan, UT) and quantum sensors (SQ512; Apogee Instruments Inc., Logan, UT) interfaced to a data logger (CR1000; Campbell Scientific) and multiplexer (AM16/32B; Campbell Scientific), respectively. Each bench had one temperature/RH probe and one quantum sensor placed at above-canopy height, and measurements were made every 30 s and recorded at 60-min intervals. All plants were grown under natural days for 4 weeks, after which NI was delivered by red + white + far-red LED lamps (Arize Greenhouse Pro; GE Lighting, Cleveland, OH) providing a TPFD of 4.5 μmol·m⁻²·s⁻¹ from 2200 to 0200 HR. The weeks of exposure to NI depended on the treatment application as described later in this article. Throughout the experiment, plants were fertigated with drip irrigation using water-soluble fertilizer at 150 mg·L⁻¹ N (Peters Excel 15–5–15 Cal-Mag Special; ICL Specialty Fertilizers).

Five treatments were evaluated in Expt. 2, with three different harvest dates depending on the treatment applied: 1) 20 weeks with NI (20NI); 2) 24 weeks with NI (24NI); 3) 28 weeks with NI (28NI); 4) 14 weeks with NI + 10 weeks under natural SDs (24NISD); and 5) 14 weeks with NI + 14 weeks under natural SDs (28NISD). To prevent light pollution within treatments, plants under 24NISD and 28NISD were placed in a separate greenhouse compartment at week 14 (4 Dec. 2019) and continued to grow under natural SDs. All environmental setpoints were similar in the two environments. Before week 14, the average daily temperature, RH, and DLI were 27 ± 3 °C, 72 ± 5%, and 21.3 ± 8 mol·m⁻²·d⁻¹. After week 14, the average daily temperature, RH, and DLI in the greenhouse compartment with 28NI, 24NI, and 28 NI were 26 ± 3 °C, 75% ± 5%, and 20.1 ± 5 mol·m⁻²·d⁻¹. The average daily temperature, RH, and DLI in the greenhouse compartment with 24NISD and 28NISD were 25 ± 4 °C, 78% ± 7%, and 21.8 ± 7 mol·m⁻²·d⁻¹ after week 14. The experimental design was a completely randomized design, with one plant per container as the experimental unit and 12 treatment replications.

Data collected. In both experiments, relative chlorophyll content was measured every 2 weeks on fully expanded leaves from all plants using a SPAD meter (SPAD-502; Konica Minolta Sensing Inc., Osaka, Japan). Data were averaged based on measurements

made on three different points within a leaf. Before each harvest, shoot height was measured from the substrate base to the tip of the newest fully expanded leaf and the total number of new tillers (shoots) for ginger and leaves for turmeric were counted for each plant. Fresh mass (FM) of shoots, roots, and rhizomes were measured following each destructive harvest. Except for rhizomes, dry mass (DM) was measured for all the aforementioned plant organs by placing bagged tissue in a forced-air drying oven at 70 °C until constant mass. For each treatment replication, a subsample of fresh rhizomes ranging from 100 to 150 g was oven-dried to estimate rhizome DM per plant. DM partitioning was then calculated as the ratio of the DM for each plant organ divided by the whole-plant DM. In Expt. 2, FM and DM of flowers and tuberous roots (also known as “stem tubers,” which are thickened parts of a rhizome used as a storage organs) produced by each plant were also measured following each destructive harvest (Fig. 1).

Crude fiber content was measured in Expt. 2 following the procedures described by Bidwell and Bopst (1921). A subsample of 100 g of fresh rhizomes was used for each treatment replication. Samples were sliced transversally to 1 mm using a mandolin slicer, dried at 50 °C until constant mass, and ground to a powder form. One gram of dried powder (initial mass) was mixed with 12.5 mL of petroleum ether and centrifuged for 5 min, after which the solvent was carefully removed with a pipette, and this step was repeated three times. Tubes were left open in a flow hood overnight for complete evaporation of the

volatile solvent, followed by the addition of 25 mL of sulfuric acid for acid digestion. Samples were then kept at 120 °C in a sand bath for 30 min, and subsequently centrifuged. Acid was removed with a pipette, and the solid residue was rinsed with 10 mL of centrifuged boiling water, after which 25 mL of sodium hydroxide were added for basic digestion. Samples were then kept at 120 °C in a sand bath for 30 min and subsequently centrifuged. After removal of the alkali, the solid was rinsed with 10 mL of boiling water and centrifuged one more time. Residue was transferred to a ceramic plate and maintained at 130 °C $\pm$ 2 °C for 2 h. After drying, each sample was weighed again (final mass). Crude fiber as a percentage of DM was calculated as final mass/initial mass $\times$ 100.

Data analyses. In Expt. 1, data from plants grown in the greenhouse compartment under natural SDs and those grown under NI were compared, where blocks were considered as random effects and photoperiod, plant type, and their interaction were considered as fixed effects. In Expt. 2, all treatment means were compared with each other. Data were subjected to analysis of variance using R version 3.6.1 (R Core Team, 2020). Least-square treatment means were compared using Tukey's honestly significant difference test ($P = 0.05$) with the Agricolae package in R.

Results

Expt. 1. The photoperiod and type of propagative material affected several aspects of growth and yield of ginger and turmeric plants (Tables 1 and 2). Overall, plants grown under

NI produced more tillers or leaves, taller plants, more shoot FM, and a higher rhizome FM (from now on referred to as “yield”) than those grown under SDs, with increases of 52%, 31%, 70%, and 29% in ginger, and 80%, 10%, 139%, and 16% in turmeric, respectively. In ginger, there was an interaction of propagative material and photoperiod in root FM, where TC ginger grown under SDs produced the highest root FM (419 g). In turmeric, there was a two-way interaction for shoot height, where plants propagated from R grown under NI were taller (113 cm) than those from any other treatment, whereas TC plants grown under SDs were the shortest (89 cm), followed by those from 2GR grown under SDs (98 cm). Turmeric plants grown under SDs also had a higher root FM than those under NI (312 vs. 104 g, respectively), which was most likely attributed to the production of tuberous roots.

TC plants tended to produce more tillers and leaves, but lower rhizome yield than plants propagated from rhizomes (Table 1). For example, TC ginger produced more than twice the number of tillers compared with plants propagated from R (17 vs. 8, respectively), and tiller number from 2GR plants (12) was intermediate between those two treatments. Similarly, TC turmeric produced 54% more leaves than plants propagated from 2GR or R. Ginger plants propagated from 2GR were at least 50% taller and produced from 42% to 76% more rhizome yield than those from TC or R, respectively. In contrast, turmeric plants propagated from R were only 12% and 7% taller than those from TC or 2GR, respectively, but their rhizome yield was at least 42% higher than that from the other two treatments. No differences among propagative materials were measured in shoot FM. However, root FM of ginger was almost three times higher in TC plants than those propagated from R (296 vs. 100 g, respectively).

For both species, plants grown under SDs produced a higher total DM than those grown under NI, most likely attributed to their higher production of roots, as the DM partitioning to rhizomes was unaffected by photoperiod, and the DM partitioning to shoots was higher in plants grown under NI (Table 2). In ginger, total plant DM was higher in plants propagated from 2GR (646 g) than that from R (406 g), but similar to that from TC (546 g). No differences among propagative materials were measured for total plant DM in turmeric, which ranged from 416 to 511 g. There was an interaction of propagative material and photoperiod, where ginger plants propagated from R grown under SDs partitioned between 120% and 576% more DM into roots than any other treatment. For turmeric, the highest DM partitioning to roots was measured in plants propagated from 2GR grown under SDs, which was between 112% and 403% higher than that of any other treatment. There was no clear trend on SPAD index in response to photoperiod or propagative material, and values were more variable in ginger than in turmeric (Fig. 2).

Fig. 1. Tuberous roots produced from ‘Indira Yellow’ turmeric plants grown under natural short days at the end of the production cycle.

Table 1. Final growth parameters measured in ginger and turmeric plants grown in a greenhouse from different propagative materials under natural short days (SDs) (<12 h) or long-day treatments provided with night interruption lighting (NI) in Expt. 1.^z

Treatment	Tiller/Leaf (no.) ^y	Shoot ht (cm) ^x	Shoot FM ^w (g)	Root FM (g)	Rhizome FM (g)
Ginger					
Propagative material (PM)					
TC	16.7 a ^v	76.8 b	211.3	295.6 a	1014.8 b
2GR	11.6 ab	117.9 a	151.9	185.1 ab	1439.7 a
R	8.3 b	78.5 b	178.0	99.7 b	816.8 b
Photoperiod (P)					
SDs	9.7 b	77.3 b	134.7 b	242.6 a	926.8 b
NI	14.7 a	101.6 a	229.5 a	142.8 b	1198.8 a
PM × P					
TC SDs	15.8	64.6	181.0	418.5 a	963.8
TC NI	17.5	89.1	241.7	172.7 b	1065.7
2GR SDs	7.8	112.0	134.6	199.4 b	1435.4
2GR NI	15.3	123.7	170.2	167.3 b	1445.0
R SDs	5.3	61.2	89.3	102.8 b	465.8
R NI	11.3	95.8	266.7	96.5 b	1167.7
PM	***	***	NS	**	*
P	*	***	**	*	***
PM × P	NS	NS	NS	*	NS
Turmeric					
PM					
TC	10.8 a	95.6 b	220.4	220.9	610.9 b
2GR	7.0 b	100.8 b	239.0	215.5	600.1 b
R	7.0 b	107.5 a	286.3	188.3	867.6 a
P					
SDs	5.9 b	96.7 b	146.7 b	312.2 a	641.2
NI	10.6 a	105.9 a	350.5 a	104.3 b	744.5
PM × P					
TC SDs	7.7	89.2 c	154.7	305.8	622.8
TC NI	13.8	101.9 b	286.1	136.0	599.0
2GR SDs	5.2	98.4 bc	127.0	350.3	679.5
2GR NI	8.8	103.2 b	351.0	80.7	520.7
R SDs	5.0	102.3 b	158.3	280.3	931.2
R NI	9.0	112.7 a	414.3	96.2	804.0
PM	*	***	NS	NS	***
P	***	***	***	***	NS
PM × P	NS	***	NS	NS	NS

^zTC = tissue culture-derived transplants; 2GR = second-generation rhizomes harvested from TC plants after 16 mo. of growth in a greenhouse; R = seed rhizomes of 'Bubba Blue' ginger and 'Hawaiian Red' turmeric.

^yTillers for ginger and leaves for turmeric.

^xMeasured on the main stem of the plants.

^wFM = fresh mass.

^vFor each species, means within columns followed by the same letter are not different based on Tukey's honestly significant difference test at $P \leq 0.05$ ($n = 6$).

***, **, * indicate statistical significance at the $P \leq 0.001$, 0.01, and 0.05 level or not significant, respectively.

Expt. 2. The production period and photoperiod affected all growth variables measured in our study, but plant varieties had similar responses within species (Table 3). Overall, extending the production period and providing NI increased tiller/leaf number, shoot FM, and yield, which was highest in ginger and turmeric plants grown under 28NI (1334 and 1003 g, respectively), followed by 24NI. All ginger plants under NI produced flowers, with a higher FM under 24NI and 28NI compared with 20NI. In contrast, no flowers were produced in ginger plants grown under SDs or in turmeric plants, regardless of treatment. There were no treatment differences in shoot diameter (data not shown) or height in both species. Root FM in ginger was higher under 28NI than 20NI and 24NI. Similarly, turmeric root FM was higher under 28NI than 28NISD. In contrast, tuberous root formation was

favored by NISD treatments (Fig. 1). Regardless of production period, plants from both species grown under NI throughout the entire production cycle produced less tuberous root FM compared with those under NISD.

Increasing the production period under NI increased total plant DM in ginger and turmeric plants, and affected DM partitioning (Table 4). Increasing the production period with SDs provided at the end of the growing cycle also increased DM partitioning of turmeric into tuberous roots and reduced DM partitioning into rhizomes, with 13% and 37% of the DM measured in 24NISD and 28NISD, respectively, partitioned to tuberous root DM. In contrast, only $\approx 1\%$ to 2% of the DM measured in those same treatments was contributed by tuberous root DM in ginger. Similar to our findings for FM (Table 3), the DM partitioning of tuberous roots in both

species was lower in plants grown under 20NI, 24NI, and 28NI compared with those under NISD. In contrast, the DM partitioning to rhizomes was highest under 24NI in both species, but similar across all other treatments, which ranged from 63% to 67% in ginger and 31% to 43% in turmeric. For both species, there was a higher DM partitioning into rhizomes under 24NI than 24NISD, but no differences were measured between 28NI and 28NISD.

Extending the production period from 20 to 28 weeks in plants consistently exposed to NI increased rhizome crude fiber content, which ranged from 19% to 36% in ginger, and from 15% to 37% in turmeric (Table 3). Furthermore, rhizomes from plants grown under 28NI had the highest crude fiber content in both species (36% in ginger and 37% in turmeric).

SPAD index remained high after week 14 in plants grown under NI but declined slowly over time in those exposed to natural SDs at the end of the production cycle (Fig. 3). The SPAD index in ginger ranged from 52 to 57 under NI treatments, and 39 to 42 under NISD treatments. Similarly, SPAD index values in turmeric ranged from 46 to 51 under NI treatments, and 34 to 47 under NISD treatments.

Discussion

Propagative material effects. Results from Expt. 1 correspond with previous studies indicating that micropropagated ginger and turmeric plants produce more shoots than rhizome-derived plants (Ravindran et al., 2007; Salvi et al., 2002; Smith and Hamill, 1996) (Tables 1 and 2). Although the concentration of plant growth regulators used during the micropropagation process of the TC transplants used in our study is unknown, higher shoot multiplication of TC plants has been attributed to the relatively high concentration of plant growth regulators used during the micropropagation process (Nasirujjaman et al., 2005; Salvi et al., 2002).

As expected, 2GR ginger plants produced more rhizome yield than those propagated from TC (Table 1). These findings are likely attributed to a greater success during establishment after transplanting, enabling 2GR plants to grow faster and taller than TC-derived plants, which regenerated through callus and, thus, lacked rhizome reserves to aid with initial plant growth (Babu and Jayachandran, 1997; Smith and Hamill, 1996). Surprisingly, ginger plants propagated from R had the same yield as TC plants, which is most likely explained by genetic differences between varieties, as micropropagated plants (both TC and 2GR) were the same unknown variety that was different from that used for R. Similarly, turmeric plants propagated from R produced the highest rhizome yield, presumably because of genetic differences in plant material. However, in contrast to ginger, there were no differences in rhizome yield between TC or 2GR-turmeric propagated plants (Table 1).

Table 2. Total plant dry mass (DM) and DM partitioning measured in ginger and turmeric plants grown in a greenhouse from different propagative materials under natural short days (SDs) (<12 h) or long-day treatments provided with night interruption lighting (NI) in Expt. 1.^z

	Total plant DM	Shoots	Roots	Rhizomes
Treatment	(g)		(%)	
Ginger				
Propagative material (PM)				
TC	546.0 ab ^y	25.1	11.1	63.8
2GR	646.4 a	23.9	7.7	68.4
R	405.5 b	25.8	17.6	56.7
Photoperiod (P)				
SDs	599.5 a	21.5 b	19.7 a	58.8
NI	404.1 b	29.1 a	6.3 b	64.6
PM × P				
TC SDs	711.9	21.9	13.8 b	64.3
TC NI	380.0	28.3	8.4 b	63.3
2GR SDs	696.4	21.4	9.9 b	68.6
2GR NI	571.4	27.6	4.5 b	67.9
R SDs	438.6	21.2	30.4 a	48.4
R NI	372.4	30.3	4.7 b	64.9
PM	**	NS	NS	NS
P	**	*	***	NS
PM × P	NS	NS	*	NS
Turmeric				
PM				
TC	415.8	35.3	12.9 ab	51.8 ab
2GR	510.9	34.7	21.5 a	43.8 b
R	510.9	33.8	11.2 b	55.0 a
P				
SDs	647.2 a	24.6 b	23.1 a	52.3
NI	331.6 b	43.4 a	8.0 b	48.6
PM × P				
TC SDs	505.4	27.9	18.0 b	54.1
TC NI	341.1	41.0	8.6 b	49.9
2GR SDs	785.5	21.9	38.2 a	40.5
2GR NI	282.0	45.8	7.6 b	46.6
R SDs	650.2	24.7	14.7 b	60.6
R NI	371.6	42.9	7.8 b	49.3
PM	NS	NS	NS	*
P	***	***	***	NS
PM × P	NS	NS	*	NS

^zTC = tissue culture-derived transplants; 2GR = second-generation rhizomes harvested from TC plants after 16 mo. of growth in a greenhouse; R = seed rhizomes of 'Bubba Blue' ginger and 'Hawaiian Red' turmeric.

^yMeans within columns followed by the same letter are not different based on Tukey's honestly significant difference test at $P \leq 0.05$ ($n = 6$).

***, **, *, NS indicate statistical significance at the $P \leq 0.001$, 0.01, and 0.05 level or not significant, respectively.

Photoperiod effects. Results from both experiments indicate that NI can be used as an effective strategy to extend the growing season, inhibit winter dormancy, and increase yield of ginger and turmeric plants (Tables 1–4; Figs. 2 and 3). Similar to our findings, Adaniya et al. (1989) reported an increase in ginger shoot growth, shoot diameter, number of flowers, and whole-plant FM as daylength increased. Ravindran and Babu (2005) also reported more shoots in ginger plants grown under natural LDs (>12 h) compared with those grown under SDs (<10 h). In addition, Pandey et al. (1996) showed that ginger plants grown under 12- or 14-h photoperiods did not enter dormancy and ultimately produced more tillers than those grown under 8- or 10-h photoperiods. There is limited information available on photoperiod responses for turmeric rhizome production.

The increased rhizome yield and overall growth under NI compared with SDs can be attributed to the effects of NI on dormancy regulation (Tables 1–4). As indicated by Masuda et al. (2007), phytochrome B detects the light stimulus in rhizome-producing plants and inhibits dormancy, increasing rhizome growth and accelerating development. The authors showed that lotus (*Nelumbo nucifera*) rhizome elongation increased with NI using blue, green, and far-red light. Nonetheless, several studies evaluating the use of NI for LD ornamental plants have shown that red + far-red lamps are more effective at regulating flowering than white lamps or LED fixtures emitting blue without or with red and far-red light (Meng and Runkle, 2016). Furthermore, it is widely accepted that the ratio of red to far-red light influences the phytochrome photoequilibrium (PPE) in plants, regulating many morphological and

physiological responses such as flowering, tuberization, bud dormancy, and plant architecture (Craig and Runkle, 2016). Light sources with a combination of red and far-red light that provide an intermediate PPE promote extension growth and flowering in LD plants. Accordingly, plants in our study grown under NI provided by incandescent lamps or red + white + far-red LEDs produced more rhizome FM than those under SDs throughout the experiment (Expt. 1) or at the end of the production period (Expt. 2).

Similar to our findings for growth, yield, and SPAD index, which was used as an indicator of active plant growth (Tables 1–4; Figs. 2 and 3), Bowman and Albrecht (2021) reported that NI can inhibit winter dormancy in citrus rootstocks. Their results showed that plants grown under high-pressure sodium (HPS) or LED lamps produced more vegetative growth compared with those under natural SDs. However, HPS lamps, which had a lower PPE, were conducive to more vegetative growth than LEDs. Under high far-red, not enough active P_{FR} (active form of phytochrome) is produced to promote a stimulus; and under low far-red, an excess of P_R (inactive form of phytochrome) is produced, inhibiting a response (Craig and Runkle, 2016). We speculate that similar phytochrome responses regulate dormancy in ginger and turmeric plants. Therefore, it is likely that lamps need to provide phytochrome-controlling wavebands for NI to help increase rhizome production under natural SDs.

In general, plants grown under SDs produced more roots than those under NI (Tables 1–4). In addition, we found that tuberous roots were mainly formed when plants in Expt. 2 were exposed to natural SDs at the end of the production cycle (NISD treatments), which was more evident in turmeric (ranging from 0% to 37%) than in ginger (ranging from 0% to 2%) (Fig. 1). Ravindran et al. (2007) had previously described fleshy and ellipsoid root tubers produced from turmeric plants grown under SDs. It is likely that rooting changes in response to photoperiod are at least partly responsible for the differences among treatments measured in total DM and DM partitioning in both experiments.

Although roots are necessary for the absorption of water and nutrients by all plants, tuberous roots seem to compete with the production of rhizomes and other plant organs, potentially affecting yield (Ravindran and Babu, 2005). For example, it appears that in Expt. 2, tuberous roots under 24NISD and 28NISD had a negative effect on shoot and rhizome growth, most likely attributed to a reallocation of photosynthates (Table 3). Moreover, according to Dixit and Srivastava (2000), active rhizome growth seems to promote translocation of primary photosynthates to freshly developing rhizomes instead of roots, which corresponds to our findings for plants grown under NI. Growth and development of storage organs such as tuberous roots can be present in several other plant species that go dormant under unfavorable conditions, such as SDs or low temperatures (Lubbe and

Fig. 2. SPAD index measured in ginger (top) and turmeric (bottom) plants grown in a greenhouse from 7 July (week 11) to 13 Dec. 2018 (week 32) in Expt. 1 using different propagative materials under natural short days (SD) (<12 h) or long-day treatments provided with night interruption lighting (NI). TC = tissue cultured transplants; 2GR = second-generation rhizomes harvested from TC plants after 16 months of growth in a greenhouse; R = seed rhizomes of 'Bubba Blue' ginger and 'Hawaiian Red' turmeric. Each data point represents the mean $\pm$ SE (n = 6). When significant, ***, **, and * indicate statistical significance at the $P \leq 0.001$, 0.01, and 0.05 level, respectively, for each factor (PM = propagative material and P = photoperiod) or their interaction (PM $\times$ P).

Henry, 2019). For example, potato (*Solanum tuberosum*) and potato yam (*Dioscorea bulbifera*) are induced to tuberize under SDs (Amador et al., 2001; Forsyth and Van Staden, 1984; Plantenga et al., 2016). Our findings indicate that the overproduction of tuberous

roots, which can be particularly significant in turmeric plants, can be reduced with NI.

In Expt. 2, only ginger plants grown under NI produced flowers (Table 3). Flowering is reportedly uncommon in edible ginger but can occur in response to LDs (Ravindran and

Babu, 2005; Ravindran et al., 2007). Studies of Japanese ginger (*Zingiber mioga*) also showed that flower bud initiation can be promoted under LDs (Stirling et al., 2002). Flowers can compete for photoassimilates with rhizomes, potentially leading to yield reductions in ginger

Table 3. Final growth parameters measured in two varieties of ginger and turmeric plants grown in a greenhouse under different production periods (20, 24, or 28 weeks) and photoperiods [continuous night interruption lighting (NI) or NI followed by natural short days (SD) at week 14] in Expt. 2.^z

Treatment ^y	Tiller/leaf (no.) ^x	Shoot ht (cm)	Shoot FM (g)	Flower FM (g)	Root FM (g)	Tuberous root FM (g)	Rhizome FM (g)	Crude fiber (%)
Ginger								
20NI	28.1 bc ^w	112.5 a	865.9 bc	0.3 b	96.2 b	0.0 b	513.5 c	19.2 bc
24NI	29.3 b	137.8 a	1242.8 b	8.5 a	114.5 b	0.0 b	912.7 b	23.7 b
28NI	55.0 a	141.3 a	2534.0 a	8.1 a	188.9 a	1.2 b	1334.4 a	35.9 a
24NISD	19.3 c	125.9 a	664.0 c	0.0 b	117.6 ab	9.8 a	479.5 c	16.9 bc
28NISD	20.6 bc	128.7 a	736.6 c	0.0 b	146.2 ab	16.1 a	594.6 c	14.1 c
Treatment (T)	***	NS	***	***	**	***	***	**
Variety (V)	NS	NS	NS	NS	NS	NS	NS	NS
T × V	NS	NS	NS	NS	NS	NS	NS	NS
Turmeric								
20NI	38.2 b	192.4 a	1911.4 bc	0.0 a	200.6 ab	0.0 c	313.2 d	15.4 c
24NI	43.0 b	187.7 a	2388.8 b	0.0 a	213.4 ab	2.4 c	802.3 b	24.2 b
28NI	84.2 a	192.8 a	3494.3 a	0.0 a	250.2 a	1.8 c	1002.7 a	36.8 a
24NISD	28.6 b	186.5 a	1524.7 c	0.0 a	198.3 ab	153.2 b	512.1 c	19.9 bc
28NISD	27.3 b	193.0 a	1463.2 c	0.0 a	180.4 b	529.6 a	598.8 c	18.4 c
T	***	NS	***	NS	***	***	***	*
V	NS	NS	NS	NS	NS	NS	NS	NS
T × V	NS	NS	NS	NS	NS	NS	NS	NS

^z‘Bubba Blue’ and ‘Madonna’ ginger; ‘Indira Yellow’ and ‘Hawaiian Red’ turmeric.

^y20NI, 24NI, and 28NI refer to 20, 24, or 28 weeks with NI, respectively; 24NISD refers to 14 weeks with NI + 10 weeks of SDs, and 28NISD refers to 14 weeks with NI + 14 weeks of SDs.

^xTillers for ginger and leaves for turmeric.

^wFor each species, means within columns followed by the same letter are not different based on Tukey’s honestly significant difference test at $P \leq 0.05$ ($n = 12$).

***, **, *, NS indicate statistical significance at the $P \leq 0.001$, 0.01, and 0.05 level or not significant, respectively.

and turmeric plants (Kandiannan et al., 2015; Vimala and Nambisan, 2005). However, in our study, the higher flower production of ginger plants grown under NI was accompanied by an increase in shoot biomass, which might have counteracted any potential reductions in yield, as more shoots led to more rhizome production (Rajyalakshmi and Umajyothi, 2014). Furthermore, it is likely that the limited number of flowers and relatively low flower FM produced

under NI had an insufficient sink strength to affect rhizome yield.

Flowering responses vary greatly among *Curcuma* species. For example, ornamental turmeric plants are attractive to consumers because in addition to their rhizome production, they have flowers with large and brightly colored top bracts. However, not all turmeric species have distinctive bracts, or flower consistently every year (Kandiannan et al.,

2015; Ravindran et al., 2007). In Expt. 1, turmeric plants grown under NI produced more flowers than those under natural SDs (data not shown). However, no flowers were produced in turmeric plants during the shorter growth period in Expt. 2, regardless of treatment (Table 1). Ravindran et al. (2007) stated that flowering of turmeric takes place after ≈ 4 months of growth, which corresponds with the natural shift to SDs in Expt. 2 (mid-October) and might explain the increase in flower production in response to NI (data not shown).

In Expt. 2, there was a clear decline in SPAD index in both species when plants were transferred to SDs at week 14 (Fig. 3). Others have suggested that SPAD index values ≥ 40 indicate acceptable plant health status in ginger (Li et al., 2018; Wang et al., 2019). Accordingly, Li et al. (2018) found that ginger plants grown under adequate growing conditions had an average SPAD index of 49, which is generally within range from values measured in both experiments, except for ginger plants propagated from 2GR and all turmeric plants in Expt. 1. Those same plants also produced more and thicker shoots and were taller than plants grown under drought stress (Li et al., 2018). Similar results were obtained in Expt. 2, as plants grown under NI had higher SPAD index values and produced more tillers or leaves than those under NISD treatments, suggesting that they were actively photosynthesizing and thus, most likely had a better ability to grow and produce more biomass. However, it is interesting to note that even if clear growth and yield differences were measured in response to photoperiod in Expt. 1, values for SPAD index were generally similar under NI and SDs. It appears that although rhizome development depends on the translocation of

Table 4. Total plant dry mass (DM) and DM partitioning measured in two varieties of ginger and turmeric plants grown in a greenhouse under different production periods (20, 24, or 28 weeks) and photoperiods [continuous night interruption lighting (NI) or NI followed by natural short days (SD) at week 14] in Expt. 2.^z

		Shoots	Roots	Rhizomes	Tuberous roots
Treatment ^y	Total plant DM (g)	(%)			
Ginger					
20NI ^y	351.7 c ^x	32.7 a ^y	1.4 b	65.9 b	0.0 b
24NI	544.6 b	22.3 b	1.6 b	76.2 a	0.0 b
28NI	892.2 a	31.2 a	1.5 b	67.3 b	0.1 b
24NISD	317.8 c	28.9 ab	2.4 ab	67.3 b	1.3 a
28NISD	379.4 c	31.8 a	3.4 a	63.1 b	1.7 a
Treatment	***	***	**	***	***
Variety	NS	NS	NS	NS	NS
Treatment × variety	NS	NS	NS	NS	NS
Turmeric					
20NI	279.0 d	61.0 a	5.2 a	33.8 bc	0.0 c
24NI	465.5 bc	42.8 b	2.8 bc	54.1 a	0.2 c
28NI	786.9 a	57.1 a	2.5 bc	40.4 bc	0.1 c
24NISD	377.9 cd	40.3 bc	3.9 ab	42.5 b	13.2 b
28NISD	576.1 b	29.7 c	2.4 c	31.1 c	36.8 a
Treatment	**	***	***	***	***
Variety	NS	NS	NS	NS	NS
Treatment × variety	NS	NS	NS	NS	NS

^z‘Bubba Blue’ and ‘Madonna’ ginger; ‘Indira Yellow’ and ‘Hawaiian Red’ turmeric.

^y20NI, 24NI, and 28NI refer to 20, 24, or 28 weeks with NI, respectively; 24NISD refers to 14 weeks with NI + 10 weeks of SDs, and 28NISD refers to 14 weeks with NI + 14 weeks of SDs.

^xFor each species, means within columns followed by the same letter are not different based on Tukey’s honestly significant difference test at $P \leq 0.05$ ($n = 12$).

***, **, *, NS indicate statistical significance at the $P \leq 0.001$, 0.01, and 0.05 level or not significant, respectively.

Fig. 3. SPAD index measured in two varieties of ginger (top) ('Bubba Blue' and 'Madonna') and turmeric (bottom) ('Indira Yellow' and 'Hawaiian Red') plants grown in a greenhouse from 4 Dec. 2019 (week 14) to 11 Mar. 2020 (week 28) in Expt. 2 under different production periods and photoperiods [continuous night interruption lighting (NI) or NI followed by natural short days (SD)]; 20NI, 24NI, and 28NI refer to 20, 24, or 28 weeks with NI, respectively. 24NISD refers to 14 weeks with NI + 10 weeks of SDs, and 28NISD refers to 14 weeks with NI + 14 weeks of SDs. Each data point represents the mean $\pm$ SE ($n = 12$). ***, **, and * indicate statistical significance at the $P \leq 0.001$, 0.01, and 0.05 level, respectively.

photosynthates, high SPAD index values do not translate into high photosynthetic efficiency. Furthermore, it is plausible that because the process is energy intensive, photosynthates are not always translocated to rhizomes, and instead, may remain accumulated in leaves (Dixit and Srivastava, 2000).

Production period effects. Based on our findings for Expt. 2, harvest time directly affects productivity of ginger and turmeric plants, with longer production periods resulting in higher yields (Table 3). For example, extending the production period from 21 to 28 weeks increased rhizome yield by 62%

and 69% for ginger and turmeric plants, respectively. Similar to our findings, Suhaimi et al. (2012) reported significant increases in ginger rhizome yield as monthly harvest times increased from 3 to 9 months after transplanting. In a field study, Hossain (2010) reported that the maximum yield of turmeric

rhizomes was obtained when shoots withered completely at the end of the production cycle, compared with plants that were still producing new leaves and shoots. The increase in rhizome yield with a longer production period is most likely attributed to the fact that both ginger and turmeric plants have a phenological cycle in which rhizome production begins after a certain growth stage (Suhaimi et al., 2012). Depending on environmental conditions and agronomic practices, the typical recommended harvest time for both species is 8 to 9 months (Nair, 2019; Sida et al., 2019). However, as shown in our results, ginger and turmeric plants grown in a greenhouse during winter can be harvested in less time, obtaining acceptable yields using NI during the entire production cycle.

Rhizome crude fiber content increased in ginger and turmeric plants consistently exposed to NI and grown during a longer production period (Table 3). Similar results were reported by Sida et al. (2019), who showed that rhizome crude fiber content increased in ginger plants grown for 9 months compared with those grown for 6 months. Our findings also correspond with those of others who have shown that rhizome crude fiber content increases as ginger plants mature (Ratnambal et al., 1987; Sanwal et al., 2012). Similarly, as the production period of turmeric increases, the content of curcumin and essential oils also increase (Hossain, 2010; Kumar and Gill, 2011; Pachauri et al., 2002).

Depending on the target market for the rhizomes, it may be desirable to harvest plants early. For example, all ginger rhizomes harvested in this trial are considered to be “baby ginger,” which is a premium product sold as an early-harvested rhizome (≈5 to 6 months after transplant) with soft skin and typically, with the presence of a short stem. Because of its distinctive quality attributes (e.g., mild pungency, low-fiber content, and nutrient-rich skin), baby ginger can be used to make sought-after beverages like fruit juices and ginger beer (Nishina et al., 1992). In contrast, mature ginger has a tough skin and a high fiber content, and thus, is typically priced lower than baby ginger (Liu et al., 2014). However, mature ginger is typically used for processed consumption where its higher pungency and fiber content are considered desirable quality attributes (Mazaud et al., 2002).

In conclusion, NI can be used as a strategy to inhibit winter dormancy in ginger and turmeric plants, which can help maintain active plant growth and lead to higher rhizome yield (rhizome FM) compared with natural SDs. In Expt. 1, NI generally resulted in a higher number of new shoots, greater rhizome yield, and increased DM partitioning to rhizomes in ginger and turmeric plants, but SPAD index was generally unresponsive to photoperiod. A higher yield was measured in 2GR ginger and R turmeric. However, TC-derived plants produced more tillers or leaves per plant. In Expt. 2, both plant varieties had similar growth responses within species. Overall, lengthening the production period and providing NI led to a clear increase in

rhizome yield and crude fiber content for both species, and the SPAD index generally declined when plants were exposed to natural SDs at the end of the production cycle (NISD). In both experiments, rhizome yield was more than 0.5 kg per plant, except for ginger under 24NISD and turmeric under 20NI (Expt. 2). Given the observed differences between propagative materials in both species, more studies are needed to determine optimal production practices for a wider range of germplasm in different regions of the United States.

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