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Strategies to Reduce Radiation Stress in Open-Field Ginger and Turmeric Production

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Abstract: Excess solar radiation can negatively affect growth and rhizome yield of ginger (*Zingiber officinale*) and turmeric (*Curcuma longa*) plants. Thus, the objective of this study was to evaluate the effect of 60% shade nets (Experiment 1) as well as white and red kaolin sprays during two production stages (early establishment vs. entire cycle) (Experiment 2) on field-grown ginger and turmeric plants. In Experiment 1, plants were propagated from seed rhizomes (R) or second-generation rhizomes from tissue-cultured plants (2GR), while only R were used in Experiment 2. There were no differences in rhizome yield in response to shade in Experiment 1, with mean values of 644 and 692 g in ginger and turmeric, respectively. Overall, 2GR ginger plants produced a higher rhizome yield (880 g) than R plants (425 g), but no yield differences were measured in turmeric. In Experiment 2, for both species and regardless of kaolin color, sprays applied during the entire cycle increased photosynthesis and stomatal conductance and reduced leaf temperature and transpiration compared to control. Rhizome yield was also up to 87% higher in ginger and 47% higher in turmeric plants sprayed with kaolin. Spraying plants with white kaolin during the early season establishment of these crops can be an effective strategy to reduce radiation stress for open-field production.

Keywords: crop protectant; kaolin; leaf temperature; rhizome yield; shade nets

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1. Introduction

Global demand for earthy spices such as ginger (*Zingiber officinale*) and turmeric (*Curcuma longa)* is increasing due to their many medicinal and edible uses [1,2]. Rhizomes from both crops have anti-cancer, anti-inflammatory, antimicrobial, and antioxidant properties [3,4]. Furthermore, ginger is widely used as a flavor additive in food and beverage products [5,6], and turmeric is often used as a coloring agent in cooking [7,8]. In 2021, the import values of ginger and turmeric rhizomes in the U.S. were USD 170 million and USD ~63 million, respectively, and import values continue to grow [9,10]. There is significant potential to increase the domestic production of these crops and meet consumer demands for locally grown products.

Ginger and turmeric are both considered shade-loving plants [6]. Therefore, excess solar radiation in places where latitude, climate, and weather patterns greatly affect insolation could limit the production of these crops. Common signs of radiation stress in ginger and turmeric plants include leaf tip burn and stunted growth, which directly affect rhizome fresh mass (from now on referred to as 'yield') [11,12]. Studies have shown that when these crops are grown under shade, leaf area, nutrient uptake, and photosynthetic rate increase, and leaf temperature and transpiration decrease, ultimately improving plant growth and yield [13–15]. Although shade nets have been shown to help protect these crops from stressors such as excessive light and heat, they often represent significant capital and maintenance costs for growers. In addition, some studies have reported that too much shade (>60%) can reduce ginger and turmeric yield, likely due to reductions in photosynthetic light [11,16–18].

As an alternative to shade nets, crop protectants such as kaolin clay have been shown to reduce radiation stress in various horticultural crops grown in open fields, such as tomato (*Solanum lycopersicum*), pomegranate (*Punica granatum*), apple (*Malus domestica*), grapevines (*Vitis*), and mango (*Mangifera indica*) [19–22]. Kaolin is an organic mineral that, when sprayed on the surface of plants, helps reflect ultraviolet and infrared radiation away from plant canopies [21,23]. Several studies have shown that kaolin sprays help reduce tissue damage, regulate leaf transpiration rates and stomatal conductance, and improve plant photosynthesis [20,24–27]. A recent study showed that spraying a mix of organic red dye with white kaolin helps further reduce leaf temperature, increase growth, and improve the water-use efficiency of citrus trees compared to conventional white kaolin applications [28].

Solar radiation in Florida ranges from 5.0 to 6.0 kWh·m^{-2}·d^{-1} [29], which can be particularly stressful for shade-loving plants. Therefore, concerns about excessive solar radiation must be addressed to develop a profitable ginger and turmeric industry in the state. The objective of this study was to evaluate strategies to reduce radiation stress for ginger and turmeric plants grown in the open field during summer months in Florida using shade nets (Experiment 1) or white and red kaolin sprays during two production stages (early establishment vs. entire cycle) (Experiment 2). We hypothesized that plants grown under shade nets would produce a higher rhizome yield compared to those grown under full sun. We also hypothesized that plants sprayed with kaolin during the entire cycle would produce a higher rhizome yield compared to unsprayed plants or to those sprayed during the early plant establishment only.

2. Materials and Methods

Experiment 1 was conducted at the University of Florida (UF) Environmental Horticulture Research Greenhouse Complex in Gainesville, FL, from 18 April 2018 to 4 February 2019. Two propagative materials were used in this study: seed rhizomes of 'Bubba Blue' ginger and 'Hawaiian Red' turmeric obtained from a commercial supplier (Hawaii Clean Seed LLC, Pahoa, HI, USA) (from now on referred to 'R'), and second-generation rhizomes of unknown ginger and turmeric varieties harvested in January 2018 from tissue-cultured plants grown for 16 months in a research greenhouse at UF (from now on referred to '2GR'). On 18 April 2018, all rhizomes (average weight of 42 and 26 g for ginger and turmeric, respectively) were placed in flat plastic trays (21 cm (h) × 27.8 cm (w) × 6.2 cm (d); T.O. Plastics, Inc. Clearwater, MN, USA) filled with sphagnum peat moss (Klasmann-Deilman, Geeste, Germany) and sprouted in a growth room for ~27 d under constant ambient temperature, relative humidity (RH), and a daily light integral (DLI) of 25 °C, 90%, and 5.7 mol·m^{-2}·d^{-1} (100 µmol·m^{-2}·s^{-1}; 16 h·d^{-1} photoperiod from 05:00 to 21:00 HR). The DLI was provided by cool white light-emitting diode (LED) fixtures (M40803; Green Creative, San Bruno, CA, USA).

On 15 May 2018, uniform sprouted rhizomes with at least one 5 cm shoot were planted into 1-gallon nursery trade containers (2.8 L) (Nursery Supplies Inc., Orange, CA, USA) filled with a substrate comprised of (v/v) 75% sphagnum peat moss, 17% perlite, and 8% perlite (Fafard®2P; Conrad Fafard, Inc., Agawam, MA, USA) and placed in a polycarbonate greenhouse. The environmental conditions in the greenhouse were monitored with a data logger (WatchDog Weather Tracker 305; Spectrum Technologies, Inc., Plainfield, IL, USA). The average daily mean temperature and solar DLI (± SD) were 24.2 ± 2.3 °C and 8.8 ± 3.2 mol·m^{-2}·d^{-1}, respectively.

A 200 m^2 experimental field plot was prepared two weeks before transplanting. After the soil was mixed and decompacted, four raised beds (1.0 m wide × 0.1 m tall × 12 m long) were manually formed, spaced 1.5 m apart, and covered with landscape fabric used as a weed barrier (Agfabric Pro; Agfabric, Vista, CA, USA). Each bed was divided into three experimental replicate sections, for a total of 12 sections. Six sections were randomly selected to be used as individual replications for a moderate shade treatment, in which 60% black shade cloth (Long's Greenhouse Enterprise, Inc. Jacksonville, FL, USA) was deployed on top of metallic tube structures (1.0 m wide × 2.5 m tall). The other six sections were left uncovered and used as individual replications for a treatment evaluating production under full sun. An empty space of 1.5 m was cleared between each section to separate treatments within beds and to minimize potential shading effects across replications. On 21 June 2018, groups of six plants per species and propagative material were randomly transplanted into individual beds within each section using a double-row and in-row plant spacing of 40-cm, resulting in a plant density of 90,000 plants·ha^{-1}. The experiment used a split-plot design in which treatment (full sun and shade) was regarded as the main plot and propagative material was regarded as the subplot. For each species, there were three blocks, each with two treatment replications that consisted of six plants per species and propagative material.

All plants were irrigated with tap water with an electrical conductivity of 0.3 dS·m^{-1}, a pH of 7.5, and 31.2 mg·L^{-1} calcium carbonate. Plants were top-dressed with 114 g of controlled-release fertilizer (Osmocote Plus™ 15N–3.9P–10K, 8 to 9-mo release; ICL Specialty Fertilizers, Dublin, OH, USA) per plant, which provided 17.1 g·L^{-1} nitrogen (N). Irrigation within beds was supplied with a double lateral line using turbulent flow drip tape (Aqua-Traxx; Toro, Bloomington, MN, USA) with 20.3 cm emitter spacing and a 1.4 L·m^{-1} flow rate.

Total rainfall measured throughout the experiment was obtained from the Florida Automated Weather Network. Temperature, RH, and DLI were recorded using a data logger (HOBO Micro Station H21-002; Onset Computer Corp., Bourne, MA, USA) placed in a central location within a treatment replication plot. Plants under shade were grown under an average daily temperature, RH, and solar DLI of 22.3 ± 7.3 °C, 82.3 ± 11.2%, and 10.3 ± 3.6 mol·m^{-2}·d^{-1}, respectively. Plants under full sun were grown under an average daily temperature, RH, and solar DLI of 23.3 ± 7.0 °C, 78.5 ± 8.9%, and 21.1 ± 10.6 mol·m^{-2}·d^{-1}, respectively. Additional details about the environmental conditions during Experiment 1 are provided in Table 1.

Table 1. Average monthly maximum (Max.), minimum (Min.), and mean air temperature (Temp.); relative humidity (RH); mean solar irradiance; daily light integral (DLI); and total rainfall measured throughout Experiment 1 (June 2018–January 2019) in Gainesville, FL, USA.

Month	Max. Temp. (°C)	Min. Temp. (°C)	Mean Temp. (°C)	Max. RH (%)	Min. RH (%)	Mean RH (%)	Mean Solar Irradiance (kWh·m^{-2}·d^{-1})	DLI (mol·m^{-2}·d^{-1})	Total Rainfall (mm)
June	36.6	21.4	27.4	98.0	48.0	83.4	5.1	39.4	205.2
July	37.1	20.1	26.2	99.0	46.0	88.0	5.3	38.2	230.0
August—Full sun	35.5	21.0	26.4	99.0	51.0	87.3	4.9	36.8	195.8
August—Shade	30.3	21.7	27.1	100.0	38.5	85.9	3.2	13.7	195.8
September—Full sun	35.6	21.4	29.6	100.0	28.5	75.7	4.6	31.3	123.7
September—Shade	31.2	21.1	28.2	100.0	23.7	81.1	3.1	11.9	123.7
October—Full sun	33.4	19.9	26.5	100.0	19.9	76.0	3.8	28.6	13.0
October—Shade	29.3	12.4	21.7	100.0	18.7	77.9	3.0	11.1	13.0
November—Full sun	30.2	0.4	18.3	100.0	26.0	84.1	3.2	25.2	95.5
November—Shade	27.5	1.8	10.6	100.0	31.4	77.4	2.7	9.6	95.5
December—Full sun	25.2	−1.0	15.5	100.0	27.6	85.3	2.9	20.1	213.6
December—Shade	20.4	0.0	14.5	100.0	32.4	83.9	2.5	7.7	213.6
January—Full sun	26.1	4.0	15.9	100.0	27.4	80.5	3.1	22.3	125.5
January—Shade	23.2	0.9	13.4	100.0	19.9	71.0	2.4	8.5	125.5

Experiment 2 was conducted at the Field and Fork farm at UF in Gainesville, FL, from 3 June to 18 November 2020. Rhizomes were obtained from the same commercial supplier (Hawaii Clean Seed LLC, Pahoa, HI, USA). On 3 April 2020, seed rhizomes of 'Bubba Blue' and 'Madonna' ginger and 'Indira Yellow' and 'Hawaiian Red' turmeric (average weight of 75 g and 50 g for ginger and turmeric, respectively) were sprouted in flat plastic trays filled with a horticultural-grade substrate comprised of (v/v) 79 to 87% peat moss, 10 to 14% perlite, and 3 to 7% vermiculite (Pro-Mix BX general purpose; Premier Tech

Horticulture, Quakertown, PA, USA). Rhizomes were kept in a poly-carbonate greenhouse covered with a 60% shade net (Aluminet I; Green-Tek Inc., Dinuba, CA, USA) for 65 d. Temperature, RH, and solar DLI were measured with a data logger (HOBO USB Micro Station; Onset Computer Corp, Bourne, MA, USA). The average daily temperature, RH, and DLI were 31 ± 4 °C, 80 ± 6%, and 10.4 ± 4.5 mol·m^{-2}·d^{-1}, respectively. Rhizomes were hand-sprayed with tap water as needed. Prior to transplanting, sprouted rhizomes with 20 to 30 cm shoots were selected to be used in the experiment.

Two passes of light disking were used to remove weeds in an unshaded 800 m^2 field plot followed by another disking pass to incorporate 5 tons·ha^{-1} of compost into the soil. One month before transplanting, 12 raised beds (0.9 m wide × 0.2 m tall × 28 m long) were manually formed. Beds were spaced 2 m apart and covered with landscape fabric as a weed barrier (Agfabric Pro; Agfabric, Corona, CA, USA) placed under a 10 cm layer of hay. On 3 June 2020, groups of three plants per species and variety were randomly transplanted into individual beds in a single row. Both ends of each plant group had one border plant that was not included in the experiment. To minimize potential issues with kaolin pollution among treatments, the in-row plant spacing was 30 cm, resulting in a plant density of 45,000 plants·ha^{-1}. Five treatments were evaluated in Experiment 2, including four biweekly kaolin (Surround WP; TKI Novasource, Phoenix, AZ, USA) sprays without (‘$White_{est}$’) or with red dye (‘Red_{est}’) (Colorback; JEM MFG, LLC., Rome, GA, USA) during the early season establishment (from June to August 2020); ten biweekly sprays of kaolin without (‘$White_{ent}$’) or with red dye (‘Red_{ent}’) during the entire growing cycle (from June to November 2020); and unsprayed plants (‘Control’). The experimental design was a randomized complete block design with six blocks, each with two treatment replications that consisted of three plants per species and variety. An empty space of 1.8 m was cleared between each replication to separate treatments within each row and to further minimize potential issues of kaolin spray pollution to neighboring plants.

Conventional (white) kaolin was prepared using 60 g·L^{-1} of product. Red kaolin was prepared using the same kaolin product rate mixed with 25 mL·L^{-1} of red dye. An extender–sticker adjuvant (SKH; Brandt Organics, Springfield, IL, USA) was added to all kaolin spray mixes at a rate of 1.5 g·L^{-1} to minimize rain wash-off. Kaolin sprays were applied every two weeks using a foliar sprayer (151.4 L 12-V County Line Deluxe Spot; Green Leaf, Inc., Fontanet, IN, USA), ensuring total plant coverage. Irrigation within beds was supplied with a double lateral line using turbulent flow drip tape (Aqua-Traxx; Toro, Bloomington, MN, USA) with 20.3 cm emitter spacing and a 1.4 L·m^{-1} flow rate. Dehydrated poultry manure pellets (5.0N–1.3P–1.7K, Chick Magic; S&R Egg Farm, Palmyra, WI, USA) were applied as fertilizer before transplanting and then again two and four months after transplanting at a rate of 2250 kg·ha^{-1} with each application.

Total rainfall, temperature, RH, and solar radiation were measured with a data logger (Mark-2; Arable, San Francisco, CA, USA), with measurements made every 60 s and recorded at 60 min intervals. The average daily temperature, RH, and solar radiation throughout the experiment were 26.4 ± 5.2 °C, 78.4 ± 12.3%, and 16.3 ± 3.4 MJ·m^{-2}·d^{-1}, respectively. Additional details about the environmental conditions during Experiment 2 are provided in Table 2.

In both experiments, SPAD index was measured one week prior to harvest on fully expanded leaves from all plants using a chlorophyll meter (SPAD-502; Konica Minolta Sensing Inc., Osaka, Japan); data were averaged based on measurements made on three different points within a leaf. In Experiment 2, only new leaves that were not covered in kaolin were used for SPAD index measurements. Fresh mass (FM) of shoots, roots, and rhizomes were measured for individual plants during each destructive harvest. With the exception of rhizomes, dry mass (DM) was measured for all plant organs by placing bagged tissue in a forced-air drying oven at 70 °C for 10 d. For each plant, only a subsample of fresh rhizomes ranging from 150 to 250 g was oven-dried to estimate rhizome DM.

Table 2. Average monthly maximum (Max.), minimum (Min.), and mean air temperature (Temp.); relative humidity (RH); mean solar irradiance; daily light integral (DLI); and total rainfall measured throughout Experiment 2 conducted in 2020 at the Field and Fork Farm in Gainesville, FL, USA.

Month	Max. Temp. (°C)	Min. Temp. (°C)	Mean Temp. (°C)	Max. RH (%)	Min. RH (%)	Mean RH (%)	Mean Solar Irradiance ($kWh \cdot m^{-2} \cdot d^{-1}$)	DLI ($mol \cdot m^{-2} \cdot d^{-1}$)	Total Rainfall (mm)
June	35.7	18.3	26.2	100.0	37.1	78.7	4.9	37.1	208.5
July	36.5	21.6	27.3	100.0	38.3	79.4	5.0	38.5	132.3
August	36.8	21.2	27.1	100.0	40.4	82.1	4.8	34.4	171.8
September	36.4	14.1	26.8	100.0	31.2	83.5	4.4	30.1	118.4
October	31.7	11.3	26.1	100.0	27.5	74.6	4.0	26.4	69.2
November	29.4	5.5	17.7	100.0	35.3	72.2	3.4	23.9	30.3

In Experiment 2, leaf temperature was measured on two different plants per treatment replication every month using an infra-red thermometer (Lasergrip 774; Etekcity, Anaheim, CA, USA). Net photosynthesis (A), stomatal conductance (g_s), and transpiration (E) were measured at week 12 after transplanting on a single fully expanded leaf per plant using a portable leaf gas exchange system (LI-COR 6400; LI-COR Biosciences, Inc, Lincoln, NE, USA). Intrinsic water-use efficiency (WUE_i) was calculated by dividing A by E. The reference leaf temperature, photosynthetic photon flux density, and CO_2 concentration inside the cuvette were set at 35 °C, 2000 $\mu mol \cdot m^{-2} \cdot s^{-1}$, and 410 $\mu mol \cdot mol^{-1}$, respectively. Gas exchange parameters were measured between 10:00 and 14:00 HR on two clear-sky days.

Data from each species were analyzed separately in both experiments. In Experiment 1, blocks were considered as random effects and treatments, propagative material, and their interaction were considered as fixed effects. In Experiment 2, all treatment means were compared to each other and blocks were treated as random effects. In both experiments, data were subjected to analysis of variance using R (Version 3.6.1; R Core Team, Vienna, Austria) [30], and least-square treatment means were compared using Tukey's honestly significant difference test (p = 0.05) in the Agricolae package in R [31].

3. Results

Experiment 1. There were no differences in growth and yield between plants of each species grown under shade or full sun, with the exception of root FM and DM, which were higher under full sun (Table 3). Rhizome yield for ginger and turmeric plants grown under shade was 619 and 696 g, respectively, whereas that of plants grown under full sun was 668 and 688 g, respectively. There were only small differences between the two propagative materials. In ginger, 2GR plants produced a rhizome yield that was 107% higher than that of R plants, which resulted in a 94% increase in rhizome DM. Similarly, 2GR turmeric plants produced a root FM that was 91% higher than that of R plants, which resulted in an 80% increase in root DM. SPAD index was 18% to 21% higher in plants grown under shade than those grown under full sun. Moreover, R ginger plants had a higher SPAD index than 2GR plants (47 vs. 41, respectively), but in turmeric, there were no differences in the SPAD index between the two propagative materials.

Experiment 2. Kaolin spray applications resulted in an increase in rhizome yield and plant growth compared to control, but the two varieties within each species did not differ in terms of growth, yield, or physiological response (Table 4). Rhizome FM of sprayed plants increased from 517 to 765 g (59% to 87%) in ginger and from 1290 to 1449 g (42% to 47%) in turmeric. For both species, plants treated with Red_{ent} and $White_{ent}$ had higher shoot and root FM and DM and higher rhizome DM than to those treated with Red_{est}, $White_{est}$, and control. However, there were no differences in rhizome FM among plants treated with Red_{est}, Red_{ent}, $White_{est}$, and $White_{ent}$. In ginger and turmeric, shoot FM, shoot DM, root DM, and rhizome DM were up to 54% and 17%, 43% and 26%, 21% and 57%, and 62% and 41% higher, respectively, in plants treated with Red_{est} and $White_{est}$ compared to control.

Table 3. Mean values and mean grouping comparison for different propagative materials of ginger and turmeric plants grown in the field under full sun and shade in Experiment 1.

Treatment	Shoot Fresh Mass (FM) (g)	Root FM (g)	Rhizome FM (g)	Shoot Dry Mass (DM) (g)	Root DM (g)	Rhizome DM (g)	SPAD Index
Ginger							
Propagative Material (PM)							
R [z]	335.4 a [y]	49.4 a	424.8 b	36.9 a	5.7 a	86.4 b	46.6 a
2GR	480.9 a	60.9 a	879.9 a	47.7 a	6.8 a	167.5 a	40.8 b
Treatment (T)							
Full sun	329.9 a	68.7 a	667.8 a	35.4 a	8.1 a	127.2 a	39.6 b
Shade	473.8 a	41.7 b	619.3 a	46.3 a	5.6 b	118.4 a	47.9 a
PM × T							
R-Full sun	316.8 a	57.5 a	452.5 a	33.5 a	6.7 a	83.4 a	43.9 a
R-Shade	354.0 a	41.3 a	397.2 a	38.0 a	5.0 a	76.7 a	49.4 a
2GR-Full sun	345.6 a	79.8 a	926.2 a	35.7 a	8.6 a	181.9 a	35.2 a
2GR-Shade	593.7 a	42.0 a	841.3 a	54.3 a	5.8 a	173.6 a	46.4 a
PM	NS	NS	***	NS	NS	***	*
T	NS	*	NS	NS	*	NS	**
PM × T	NS	NS	NS	NS	NS	NS	NS
Turmeric							
Propagative Material (PM)							
R	582.8 a	68.1 b	691.5 a	62.1 a	8.3 b	120.3 a	32.8 a
2GR	442.8 a	130.0 a	692.8 a	55.2 a	14.9 a	116.7 a	33.7 a
Treatment (T)							
Full sun	452.8 a	118.3 a	688.2 a	47.4 a	14.1 a	114.4 a	30.3 b
Shade	572.9 a	79.8 b	696.1 a	53.5 a	9.3 b	118.2 a	36.2 a
PM × T							
R-Full sun	529.8 a	78.0 a	619.7 a	55.6 a	8.6 a	119.3 a	30.0 a
R-Shade	635.8 a	58.2 a	663.3 a	59.2 a	7.1 a	124.8 a	35.6 a
2 GR-Full sun	375.7 a	158.5 a	656.7 a	46.8 a	16.4 a	113.5 a	30.5 a
2 GR-Shade	510.0 a	101.5 a	628.8 a	54.3 a	13.7 a	122.2 a	36.8 a
PM	NS	***	NS	NS	***	NS	NS
T	NS	**	NS	NS	**	NS	***
PM × T	NS	NS	NS	NS	NS	NS	NS

[z] 'R' = plants propagated from seed rhizomes; '2GR' = plants propagated from second-generation rhizomes harvested from tissue-cultured plants grown for 16 months. [y] For each species, means within columns followed by the same letter are not different based on Tukey's HSD test at $p \leq 0.05$ (n = 12 for main effects; n = 6 for interactions). ***, **, *, and NS indicate statistical significance at the 0.001, 0.01, and 0.05 $p \leq$ level or not significant, respectively.

In ginger, plants treated with Red_{ent} or $White_{ent}$ produced 22% to 86% more shoot FM, 21% to 73% more shoot DM, 11% to 40% more root DM, and 24% to 76% more rhizome DM compared to those treated with Red_{est}, $White_{est}$, and control (Table 4). Similarly, in turmeric, plants treated with Red_{ent} or $White_{ent}$ produced 35% to 54% more shoot FM, 14% to 44% more shoot DM, 48% to 132% more root DM, and 27% to 68% more rhizome DM than those treated with Red_{est}, $White_{est}$, and control.

Regardless of species, no differences were measured for SPAD index between plants treated with Red_{est}, $White_{est}$, Red_{ent}, and $White_{ent}$ (Table 4), with values ranging from 49 to 51 in ginger and from 45 to 47 in turmeric. However, plants treated with kaolin had higher SPAD index values than those in the control, which had an average value of 37 in ginger and 34 in turmeric. For both species, plants treated with Red_{ent} or $White_{ent}$ had higher A, g_s, and leaf temperature, and lower E compared to those treated with Red_{est}, $White_{est}$, and control. Furthermore, ginger plants treated with Red_{ent} and control had the highest (17.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$) and lowest A values (9.9 $\mu mol \cdot m^{-2} \cdot s^{-1}$), respectively, whereas A for all other treatments ranged from 13.2 to 14.7 $\mu mol \cdot m^{-2} \cdot s^{-1}$. In turmeric, A was highest in plants treated with Red_{ent} (15.6 $\mu mol \cdot m^{-2} \cdot s^{-1}$) or $White_{ent}$ (16.2 $\mu mol \cdot m^{-2} \cdot s^{-1}$), and values for all other treatments ranged from 9.5 to 12.9 $\mu mol \cdot m^{-2} \cdot s^{-1}$. For both species, E

was higher in plants treated with Red_{est}, $White_{est}$, and control compared to those treated with Red_{ent} or $White_{ent}$, with values ranging from 2.9 to 3.3 $mmol \cdot m^{-2} \cdot s^{-1}$ in ginger and from 4.3 to 4.7 $mmol \cdot m^{-2} \cdot s^{-1}$ in turmeric. For both species, plants treated with Red_{ent} or $White_{ent}$ had higher g_s values (ranging from 424.7 to 508.9 $mmol \cdot m^{-2} \cdot s^{-1}$ in ginger and 647.8 and 716.3 $mmol \cdot m^{-2} \cdot s^{-1}$ in turmeric, respectively) than those treated with Red_{est}, $White_{est}$, and control (ranging from 213.2 to 315.1 $mmol \cdot m^{-2} \cdot s^{-1}$ in ginger and 305.4 to 442.1 $mmol \cdot m^{-2} \cdot s^{-1}$ in turmeric). Plants from both species treated with kaolin had higher WUE_i values than control, and values were generally higher in plants treated during the entire growing cycle than those treated during the early season establishment only.

Table 4. Final growth and physiological parameters measured in two varieties of ginger and turmeric plants grown in an open field treated with white, red, or no kaolin sprays (control) during two different production stages (early establishment vs. entire cycle) in Experiment 2 [z].

Treatment [y]	**Shoot Fresh Mass (FM) (g)**	**Root FM (g)**	**Rhizome FM (g)**	**Shoot Dry Mass (DM) (g)**	**Root DM (g)**	**Rhizome DM (g)**	**SPAD Index**	**A^x ($\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$)**	**E ($mmol\ H_2O \cdot m^{-2} \cdot s^{-1}$)**	**g_s ($mmol\ H_2O \cdot m^{-2} \cdot s^{-1}$)**	**WUE_i ($\mu mol\ CO_2 \cdot mmol\ H_2O$)**
Ginger											
Control	724.1 c [w]	78.3 b	869.9 b	93.5 c	9.6 b	198.3 c	36.7 b	9.9 d	3.3 a	213.2 c	2.8 c
Red_{est}	1116.3 b	82.8 b	1386.6 a	123.8 b	10.2 b	321.4 b	50.3 a	13.2 c	3.0 ab	341.3 b	4.2 b
$White_{est}$	1098.5 b	87.3 b	1495.7 a	133.4 b	11.6 b	303.6 b	48.9 a	14.0 bc	2.9 ab	315.1 b	5.0 a
Red_{ent}	1345.6 a	100.4 a	1600.5 a	156.7 a	13.4 a	375.1 a	50.7 a	17.5 a	2.7 bc	424.7 a	6.9 a
$White_{ent}$	1298.7 a	98.3 a	1634.9 a	161.5 a	12.9 a	349.5 a	49.2 a	14.7 b	2.4 c	508.9 a	5.8 a
Treatment (T)	**	**	**	***	***	**	**	***	***	**	**
Variety (V)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
T × V	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Turmeric											
Control	2012.3 c	100.3 c	3064.1 b	145.6 c	14.3 b	278.9 c	34.2 b	9.5 c	4.7 a	305.4 c	1.9 c
Red_{est}	2345.2 b	223.5 b	4353.8 a	184.1 b	18.5 b	369.0 b	45.0 a	12.9 b	4.5 a	442.1 b	2.7 b
$White_{est}$	2298.7 b	201.1 b	4397.2 a	167.4 b	22.5 ab	394.2 b	44.7 a	12.1 bc	4.3 a	407.6 b	2.9 b
Red_{ent}	3067.3 a	269.8 a	4512.9 a	210.3 a	25.8 a	445.3 a	46.5 a	15.6 a	3.2 b	716.3 a	5.4 a
$White_{ent}$	3102.7 a	254.2 a	4452.5 a	206.9 a	33.2 a	468.2 a	45.3 a	16.2 a	3.4 b	647.8 a	4.2 a
Treatment (T)	***	***	**	***	**	***	**	**	**	***	*
Variety (V)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
T × V	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[z] 'Bubba Blue' and 'Madonna' ginger; 'Indira Yellow' and 'Hawaiian Red' turmeric. [y] Red_{est} and $White_{est}$ refer to kaolin with or without red dye, respectively, applied during early season establishment (four biweekly applications). Red_{ent} and $White_{ent}$ refer to kaolin with or without red dye, respectively, applied during the entire growing cycle (ten biweekly applications). [x] A, E, g_s, and WUE_i refer to net photosynthesis, transpiration, stomatal conductance, and intrinsic water-use efficiency, respectively. [w] For each species, means within columns followed by the same letter are not different based on Tukey's HSD test at $p \leq 0.05$ (n = 12 for main effects; n = 6 for interactions). ***, **, *, and NS indicate statistical significance at the 0.001, 0.01, and 0.05 $p \leq$ level or not significant, respectively.

Kaolin sprays resulted in a general decrease in the maximum leaf temperature measured each month compared to control, but there were no differences in leaf temperature between plants sprayed with white or red kaolin (Figure 1). Leaf temperature in ginger and turmeric plants treated with Red_{est} or $White_{est}$ was lower than that in control plants during the early season establishment (from June to August 2020), with decreases in monthly average temperature values ranging from 2.6 to 6.7 °C in ginger and from 3.1 to 5.6 °C in turmeric. After August, no differences in leaf temperature were measured among plants sprayed with Red_{est}, $White_{est}$, and control. Regardless of kaolin color, turmeric plants treated with Red_{ent} or $White_{ent}$ (which received biweekly kaolin applications until November) had lower leaf temperature values from September through November compared to those treated with Red_{est}, $White_{est}$, and control plants.

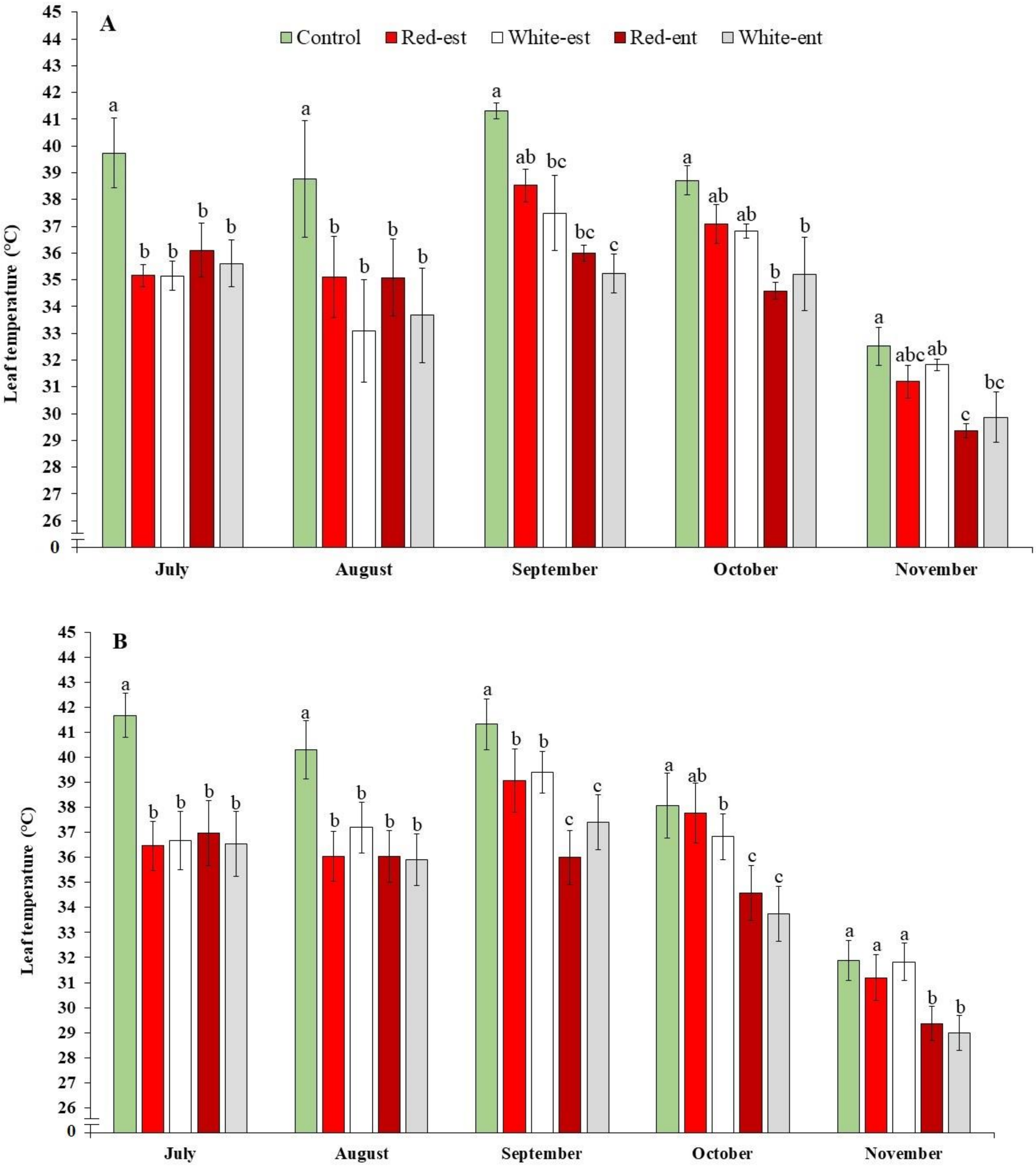

Figure 1. Average monthly leaf temperature measured in ginger (**A**) and turmeric (**B**) plants grown in an open field treated with white, red, or no kaolin sprays (control) during two production stages (early establishment vs. entire cycle) in Experiment 2. Red_{est} and $White_{est}$ refer to kaolin with or without red dye, respectively, applied during early season establishment (four biweekly applications). Red_{ent} and $White_{ent}$ refer to kaolin with or without red dye, respectively, applied during the entire growing cycle (ten biweekly applications). Bars represent means ±SE (n = 6). Different letters indicate statistical differences among treatments based on Tukey's HSD test at $p \leq 0.05$ (n = 6).

4. Discussion

Shade effects. Although high light and heat stress are known to negatively affect growth and yield of ginger and turmeric plants, our results for Experiment 1 show that using shade did not provide advantages compared to production under full sun (Table 3). Considering that some level of shade is typically recommended for these crops [11,13,32–34], our findings suggest that the 60% shade level used in this study was excessive to increase rhizome yield. Accordingly, studies with ginger have reported higher rhizome yields under low (20% to 40%) compared to high (>60%) shade levels [13,16,35]. For example, Ajithkumar et al. [16] showed that the dry rhizome yield of ginger plants grown under 80% shade decreased by 51%, 151%, 113%, and 45% compared to those grown under full sun or 20%, 40%, or 60% shade, respectively. Similarly, studies with turmeric have shown that while shade levels from 30% to 50% increase vegetative growth and rhizome yield, shade >70% reduces yield [17,18]. Ferreira et al. [34] reported no differences in rhizome yield in turmeric plants grown under 70% shade or full sun, and Sharangi et al. [14] suggested that 50% shade is an optimum level to maximize photosynthesis and biomass production in turmeric. However, others have shown that shade levels ≥50% are adequate to increase rhizome yield. For example, Ghasemzadeh et al. [36] found that nutrient uptake of ginger plants was higher under 60% shade compared to under full sun, which helped increase rhizome yield. Similarly, Aly et al. [37] reported rhizome yields of 148 g, 255 g, and 366 g in ginger plants grown under full sun, 30% shade, and 60% shade, respectively. Furthermore, Sivaraman [38] suggested that turmeric plants grown under ≥25% shade allocate more photosynthates to shoot rather than rhizome growth, which ultimately affects yield. This corresponds with the findings of Ruberti et al. [39], who suggested that plants grown under excessive shade allocate more resources to shoot growth than rhizome production.

The inconsistency in results from the various studies described above suggest that there are plastic responses to shade that affect the growth and yield of ginger and turmeric plants. Some have suggested that these results could be attributed to the production of multiple phenotypes from a single genotype, which are affected by biotic and abiotic stressors in the growing environment [40–42]. Both ginger and turmeric rhizomes are often imported to their final production site. Therefore, the same varieties can be adapted to different regions of the world and may produce different phenotypes, some of which may be better adapted to shade than others [13,43]. In addition, studies have shown that radiation requirements in ginger and turmeric vary across the different growing stages. In general, plants benefit from shade during early field establishment but can make use of additional light and warmer temperatures for photosynthesis as they grow and produce more shoots and rhizomes [44,45].

Although shade did not increase yield in Experiment 1, plants from both species grown under shade had higher SPAD index values than those grown under full sun (Table 3). These findings suggest that shade helped alleviate stress from high solar radiation. Studies with ginger have reported an increase in chlorophyll content with higher shade levels [36,46–48]. In our study, ambient temperature was lower under shade compared to full sun (Table 1). Others have reported similar temperature reductions when using shade compared to full sun, which affect the synthesis of photosynthetic pigments such as chlorophyll [49–52]. It is likely that shade helped maintain leaf temperature closer to the optimal levels for these crops compared to full sun. However, the 60% shade level used in our study likely reduced solar radiation to sub-optimal levels, negating the potential benefits in rhizome yield.

The higher rhizome yield measured in ginger plants propagated as 2GR compared to those propagated as R in Experiment 1 can likely be attributed to genetic differences, as the two propagative materials are different varieties (Table 3). In general, tissue-cultured plants are low-yielding in the first year but can have similar or higher rhizome yields than plants propagated from seed rhizomes after the second year of production [53]. Babu et al. [48] reported large variability in rhizome yield among 10 ginger varieties grown under 50% shade, illustrating the vast genetic difference in plant responses for these crops.

Kaolin effects. Regardless of color, growth and yield were generally higher in plants treated with kaolin sprays compared to control, illustrating the benefits of reducing solar radiation stress in ginger and turmeric plants (Table 4). Other studies evaluating the use of kaolin sprays have shown similar growth and yield responses in multiple crop species [19–22,54,55]. These positive effects are often attributed to the reflection of solar radiation away from plant canopies, as well as improvements in the distribution of light within plant canopies, both of which help reduce leaf temperature and improve gas exchange [20–22,26,56,57]. Continuous exposure to excess light and temperature can damage the photosynthetic apparatus of plants, leading to membrane injuries that interfere with several plant functions, ultimately decreasing growth and yield [21,58]. This corresponds with our findings showing that untreated control plants had a higher leaf temperature and lower growth and yield compared to those treated with kaolin sprays (Figure 1). Similar results have been reported in several plant species, including pepper (*Capsicum annum*) ([59], tomato [60], rose (*Rosa* spp.) [61], potato (*Solanum tuberosum*) [62]), and grapevines [63], among others. Decreases in leaf temperature with kaolin sprays often result in cooler microclimates within plant canopies [28], which have also been shown to improve water-use efficiency.

Overall, our results for Experiment 2 show that regardless of color, ginger and turmeric plants that were treated with kaolin sprays during the entire growing cycle produced more biomass and had higher A, g_s, and WUE_i and lower E compared to those that received applications during the early season establishment only (Table 4). However, there were no differences in yield between applications during the two production stages, suggesting that kaolin sprays are not necessary during the entire growing cycle of these crops. Accordingly, others have shown that reducing radiation stress with kaolin sprays is particularly beneficial during the establishment period of various field crops, as these sprays help minimize transplant shock upon transplanting [60,64,65].

Although A was higher in ginger plants treated with red kaolin compared to those treated with white kaolin and control plants, no differences were measured in yield (rhizome FM) for plants treated with the two kaolin colors. Salvatierra [28] reported that red and white particle films enable higher light transmission within plant canopies than green, purple, and blue particle films in citrus trees. The author found that although the red to far-red ratio between white and red kaolin-sprayed plants was similar, red kaolin enabled a higher transmittance of red and far-red light. In contrast, white kaolin had more stable transmittance throughout the photosynthetic spectrum. It is plausible that the general lack of differences between plants treated with the two kaolin colors can be attributed to the dose of red dye used in our study, which may not have been sufficient to change the light transmittance and reflectance compared to white kaolin.

The positive responses to the gas exchange parameters measured in plants treated with kaolin sprays suggest that kaolin applications do not interfere with proper gas exchange, which has been described as a concern when kaolin covers the surface of plants (Table 4). The small particle diameter of kaolin spray droplets (<2 μm) seems to enable proper gas exchange in plants [26], even though studies have postulated that kaolin can partially obstruct stomata [56] and consequently reduce A, g_s, and E [56,66–68]. In contrast, others have shown increases in photosynthetic activity due to kaolin sprays applied to different plant species, such as apple, strawberry (*Fragaria* × *ananassa*), and grapefruit (*Citrus* × *paradisi*) [27,64,69], which correspond with our findings for Experiment 2. Brito et al. [20] explained that kaolin sprays help improve photosynthetic activity by minimizing the negative effects of high-radiation stress on Rubisco activity, photorespiration, and leaf oxidative stress [20,57].

Considering that A was higher in ginger and turmeric plants treated with kaolin sprays compared to untreated control plants, it is likely that the higher biomass and yield measured in plants treated with kaolin was partly driven by a balance between reducing E and increasing g_s, which promoted the photosynthetic rate of the plants (Table 4). Similar to our findings, increases in g_s after the use of kaolin sprays have been reported by others [60,64,70]. This response is mainly attributed to a reduction in vapor pressure deficit (VPD), which is one of the most influential environmental factors in stomatal function and photosynthesis [71]. Kaolin produces an antitranspirant effect in plants, often reducing VPD and thus, decreasing the evaporative demand of plants [72].

Regardless of color and application stage, ginger and turmeric plants treated with kaolin sprays had SPAD index values that were up to 32% and 38% higher, respectively, than those in control plants. Similar results have been reported by others in walnut (*Juglans regia*) and fenugreek (*Trigonella foenum-graecum*) [55,73]. It is widely known that radiation stress can damage photosynthetic pigments in plants such as chlorophyll and carotenoids, causing leaf chlorosis [74]. Based on the higher SPAD index values measured in plants treated with kaolin compared to control, it appears that kaolin sprays help protect leaves from solar radiation stress by inhibiting the degradation of chlorophyll.

5. Conclusions

The 60% shade level used in Experiment 1 may have been excessive to increase the rhizome yield of ginger and turmeric plants. However, lower shading percentages might be beneficial for these crops and should be evaluated in future studies, especially when considering that SPAD index values were generally higher in plants grown under shade than under full sun. Based on results from Experiment 2, kaolin foliar sprays can be used as a strategy to reduce radiation stress in ginger and turmeric plants grown in open fields during the summer months in Florida. We found that kaolin sprays reduced leaf temperature and E and increased plant growth, rhizome FM, A, g_s, and SPAD index values compared to untreated control plants. However, our results suggest that adding a red dye and continued application during the entire growing cycle are not necessary for yield increases. Red dye would increase material costs and cleaning labor for both spray equipment and harvested rhizomes. Therefore, spraying plants with white kaolin during the early season establishment of these crops is the recommended strategy for open-field production. More studies are needed to determine the optimal kaolin doses and application rates in ginger and turmeric plants. In addition, economic studies are needed to determine the profitability of using either shade nets or kaolin sprays during the commercial production of these crops, with particular consideration of the added materials and labor costs.

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