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Temperature Influences Yield, Reproductive Growth, Harvest Index, and Oil Content of Hydroponically Grown 'Georgia Red' Peanut Plants

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***Abstract*. 'Georgia Red' peanut (*Arachis hypogaea* L.) was grown hydroponically at 20/16 °C, 24/20 °C, 28/24 °C, and 32/28 °C, day/night air temperatures to evaluate effects on pod and seed yield, flowering, harvest index, and oil content. Ten-day-old peanut seedlings were transplanted into rectangular nutrient film technique troughs (0.15 × 0.15 × 1.2 m) and grown for 110 days. Growth chamber conditions were as follows: photosynthetic photon flux (PPF) mean of 436 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 12 h light/12 h dark cycle, and 70% ± 5% relative humidity. The nutrient solution used was a modified half-Hoagland with pH and electrical conductivity maintained between 6.5 to 6.7, and 1000 to 1300 $\mu S \cdot cm^{-1}$, respectively, and was replenished weekly. Vegetative growth (foliage, stem growth, total leaf area, and leaf number) was substantially greater at increasingly warmer temperatures. Reproductive growth was significantly influenced by temperature. Flowering was extremely sensitive to temperature as the process was delayed or severely restricted at 20/16 °C. The number of gynophores decreased with temperature and was virtually nonexistent at the lowest temperature. Pod yield increased with temperatures up to 28/24 °C but declined by 15% at the highest temperature (32/28 °C). Seed yield, maturity, and harvest index were highest at 28/24 °C. Oil content (percent crude fat) increased an average of 23% and was highest at the warmest temperature (32/28 °C). These results clearly suggest that vegetative and reproductive growth, as well as oil content of peanut in controlled environments, are best at warmer temperatures of 28/24 °C to 32/28 °C than at cooler temperatures of 20/16 °C to 24/20 °C.**

Peanut (*Arachis hypogaea* L.) is the fourth most important source of edible oil depending on cultivar, and is high in protein (Davidson et al., 1982). The plant is among several crops selected by the National Aeronautics and Space Administration's (NASA) Advanced Life Support (ALS) program, which is based on the concept of using photosynthesis and transpiration to produce oxygen, food, and potable water, while removing carbon dioxide (Tibbitts and Alford, 1982). As part of the ALS program, the Center for Food and Environmental Systems for Human Exploration of Space at Tuskegee University is evaluating various aspects of peanut growth in hydroponics, including biocompatibility with sweetpotato (Mortley et al., 1998), photoperiod (Rowell et al., 1999), relative humidity (Mortley et al., 2000), and carbon dioxide (Stanciel et al., 2000).

Temperature plays a critical role in the growth and development of peanut plants, and it appears that optima are different depending on the phase (reproductive or vegetative) of development (Ketring et al., 1982). Wood (1968) evaluated diurnal temperatures ranging from 20/25 ºC to 30/35 ºC at early flowering on peanut growth and development and suggested that a midrange temperature (25/25 ºC) enhanced relative growth and net assimilation rates as well as flowering. Reproductive growth was reduced at regimes of 30/35 ºC and 35/25 ºC. Ketring (1984) exposed peanut plants to 30, 32, or 35 ºC during the light period in combination with a constant 22 ºC during the dark period and reported reduced vegetative growth (total leaf area, stem elongation), number of subterranean gynophores, and the weight of mature seeds at 35 ºC. Bagnall and King (1991) showed that a cooler diurnal temperature of 24/19 ºC reduced growth rates and extended the time to the appearance of the first flower in peanut plants, which, subsequently, decreased flower and gynophore production. Rowell et al. (1999) reported that peanut plants grown hydroponically by use of the nutrient film technique (NFT) and exposed to a diurnal 28/22 ºC produced greater pod, immature seed yield and higher harvest index compared to plants grown at a constant 28 ºC.

After an extensive review of the literature, Ketring (1984) suggested that the optimum mean air temperature for vegetative growth of peanut seemed to range between 25 and 30 ºC while that for reproductive processes ranged between 20 and 25 ºC.

The amount of oil in peanut seeds has been shown to vary with the cultivar, market-type (Runner, Virginia, Valencia, or Spanish), and the environmental conditions under which the seeds were produced (Sanders et al., 1995). Total oil content among the four market-types ranged between 44% and 56% (Ahmed and Young, 1982; Cobb and Johnson, 1973; Holaday and Pearson, 1974). Brown et al. (1975) reported that the composition of peanut oil changes with temperature. They found increases in monounsaturated oils and decreases in polyunsaturated oils as temperatures increased. Total oil content (dry weight basis) also increases as seeds become mature, and temperature does affect maturity (Pattee et al., 1974; Sanders et al., 1982).

Because the wide assortment of potential candidate crop species has varying environmental requirements which would not be practical in a bioregenerative life support program, it is accepted that mixed cropping systems will be used, requiring environmental compromises including temperature. Our objective was to determine the effect of diurnal air temperature on seed yield, reproductive growth, harvest index and oil content of peanut when grown hydroponically using the nutrient film technique.

Materials and Methods

Experiments were conducted in a randomized complete block design with three replications in time. Four reach-in growth chambers (Percival Co., Boone, Iowa) were used, and each experiment lasted ≈110 d.

Starting transplants. 'Georgia Red' seeds were sown in a moist commercial Jiffy Mix (Batavia, Ill.) medium in TLC Pro-Trays transplant flats (TLC Polyform, Inc., Plymouth, Minn.) and covered with ≈0.6 cm of the medium. Trays were placed in a growth chamber with a 14/10 h daily light period, a matching 28/22 °C thermoperiod, and a constant 70% relative humidity. Seeds were watered every three days with deionized water, and seedlings were grown for ≈2 weeks.

Treatments and planting. The four diurnal temperature treatments were 20/16 °C, 24/20 °C, 28/24 °C, and 32/28 °C. Four seedlings were transplanted into each of two NFT growth channels (0.15 × 0.15 × 1.2 m). Before transplanting, seedlings were carefully removed from each cell, and excess medium was removed by rinsing roots in tap water. Damage to the developing root system was minimized. Seedlings were spaced 25 cm apart through openings made in a flexible perforated PVC-1 grid. The grid was 0.32 cm thick with perforations being 0.32 cm in diameter on 0.56-cm centers, which facilitated the entry of the developing gynophores into the pod production zone.

Nutrient solution. A modified half-strength Hoagland nutrient solution (Hoagland and Arnon, 1950) with an additional 2 mM of Ca and N were used. The solution was supplied to the plants in each channel from 30.4-L reservoirs with in-line pumps (Little Giant Pump Co., Oklahoma City, Okla.). Growth channels were on a 1% slope to facilitate return of the nutrient solution to the reservoir by gravity flow. The nutrient solution was replenished once per week with a weak solution (one-third strength

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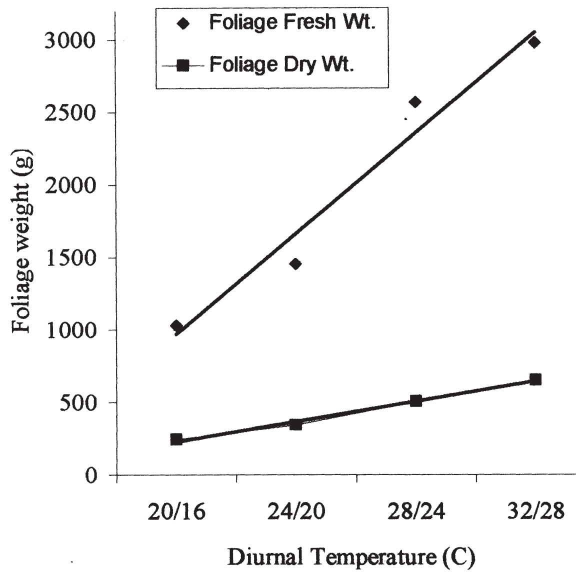

Fig. 1. Relationship between foliage fresh and dry weight and diurnal temperature of hydroponically grown 'Georgia Red' peanut plants. The best fit relationships are for foliage fresh weight (Y = 273.6 + 693.8X, $r^2 = 0.96$) and for dry weight (Y = 90.7 + 138.6X, $r^2 = 0.99$).

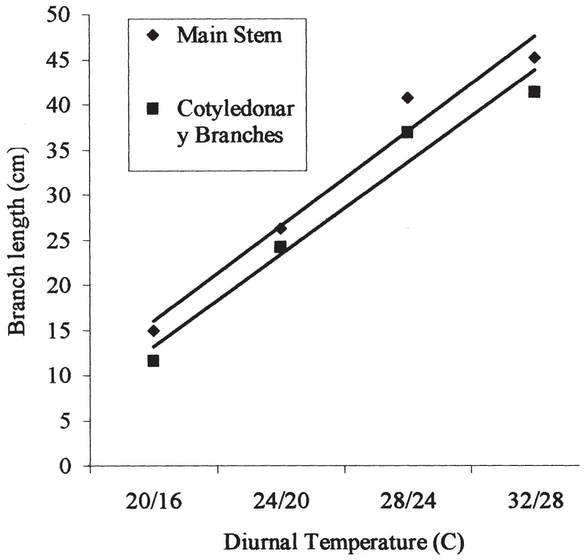

Fig. 2. Relationship between length of main and cotyledonary branches and diurnal temperature of hydroponically grown 'Georgia Red' peanut plants. The best fit relationships are for main branches (Y = 5.6 + 10.5X, $r^2 = 0.96$) and for cotyledonary branches (Y = 3.0 + 10.2X, $r^2 = 0.96$).

Hoagland) and pH adjusted to a range of 6.4 to 6.7. Electrical conductivity ranged between 1000 to 1300 $\mu S \cdot cm^{-1}$. Solution temperature was similar to that of the air within each growth chamber.

Growth chamber conditions. Growth chamber conditions included a constant relative humidity of 70% ± 5%. The photosynthetic photon flux (PPF) at the top of the plant canopy (≈20 cm above the plants) averaged 436 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and was provided by cool-white fluorescent lamps.

Measurements. Beginning at ≈42 d after planting and at day 56, 83, and 98 stomatal conductance and transpiration were measured at the middle of each light period on the second fully expanded leaf on the main stem, with a steady-state porometer (LI-1600; LI-COR, Lincoln, Nebr.). Main stem and cotyledonary branch lengths were measured beginning 21 d after planting and at 5-dintervals thereafter until harvest. At flowering, and at 4-dintervals thereafter until day 62, the total number of flowers reaching anthesis were counted and recorded.

Harvest. Plants were harvested 110 d after planting and, fresh weights of component plant parts were determined and dried at 70 °C for 72 hours. All fully expanded leaves were removed from each plant and counted, and total leaflet area was determined using a leaf area meter (LI-3100; LI-COR). Pods were removed from each plant, counted, weighed, and dried at 35 °C for 72 h before separation into 'mature' or 'immature' and weighed. Pods were shelled and seeds classified as mature and immature according to the technique of Rucker et al. (1994). Harvest index [(seed weight/total plant weight) x 100] was calculated after all plant tissues were dried.

Oil determination. Peanut oil was extracted in duplicate from 200 mg of ground peanut seeds with 5 mL of 2 methanol : 1 chloroform : 0.8 water (by volume) and methylated by BF/methanol (Sigma Chemical Co., St. Louis Mo.) (Wu et al., 1997).

Experiments were repeated and treatments were switched between chambers to minimize chamber effects. Data were combined by experiments and subjected to linear regression analyses by the General Linear Models procedure (SAS Institute, 1989-1996). Linear and quadratic effects were partitioned from the main effect of diurnal temperature.

Results and Discussion

Vegetative growth. Temperature significantly influenced the development of the peanut plants. Plants grown under increasingly warmer temperatures produced significantly more fresh and dry foliage biomass compared to plants grown at the cooler temperatures (Fig. 1). This response was manifested as a linear increase in foliage biomass as temperature increased. Elongation growth (main stem and cotyledonary branch lengths) and total leaf area were significantly increased by increasing temperature (Figs. 2 and 3). The number of leaves produced per plant increased substantially with temperature and was greatest at the warmest temperature of 32/28 °C (Table 1). Leaf temperature, stomatal conductance, and transpiration increased with temperature up to 28/24 °C but declined an average of 23% at 32/28 °C (Table 1).

Reproductive growth. Flowering was initiated an average of 17 d after planting among plants grown at 28/24 °C and 32/28 °C and by 22 and 32 d after planting for plants grown at 24/20 °C or 20/16 °C, respectively (Fig. 4). Only flowers reaching anthesis were counted. The number of flowers produced per plant was similar at 24/20 °C and 28/24 °C, and marginally lower among plants grown at 32/28 °C. In contrast flowering was severely restricted among plants grown at the lowest temperature (20/16 °C). Thus, flowering was extremely sensitive to a temperature lower than 24/20 °C, and to a lesser extent, at the highest temperature used in this study.

The number of gynophores produced per plant was greater among plants grown at the higher temperatures (Fig. 5). The number of gynophores decreased with temperature, and they were virtually nonexistent at the lowest temperature. Therefore, as with flowering, gynophore production was inhibited by low temperature (20/16 °C) and mildly sensitive to a higher temperature (32/28 °C).

The total number of pods produced per unit area as well as pod fresh and dry biomass increased with temperature up to 28/24 °C but declined an average of ≈15% when grown at 32/28 °C (Table 2). Temperature also significantly influenced pod maturity. The number and weight of mature pods increased with temperature and was highest among plants grown at 28/24 °C (Table 2). Commensurate with the higher yield of mature pods, the number and weight of immature pods also increased with temperature up to 28/24 °C and declined at 32/28 °C. Thus pod production (number and mass) was highest at 28/24 °C.

Seed maturity, total yield, and harvest index were significantly affected by diurnal temperature treatments (Table 3). While the number of mature seeds increased with temperature up

Fig. 3. Relationship between total leaf area and diurnal temperature of hydroponically grown 'Georgia Red' peanut plants. The best fit relationship is Y = 139.0 + 1117X, $r^2 = 0.99$.

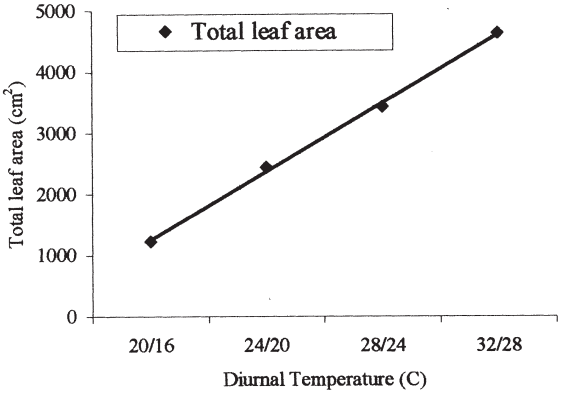

Table 1. Leaf number and temperature, stomatal conductance, and transpiration of hydroponically grown 'Georgia Red' peanut in response to diurnal temperature.

Temp (°C)	Leaf no.	Leaf temp (°C)	Stomatal conductance ($mol\cdot m^{-2}\cdot s^{-1}$)	Transpiration ($\mu mol\ H_2O/m^2/s$)
20/16	76	20.1	0.39	5.91
24/20	129	24.6	0.53	6.53
28/24	162	26.7	0.72	8.91
32/28	257	29.2	0.52	7.17
Linear	***	**	**	**
Quadratic	NS	NS	**	**

^{NS,*,**,***}Nonsignificant or significant at $P = 0.05, 0.01$, or 0.001, respectively.

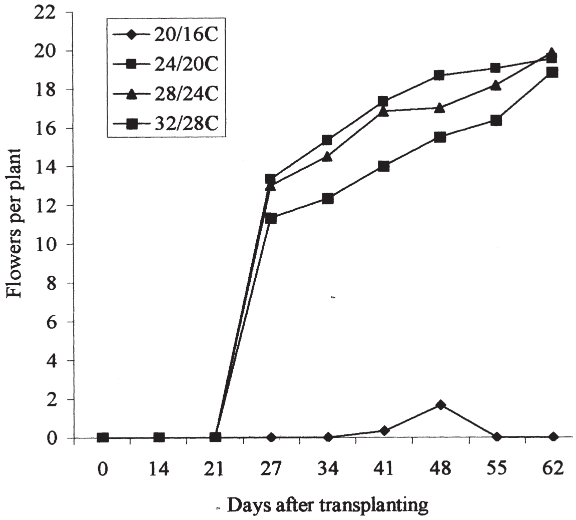

Fig. 4. Mean number of flowers per plant on various days after transplanting of hydroponically grown 'Georgia Red' peanut plants in response to diurnal temperature.

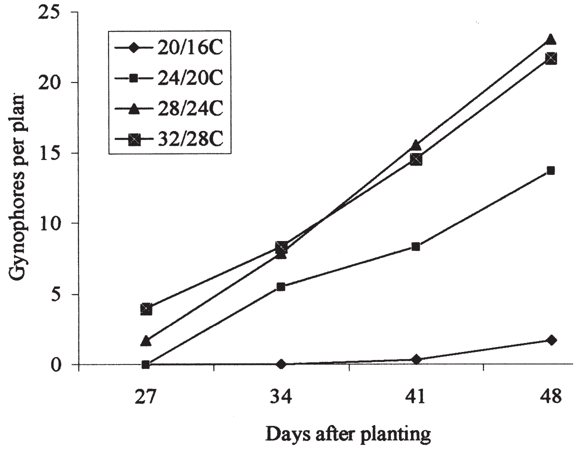

Fig. 5. Mean number of gynophores per plant on various days after transplanting of hydroponically grown 'Georgia Red' peanut plants in response to diurnal temperature.

to 28/24 °C and declined ≈8% at 32/28 °C, the number of immature seeds produced increased with temperature and was greatest at the highest diurnal temperature. Mature, immature, total seed yield and harvest index were maximized at 28/24 °C. The increased harvest index means that more dry matter was distributed to seeds of plants grown at 28/24 °C than to the vegetative parts. Thus, all yield parameters, except the number of immature seeds, were optimized at 28/24 °C. Plants grown at the highest temperature (32/28 °C) produced the greatest number of immature seeds but the total seed mass at 32/28 °C was lower than at 28/24 °C.

Oil content. The oil content (percent crude fat) was influenced by diurnal temperature. The oil content of the seeds increased an average of ≈23% as temperature increased from 20/16 °C to 32/28 °C (Fig. 6). Oil content was similar among plants grown at 24/20 °C and 28/24 °C. Clearly, increasingly warmer temperatures did enhance the oil content of peanut seeds.

These results clearly support prior research findings that temperature is a major determinant influencing growth and development of peanut (Cox, 1979; Ong, 1986; Ketring, 1982). An assessment of the effects of the different temperature treatments on total vegetative growth was made by measuring fresh and dry foliage biomass, elongation growth of main stem and cotyledonary branches, total leaf area, and the number of leaves produced per plant at harvest. Temperature exerted a very strong influence on vegetative growth of peanut plants as evidenced by the high r^2 values (Figs. 1–3), indicating a high correlation between temperature and vegetative growth.

There are reports that suggest that both warm days and cool nights promote vegetative growth of legumes (Summerfield and Wein, 1980). For example, branching and dry matter accumulation in cowpea is promoted significantly by warm nights but only marginally by warm days (33 °C). Cooler nights have been shown to limit water uptake but may also favor root growth at the expense of shoot growth, lessen dark respiration of whole plants, and promote vegetative growth (Crockston et al., 1974). In contrast other researchers have shown that warmer day temperatures have affected the accumulation of dry matter in vegetative parts of legumes much more than high night temperatures (Dale, 1964). Judging from the significant linear increase in total vegetative growth, our results suggest that the warmer temperatures exerted a major influence on the overall enhancement in vegetative growth of the plants, mainly through an increase in leaf size (leaf area) as well as in the number of leaves produced.

The rate of progression towards the appearance of the first flower was most rapid at the warmer temperatures (28/24 °C and 32/28 °C). These results suggest that 'Georgia Red' peanut plants progressed to flowering with different sensitivities at 20/16 °C and 24/20 °C confirming the findings of others (Bagnall and King, 1991) that temperature influences not only the time of appearance of the first flower but also the total number produced per plant.

Gynophore production was inhibited to a greater extent at the lowest temperature and marginally at the highest temperature. Growth inhibition at low temperature is mainly related to a slowing of metabolic activities, particularly a depression in carbon assimilation (Bagnall et al., 1988), as reflected in the reduced stomatal conductance (Table 1). The lower number of gynophores produced by plants grown at 32/28 °C relative to those produced at 28/24 °C could be due in part to the fact that the sensitivity of heat stress in peanut extends from about 6 days before anthesis until ≈15 d after flowering (Vara Prasad at al., 1999), thereby reducing fertilization and ultimately the number of gynophores produced.

Temperature also significantly impacted the partitioning of dry matter to both pods and seeds. For example, dry matter partitioned to pods and seeds was highest at 28/24 °C but declined 16% and 17%, respectively, at 32/28 °C. Similarly, harvest index declined 28% as temperature increased from 24/20 °C to 28/24 °C, suggesting that more dry matter was partitioned to seeds relative to the foliage. That reproductive response and harvest index were maximized at 28/24 °C coupled with a higher stomatal conductance indicate that 28/24 °C is within the temperature optima for these processes in a controlled environment.

Table 2. Pod yield of hydroponically grown 'Georgia Red' peanut in response to diurnal temperature.

Temp (°C)	Pod no.	Pod fresh mass ($g\cdot m^{-2}$)	Pod dry mass ($g\cdot m^{-2}$)	Mature pod no.	Mature pod fresh mass ($g\cdot m^{-2}$)	Immature pod no.	Immature pod dry mass ($g\cdot m^{-2}$)
20/16	101	158	33	73	30.1	29	1.6
24/20	478	553	147	294	136.1	176	9.5
28/24	767	910	326	449	300.8	304	24.5
32/28	685	746	275	413	259.5	251	15.0
Linear	***	*	**	***	***	*	***
Quadratic	*	*	*	*	*	NS	*

^{NS,*,**,***}Nonsignificant or significant at $P = 0.05, 0.01$, or 0.001, respectively.

Table 3. Seed yield of hydroponically grown ‘Georgia Red’ peanut in response to diurnal temperature.

Temp (°C)	Mature seed no.	Immature seed no.	Mature seed yield (g·m^{-2})	Immature seed yield (g·m^{-2})	Total seed yield (g·m^{-2})	Harvest index (%)
20/16	57	60	12	4.8	17	4.0
24/20	296	279	80	12.4	98	22.6
28/24	625	310	233	18.2	246	31.5
32/28	574	373	193	8.6	202	22.8
Linear	***	*	***	NS	***	***
Quadratic	*	NS	*	NS	*	***

^{NS,*,**,***}Nonsignificant or significant at $P = 0.05$, 0.01, or 0.001, respectively.

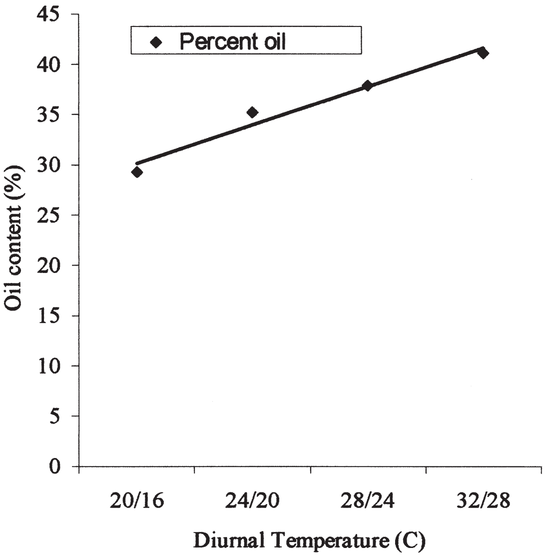

Fig. 6. Relationship between total oil content and diurnal temperature of hydroponically grown ‘Georgia Red’ peanut plants. The best fit relationship is Y = 26.3 + 3.8X, $r^2 = 0.96$.

Total oil content increased significantly with increasingly warmer temperatures and was 40% greater at the highest temperature. According to Sanders et al. (1995), total oil content of peanut seeds is strongly influenced by maturity and the cultural conditions under which the seeds were produced. Total oil content obtained in this study was lower than that reported above, ranging from 29% to 41% at, but were equal to or greater than those reported for ‘Georgia Red’ in other studies (Wu et al., 1997). The lower oil content may be partly due to cultivar differences, as well as the environmental conditions including the high humidity in NFT, under which the plants were grown. Holaday and Pearson (1974) have reported a significant correlation between total oil content and environmental conditions, and Pattee et al. (1974) and Sanders et al. (1982) reported increased oil content with increased seed maturity and seed dry weight.

Our results showed that peanut vegetative and reproductive growth, pod and seed yield, harvest index, and oil content in controlled environments, are influenced by diurnal temperature. Based on the overall plant responses, we propose that a suitable temperature optima for growth of ‘Georgia Red’ peanut in a controlled environment range between 28/24 °C and 32/28 °C. This research is significant in that it establishes temperature optima in a controlled environment. However, in a mixed cropping system characteristic of the advanced life support program, it may be difficult to provide separate temperatures for each crop since requirements vary.

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