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PLANT GROWTH IN RELATION TO WAVE-LENGTH BALANCE

(With Four Plates)

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INTRODUCTION

There can be little doubt that wave-length distribution exerts an enormous influence on the growth of plants. Numerous experiments show that stem elongation is greatly retarded under blue light, whereas an acceleration takes place in the red and near infrared regions. Chlorophyll production takes place better toward the red than toward the blue end of the visible spectrum. Phototropic sensitivity is greatest in the blue and zero in the red. For equal amounts of energy falling on the leaf, two maximal regions of CO_2 absorption have been found—one in the red, the other in the blue. It thus appears that a wave-length region best suited to a given plant process may be entirely without effect upon another.

In plant nutrition studies, experiments have shown that there is a general balance in the proportionate amounts of mineral elements of a nutrient solution that brings about a favorable growth response in plants. Although there may be considerable latitude in the ratio of amounts of elements in such a solution, it may be said that a balanced condition exists.

In a somewhat analogous manner, it is possible to think of the light requirements of plants as a balanced condition of intensities of different wave lengths which bring about good plant growth. Both light intensity and wave-length distribution vary to a considerable extent over the earth's surface. Likewise the character of the vegetation varies. Since plants have been growing on the earth for countless ages, it is reasonable to assume that their physiology is adjusted best to sunlight. Although there is experimental evidence to show that different processes go on better in some wave-length regions of the spectrum than in others, yet the best growth, when all the processes are considered simultaneously, apparently takes place in the natural light of the sun. A direct experimental comparison between sunlight and artificial light is, of course, difficult to make because of the great number of variables entering into the problem.

Numerous experiments have been made for the purpose of growing plants under artificial illumination. The object of many such experiments was to find a satisfactory artificial light which could be operated economically on a commercial scale. In other experiments the technical and scientific aspects were the main objectives. So far as is known, there is no available light source which is like that of the sun in its wave-length distribution. Plants have been grown fairly successfully in a few instances under well-controlled laboratory conditions, but the problem is by no means solved. It may even be found that plants can be grown normally under greatly reduced intensities of light provided a proper proportion between the intensities of its component wave lengths is worked out.

The purpose of the present report is to discuss briefly some preliminary experiments dealing with the question of a wave-length balance of artificial light.

EXPERIMENTATION

In the experiments herein described, plants were grown between two different light sources. Three or more types of lights could be used, but for this preliminary survey it was thought best to limit the wave-length distribution to two types. All the experiments were conducted in a small room (approximately 15 x 10 ft. x 8 ft. high) the walls and ceilings of which were painted a flat black to minimize scattered light effects. Both temperature and humidity were automatically controlled. The plants were grown in 1-quart jars containing nutrient solution. Each culture was placed on a small rotating table and usually grown for 3 weeks with a daily light period of 12 to 18 hours. By constantly rotating the plants (3.4 r.p.m.) on an axis parallel to their stems, the phototropism of these stems was reduced to zero. The leaves in some experiments showed phototropic response. The wave-length distribution depended upon the light source. The intensity was regulated largely by the distance the culture was placed from the light.

In an earlier paper Johnston (1932) found that the excess of near infrared of the Mazda lamp caused a distinct yellowing of tomato leaves. If this region of the spectrum was not actually destructive to chlorophyll, it was of little or no benefit to its formation. It would thus appear that more nearly normal color could be obtained by reducing the infrared or by increasing the intensity of the rest of the spectrum. An experiment was therefore planned in which this was partially accomplished by building up the blue end of the spectrum.

Experiment 1.—Two 1,000-watt projection Mazda lamps (115 v.) were placed 1 meter apart. Surrounding each lamp was a clear Pyrex thermos bottle blank fitted with a water inlet and outlet. The radiation of each lamp was thus filtered through 5 mm of water. The constant flow of water through this jacket was a great aid in maintaining a constant temperature condition in the room, since a great deal of heat was thus removed.

A copper sulphate (sp. gr. 1.08, about 8 percent) filter (6 cm thick) was placed in front of one of the lamps. This was the added blue light source. The individual rotating plant cultures were located at positions relative to these two light sources which gave the intensity values expressed as watts/cm^2 in table 1.

TABLE 1.—*Radiation intensities and plant data from experiment 1*

Culture no.	Light intensity watts/cm²			Stem ht. cm	Total dry wt. gram
	White	Blue	Total		
1	.0396	.0006	.0402	5.0	.086
2	.0285	.0010	.0295	7.1	.102
3	.0166	.0014	.0180	6.1	.043
4	.0064	.0027	.0091	6.3	.025
5	.0046	.0054	.0100	3.8	.019

Marglobe tomato seeds were sprouted between moist filter paper at a temperature of 25° C. for 3 days. The sprouted seeds were then transferred to a germination net, and after about a week of growth five similar seedlings were selected and set out in quart jars, one per jar, and placed on the five small rotating tables. After 2 weeks of growth these plants were measured and dried in an oven at 103° C. to obtain the dry weight. These data are also shown in table 1.

Because of the meagerness of data, no definite conclusions can be drawn. The first three plants were heavier than similar ones grown in the north and south laboratory windows. Although the total intensity of no. 1 was greatest, yet maximum dry weight occurred in plant no. 2. Here the added blue radiation was about 3 percent of the total as compared to 1.5 percent in plant no. 1, which was yellow-green in color. Plant no. 2 was a light green when compared to plants 3, 4, and 5, whose percentage of added blue to total radiation were respectively 8, 30, and 54.

Experiment 2.—The next experiment was very similar to that just described. Here again individual variation was too great to draw any accurate conclusions.

Experiment 3.—In the next experiment three duplicate sets of tomato plants were grown under three different sets of light conditions. In front of one lamp a Corning heat-absorbing 212 percent red filter was placed. In front of the other lamp a filter jar containing a M/2 $CuSO_4$ solution was placed. Both filters cut off at 6040 A, the $CuSO_4$ solution transmitting light of shorter wave length and the Corning filter transmitting light of longer wave length. Two duplicate sets of cultures were placed between these filtered light sources. A third set was located to the rear of the blue filter light in such a position that the plants received only the full Mazda spectrum. Intensities were measured at the beginning and at the end of the experiment. These average values, together with the plant data for 3 weeks' growth are given in table 2.

TABLE 2.—*Radiation intensities and average plant data from experiment 3*

Culture nos.	Radiation intensity watts/cm²				Average data per plant		
	Red	Blue	White	Total	Stem ht. cm	Root length cm	Total dry wt. gram
1 and 2........	.0055	.0022	....	.0057	6.3	38	.026
3 and 4........	.0028	.0011	....	.0039	7.4	50	.038
5 and 6........	....	....	.0056	.0056	8.0	44	.028

The greatest amount of dry weight was produced by cultures 3 and 4, although the total light intensity was less than under the other two conditions of growth. Here the blue radiation was about 28 percent of the total. Although these data are meager, there is an indication that considerable differences in growth are obtained by manipulating the wave-length distribution as well as the total intensity.

Experiment 4.—In the next experiment wave-length distribution was further restricted by using neon and mercury grids as light sources. These were constructed in our laboratory by Mr. L. B. Clark. In order to increase the intensities a mirror was placed back of each. Three duplicate cultures were placed between these two light sources, each culture jar containing three tomato seedlings. This increased the number of plants per treatment to six. Because of reflections in the mirrors some red light came from the blue side and some blue light came from the red side of the cultures. As will be seen in table 3, the intensity of radiation was considerably less than in the earlier experiments. The plants were grown for 26 days and then harvested. The average stem height and total dry weight per plant for each of the three light conditions appear in the same table.

Although the stems of plants in group 1-2 were thicker than those in the other groups, their leaves were quite yellow. Here again yellowing is associated with energy distribution where the greatest amount is found in the red end of the spectrum. The plants in group 5-6 had the best color, even though the total amount of energy was about half that of group 1-2. These leaves had flat smooth surfaces, while those in group 1-2 were quite pointed and curled. The general appearance of these plants is shown in plate 1. After another experiment with these lamps it was definitely indicated that the plants were getting insufficient illumination.

Experiment 5.—To increase the radiation, a General Electric 400-watt high-pressure mercury lamp was substituted for the mercury

TABLE 3.—*Radiation intensities and average plant data from experiment 4*

Culture no.	Radiation intensity at beginning of experiment watts/cm² Neon (red)	Mercury (blue)	Total	Average data per plant Stem ht. cm	Total dry wt. gram
1	.00023	.00002	.00025	6.6	.029
2	.00019	.00002	.00021	6.6	.029
3	.00008	.00002	.00010	3.6	.014
4	.00008	.00002	.00010	3.6	.014
5	.00005	.00007	.00012	3.4	.013
6	.00005	.00007	.00012	3.4	.013

grid and four instead of two transformers were used with the neon lamp. The daily light period was increased from 12 hours to 18 hours. Because of the marked decrease in the life of the neon lamp under these forced conditions, the experiment was discontinued at the end of 20 days. In this exploratory experiment no accurate intensity measurements were made. However, general improvement in growth was noted.

Experiment 6.—To increase further the light intensity, a 1,000-watt, 110-volt projection lamp housed in a water jacket as noted earlier (experiment 1) was substituted for the neon grid lamp. Three plants per quart culture jar were used and the cultures run in duplicate so far as the light relations were concerned. Throughout all the previous experiments the plants were grown in a three-salt nutrient solution similar to that used by Johnston and Dore (1929). In this experiment cultures 2, 4, and 6 had $(NH_4)_2SO_4$ added to the former solution which contained $Ca(NO_3)_2$, $MgSO_4$, and KH_2PO_4

and traces of Mn, B. Iron was added as $FeSO_4$ to all cultures from time to time as conditions demanded. Because the Mazda lamp was run at about its voltage limit its life was short, and replacements were necessary every 6 or 7 days. The plants were grown for 3 weeks with a daily light period of 18 hours. The added heat from the lamps caused a slight daily temperature fluctuation. The average maximum was 24° C. and the average minimum 21.5° C. This resulted in a change in humidity which averaged 57 and 51 percent for the dark and light periods respectively. As found in previous experiments, a temperature fluctuation is beneficial to the tomato plant. Better growth was obtained by subjecting the plants to a lower dark period

TABLE 4.—*Radiation measurements at beginning of experiment 6*

Culture nos.	Watts/cm²			Foot-candles with small G. E. meter		
	Mazda	Mercury	Total	Mazda	Mercury	Total
1 and 2	.0404	.0013	.0417	2,800	200	3,000
3 and 4	.0172	.0031	.0203	1,200	600	1,800
5 and 6	.0065	.0067	.0132	550	1,000	1,550

TABLE 5.—*Plant data from experiment 6 expressed as averages per plant*

Culture no.	Stem ht. cm	Green wt. grams Tops	Dry wt. gram		
			Tops	Roots	Total
1	17.5	6.6	.529	.139	.668
2	21.1	7.8	.671	.174	.845
3	18.9	5.6	.463	.091	.554
4	20.9	6.1	.469	.074	.543
5	23.5	5.0	.384	.074	.458
6	23.8	5.4	.371	.057	.428

temperature (about 3° C. lower) than by maintaining a constant temperature during the dark and light periods.

The intensity measurements which were made at the beginning of the experiment are presented in table 4.

After 3 weeks of growth the plants were photographed (pl. 2) and harvested. Data giving average stem height, green weight of tops, and dry weight of tops and roots are given in table 5.

Both the illustrations and plant data show that this group of plants was normal in appearance and comparable to good greenhouse plants. It was by far the best we have grown under the 100 percent artificial conditions of our laboratory. In an earlier publication, Johnston (1932) reported that tomato plants exposed to an intense illumination from a Mazda lamp grew very well but soon became yellow in color.

The near infrared radiation was apparently destructive to chlorophyll or inhibited its formation. This again appeared to be the case for the three plants in culture 1. However, one of the most interesting observations made in this experiment was that the color of the plants in culture 2, which received the same radiation intensity as those of no. 1, was much greener. This color difference is seen to some extent in plate 2 as differences in light and dark tones of the plants in the upper and lower figures. This was also true for the plants in cultures 4 and 6, as compared with cultures 3 and 5 respectively, which were grown under similar light conditions. All the plants grown in nutrient solution to which $(NH_4)_2SO_4$ had been added were greener than the corresponding ones without this additional nitrogen. This observation suggests the influence of the type of radiation on the uptake of mineral nutrients. This same solution without the $(NH_4)_2SO_4$ has been used in growing tomato plants in the greenhouse but the characteristic chlorotic effects were not noted until the plants were grown under Mazda lamps.

The percentages of added mercury radiation to total illumination were 3, 15, and 50 respectively for cultures 1-2, 3-4, 5-6. The green color of the leaves was deeper where this percentage was larger. A more striking color difference occurred, however, between the plants in cultures with and without the $(NH_4)_2SO_4$.

The average total dry weight per plant for each of the three light conditions 1-2, 3-4, 5-6 was .757, .549, and .443 gram respectively. Under these three light conditions the efficiency in the production of dry weight per watt/cm^2 was 18, 27, and 34 respectively. Although the total intensity of 5-6 was about a third that of 1-2, on the basis of efficiency in producing dry weight per unit energy, the less intense radiation was about double that of the more intense.

One other factor in addition to wave-length distribution must be recognized in an experiment of this type. One lamp (Mazda) gave practically continuous illumination; the other (mercury, 60-cycle), a fluctuating illumination varying from a minimum considerably below the average to a maximum much greater than the average as determined by the thermocouple and photoelectric cell. McAlister (1937) clearly shows that a change in efficiency of carbon dioxide assimilation occurs with frequency of intermittency of illumination. Although it may be comparatively safe to compare the different cultures in any one experiment since the " flicker " effect is doubtless the same, it is impossible to compare results of experiments in which the light is continuous with those in which it is intermittent or with those in which it is half continuous and half intermittent.

Experiment 7.—An experiment varying a little from the one just described was next performed. In this, five cultures of tomato seedlings were placed around the Mazda lamp at positions which gave them approximately equal light intensities from this lamp. A sixth culture was located at a position where the Mazda intensity was about half that of the other cultures. The intensities of each of the two lamps for each culture of these plants are best seen in table 6.

After 18 days the plants were harvested and their dry weights determined. The plant data appear in tables 7 and 8.

TABLE 6.—*Radiation measurements*[1] *from experiment 7*

Culture no.	Watts/cm²			Foot-candles with small G. E. meter		
	Mazda	Hg	Total	Mazda	Hg	Total
1	.0234	.0097	.0331	1,300	2,000	3,300
2	.0241	.0018	.0259	1,300	300	1,600
3	.0241	.0013	.0254	1,400	200	1,600
4	.0240	.0013	.0253	1,400	200	1,700
5	.0231	.0039	.0270	1,300	600	1,900
6	.0112	.0090	.0202	600	1,900	2,500

[1] Since the original Mazda lamp was replaced after 6 days, these measurements were made on the second lamp on the 10th day of the experiment.

TABLE 7.—*Stem height (cm) data from experiment 7*

Plant	Culture number					
	1	2	3	4	5	6
a	16.5	16.2	19.0	18.5	22.2	19.8
b	15.8	18.0	15.5	22.3	22.5	19.5
c	14.5	19.4	19.0	20.0	20.6	18.5
Av. ht. at harvest	15.6	17.9	17.8	20.3	21.8	19.3
Av. original ht.	2.3	2.1	2.2	1.6	1.9	1.8
Av. increase in ht.	13.3	15.8	15.6	18.7	19.9	17.5

TABLE 8.—*Average green and dry weights (grams) of plants from experiment 7*

Culture no.	Green wt. Tops	Dry wt.		
		Tops	Roots	Total
1	6.1	.713	.199	.912
2	4.2	.311	.044	.355
3	4.8	.391	.060	.451
4	5.8	.467	.064	.531
5	6.6	.582	.099	.681
6	6.3	.610	.145	.755

During the experiment water was added and fresh nutrient solution renewed as required. Because of frequent stopping of rotating table no. 1, these plants were slightly burned. These plants had the shortest internodes. Plants in culture 6 had next to the shortest internodes and were the best green. The leaves of plants in cultures 2, 3, 4, and 5 were slightly chlorotic. In order of their dry weights, plants in cultures 1, 6, and 5 were the best. It is interesting to compare the total dry weight per unit total energy with the percentage of energy received from the mercury lamp (table 9).

Table 9.—*Comparison of dry weight efficiency with amount of radiation from the mercury lamp*

Cultures	1	2	3	4	5	6
Ratio total dry wt. to watts/cm²	27.6	13.7	17.8	21.0	25.2	37.4
Percentage radiation from mercury lamp	29	7	5	5	14	45

Plants in cultures 6, 1, and 5 produced the greatest amount of dry weight per watt/cm². These same cultures in the order given received the largest percentages of radiant energy rich in the blue. Total energy (table 6) was greatest for culture 1 and least for culture 6. Cultures 2, 3, and 4 were practically equal. Thus, plants of culture 1 had the greatest total dry weight, and those of 6 were second. However, for greatest efficiency in the production of dry weight, plants in culture 6 were much better than those in culture 1. This is evidently related to the greater percentage of shorter wave length in the one case than in the other. When light intensity as measured by the foot-candle meter is considered, plants of culture 1 are shown as receiving the greatest amount of light and those of culture 2 the next greatest amount.

By consulting the table of stem heights it will be noted that the average height at harvest for plants in culture 1 was less than any of the other groups although the average original height was greatest. The least average stem elongation shown by this group may be correlated with the greatest amount of total energy received by these plants. But little difference in stem height is seen between plants of the other cultures. Likewise there is but little difference in total energy received by these same cultures. Other observations bear out this same point that an intense light retards stem elongation more than a less intense one. Although the shorter wave lengths have a greater retarding effect, this difference between plants of cultures 6 and 1 must have been offset by the differences in total radiation intensities.

Experiment 8.—In the last experiment of this series, the same types of lamps were used. Also each culture contained three tomato plants. The first four cultures (nos. 1, 2, 3, 4) were arranged around the mercury lamp at approximately equal distances. The other two (nos. 5 and 6), together with those numbered 3 and 4, were located about equal distances from the water-cooled 115-watt Mazda projection lamp. The intensity measurements taken at the beginning of the experiment are shown in table 10.

TABLE 10.—*Radiation measurements in experiment 8*

Culture no.	Intensity measurements: Watts/cm² Mazda	Watts/cm² Hg	Watts/cm² Total	Foot-candles Mazda	Foot-candles Hg	Foot-candles Total
1......	.0071	.0048	.0119	350	700	1,050
2......	.0071	.0047	.0118	350	700	1,050
3......	.0140	.0046	.0186	800	700	1,500
4......	.0144	.0045	.0189	800	700	1,500
5......	.0137	.0010	.0147	900	200	1,100
6......	.0146	.0010	.0156	900	200	1,100

At the end of three weeks the plants were photographed and harvested. Since each culture of three plants was duplicated, the average of the six plants is shown in table 11.

TABLE 11.—*Plant data from experiment 8 expressed as averages per plant*

Culture nos.	Plant data expressed as averages per plant: Final stem ht. (cm)	No. of leaves	Green wt. of tops (g)	Total transpirational water loss (ml)	Dry weight (g) Tops	Dry weight (g) Roots	Dry weight (g) Total
1 and 2....	18.3	6	3.5	157	.240	.042	.282
3 and 4....	20.8	7	6.1	251	.437	.097	.534
5 and 6....	15.8	5	2.6	98	.140	.021	.161

Plants of cultures 3-4 were best in general appearance and had the thickest stems. Those of cultures 5-6 were lightest green. Plants with longest roots were found in cultures 5-6; those with shortest roots occurred in cultures 1-2.

The general appearance of the cultures about the two lamps in this experiment may be seen in plate 3, and the appearance of the tops and roots of the plants at the end of the experiment is seen in plate 4.

It will be recalled that in experiment 6 the ratio of dry weight to total energy increased with the percentage of added radiation from the mercury lamp. Also in experiment 7, table 9, the three cultures in which the greatest dry weight was produced per watt/cm^2 were the same three cultures which received the greatest percentage of radiation from the mercury lamp. In experiment 8, however, an exception occurred. The dry weight efficiencies for the three groups of cultures 1-2, 3-4, 5-6, were 23.8, 28.6, 10.7 respectively, while the percentages of total radiation attributed to the mercury lamp were 40, 25, and 7 for these same cultures in the order given. It is not clear from the data at hand why this exception occurred.

In order to compare all these data which are fairly comparable, table 12 has been constructed. Since two types of solutions were used in experiment 6, cultures 2, 4, and 6 were selected as their solutions

TABLE 12.—*Average dry weight production per unit total radiation (Mazda plus mercury lamp) in relation to percentage of radiation from the mercury lamp*

Experiment number	Culture number	Dry wt. per watt/cm^2	Percentage radiation from mercury lamp
7	6	37.4	45
8	3	32.7	25
6	6	32.4	51
8	1	28.2	40
7	1	27.6	29
6	4	26.8	15
7	5	25.2	14
8	4	24.4	24
7	4	21.0	5
6	2	20.3	3
8	2	19.4	40
7	3	17.8	5
7	2	13.7	7
8	6	11.0	6
8	5	10.3	7

were similar to those used in experiments 7 and 8. All plant values given in this table are the averages of three plants. There is a slight difference in the duration of the three experiments which should be kept in mind in making this comparison. In these experiments, 6, 7, and 8, the plants were grown for 20, 18, and 21 days respectively.

The data showing dry weight produced per unit total energy in table 12 have been arranged from greatest to least value. The corresponding values showing the percentages of total radiation that are obtained from the mercury lamp fall roughly into two groups. The first eight values are high (14 to 51 percent). The remaining seven with the exception of culture 2 in experiment 8 are low (3 to 7 percent). Although there is no regular decrease in these percentage values with the decrease in dry weight per unit total radiation, there appears to be a general decrease in dry weight efficiency with illumination containing less of the shorter wave lengths found in the mercury lamp.

DISCUSSION

Plants have been grown by Harvey (1922), Hendricks and Harvey (1924), and others under Mazda lamps. Davis and Hoagland (1928), Arthur, Guthrie and Newell (1930), Garner and Allard (1931), Steinberg and Garner (1936), and others have conducted numerous experiments in which good growth was obtained with Mazda lamps for various lengths of daily light and dark periods. Many other investigators both in Europe and in this country have shown that plants may be grown in artificial light whose wave-length distribution is continuous from blue-violet to red. Other investigators have determined the growth of plants in different portions of the spectrum. Here it was necessary to use glass or liquid filters. Others, like Roodenburg (1932), have used gaseous discharge lamps such as neon. Most of these experiments indicate the necessity of the full visible spectrum for normal growth. Popp's (1926) results indicate that the blue-violet end of the spectrum is necessary for normal growth although the ultraviolet may not be indispensable. Shirley (1929) states that " The entire visible and ultra-violet solar spectrum is more efficient for the growth of the plants studied than any portion of it used; the blue region of the spectrum is more efficient than the red region." Schappelle (1936) concluded that white light is best for normal plant response. Either end of the visible spectrum without the other causes abnormal growth. Infrared, between 0.8 μ and 2.0 μ was ineffective in bringing about fruiting of *Marchantia,* while red and blue lights were of approximately equal effectiveness.

Arthur and Stewart (1935) made a comparison of the growth of buckwheat plants under Mazda, neon, sodium, and mercury vapor lamps. For short periods of 8 to 10 days the sodium lamp was found to be most efficient in the production of dry weight. No relation was found between the absorption bands of chlorophyll and the emission bands of the various lamps. These gaseous discharge lamps produced plants with greener leaves than the Mazda lamps. Later Arthur and Harvill (1937) show that the sodium lamp alone is not ideal for the continuous growth of plants over long periods of time. If, however, the continuous exposure from the sodium lamps is supplemented by an exposure of 2 hours per day from an 85-watt capillary mercury vapor lamp, excellent leaf color and flowering could be produced in such plants as begonia, gardenia, cotton, geranium, buckwheat, and snapdragon. Although this light source was not satisfactory for the tomato plant, the authors point out that other wave bands of light may be found which should be added or subtracted for the best growth of some plants such as the tomato.

Dastur and Mehta (1935) determined the rate of photosynthesis in approximately equal intensities of red, blue, and white light. Photosynthetic activity was greatest in the white light, intermediate in the red light, and least in the blue light. They state that both the red and blue regions are necessary for normal photosynthesis.

Equally interesting are the results of Hoover's (1937) investigation on determining the rate of CO_2 absorption as a function of wave length on the basis of equal incident energy. The principal maximum occurred at 6500 A in the red, and a secondary maximum came at 4400 A in the blue. The greater transmission and reflection of radiation in the green region decreased the effectiveness in that portion of the spectrum. The limits of CO_2 absorption were placed between 7200 A and 7500 A in the red, and below 3650 A in the blue end of the spectrum.

Dastur and Solomon (1937) show the importance of the blue-violet end of the spectrum in photosynthesis in a series of experiments in which plants are grown in the light of a carbon arc, in "mixed" light where the gas-filled electric lamp light has superimposed upon it a beam of blue-violet light, and in the light of the gas-filled electric lamp alone. The "mixed" light was composed of two beams originating in a single source (1,000-watt flood lamp) and reflected to the plant by mirrors. One beam was passed through a copper sulphate filter which limited the wave-length band to the region 4200 A to 4720 A. These beams (white and blue) were reunited in the proportion 1 : 1 on an intensity basis. Plants grown in these three lights showed greatest photosynthetic activity in the carbon arc light, intermediate in the "mixed" light, and least in the gas-filled electric bulb light. This follows the order of richness in blue-violet light of the three sources.

From the foregoing discussion it would appear that plants can be grown in artificial light, but for more or less normal growth the light should include those wave lengths found in the visible solar spectrum. An increase in intensity or the absence of a given portion of this spectrum brings about abnormal growth responses. Undoubtedly, the more nearly the artificial light resembles sunlight in its energy distribution, the more nearly normal are the plant growth responses.

In the experiments reported in the present paper, a method for mixing artificial lights was used, but one quite different from that used by the above-mentioned investigators. A beginning was made by using two light sources, one rich in red, the other rich in blue light. By locating the plants on small rotating tables at different distances from these light sources, practically any intensity ratio of the two could be obtained. With this general scheme the number of lights could be increased, thus making it possible to study the effects of any given mixture of restricted wave-length regions on the growth of plants. With each added light, however, the interpretation of data becomes more difficult. By using this method it is difficult to grow many duplicate individuals at one time, especially if they grow large. This objection may be met in part by repeating an experiment often enough to obtain more reliable statistical data.

The first two experiments with the Mazda light vs. the Mazda light filtered through a $CuSO_4$ solution were mostly exploratory in nature. There is some indication that the greatest dry weight produced is associated with wave-length distribution and not entirely correlated with intensity of radiation. Although the data of experiment 3 are meager, a considerable difference in growth was obtained between plants receiving different amounts of red (wave lengths longer than 6040 A) and blue (wave lengths shorter than 6040 A). The dry weight increase for the plants receiving red-blue light in the ratio 72:28 was about 40 percent over those receiving white light and those receiving a mixture in the proportion 96:4, although the total intensities of these two cultures were over 40 percent greater.

An attempt was made to change the type of red and blue light by the use of neon and mercury grids. In these experiments (nos. 4 and 5) it was found that the intensity of radiation was too low for good growth. This made it impossible to draw any definite conclusion regarding the proportion of red to blue that gave best growth. Yellowing or lack of greenness was associated with those light mixtures predominant in red.

In order to obtain lights of higher intensities, one rich in red, the other rich in blue, the water-jacketed projection Mazda lamp used in experiments 1 and 2 and the 400-watt high-pressure mercury lamp used in experiment 5 were employed. With this combination of lights very good growth was obtained under 100 percent artificial conditions. Because of this good growth and the increased number of plants per treatment, more weight can be attached to the data from experiments 6, 7, and 8, than to the earlier ones. Where light and not carbon dioxide is the limiting factor, the dry weight increases with increased illumination. Hoover, Johnston, and Brackett (1933), working with wheat plants, found that in normal air CO_2 became limiting at a light intensity of about 0.05 to 0.06 watts/cm^2. In none of these experiments with the tomato plant was the intensity greater than these values. Although the two plants may not behave exactly alike, it is reasonable to suppose they are similar enough to assume that at no time was CO_2 the limiting growth factor. In order to accentuate growth differences due to wave-length mixtures and minimize the effect of intensity on dry weight production, the dry weight data were divided by watts/cm^2. This dry weight efficiency of comparable cultures in the last three experiments was used as a criterion of the effect short-wave (blue) radiation added to that of longer wave length had on plant growth. It would appear from the data given in table 12 that a greater amount of dry weight is produced with a Mazda light by enriching it with blue from a mercury lamp to the extent of 14 to 51 percent under the conditions of these experiments. Care should be exercised in drawing any far-reaching conclusions, for with a change in quality or wave-length distribution of the Mazda or other source rich in red, changes undoubtedly will be necessary in other portions of the spectrum. Although for good growth plants very probably tolerate a rather wide range in wave-length distribution, yet it would appear that the more nearly this distribution in artificial light approaches that of sunlight the better will the plants grow.

SUMMARY

Emphasis is placed on the importance of quality or wave-length distribution of light in affecting plant growth. A method and several experiments are described in which plants were grown in "mixed" lights. By placing the plants on small rotating tables between two light sources, one rich in red, the other rich in blue, the proportion of each type of radiation falling on each culture was varied by the position of the culture with reference to the light sources.

As found in previous experiments, yellowing of leaves occurred in light rich in near infrared. Since this trouble could be corrected to a considerable extent by the type of nutrient solution used, it indicates the importance of wave-length distribution on the uptake of mineral nutrients.

Excellent growth under entirely artificial conditions was obtained with plants grown between a 1,000-watt, water-jacketed, projection Mazda lamp and a 400-watt, high-pressure mercury lamp. The posi-

tions of the plants for good growth were such that from 14 to 51 percent of the total radiation falling on them came from the mercury lamp. In several cases better growth was attained in one mixture of wave-lengths than in another where the total intensity was higher. However, the relatively high growth efficiency may in part be due to an intermittency effect occurring in gaseous discharge tubes such as the mercury lamp here used.

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EXPLANATION OF PLATES

PLATE 1

Tomato plants grown for 26 days under the following intensities (watts/cm^2). Daily illumination was 12 hours.

Culture	Neon	Mercury
1	.00023	.00002
3	.00008	.00002
5	.00005	.00007

PLATE 2

Tomato plants grown for 21 days under the following intensities (watts/cm^2). Daily illumination was 18 hours.

Culture	Mazda (water-cooled)	Mercury (400 watt)
1 and 2	.0404	.0013
3 and 4	.0172	.0031
5 and 6	.0065	.0067

The darker green leaves in cultures 2, 4, and 6, due to the added $(NH_4)SO_4$, appear in the illustrations as a deeper shade than those in cultures 1, 3, and 5.

Plate 3

General arrangement of cultures in experiment 8 on rotating tables placed about the two light sources. The Mazda lamp encased in a water jacket is on the left and the 400-watt mercury lamp on the right. The small rotating tables turned at the rate of 3.4 r.p.m. This prevented phototropic curvature of the stems but not of the leaves which, although turgid, appear wilted.

Plate 4

Tomato plants grown for 21 days under the following intensities ($watts/cm^2$). Daily illumination was 18 hours.

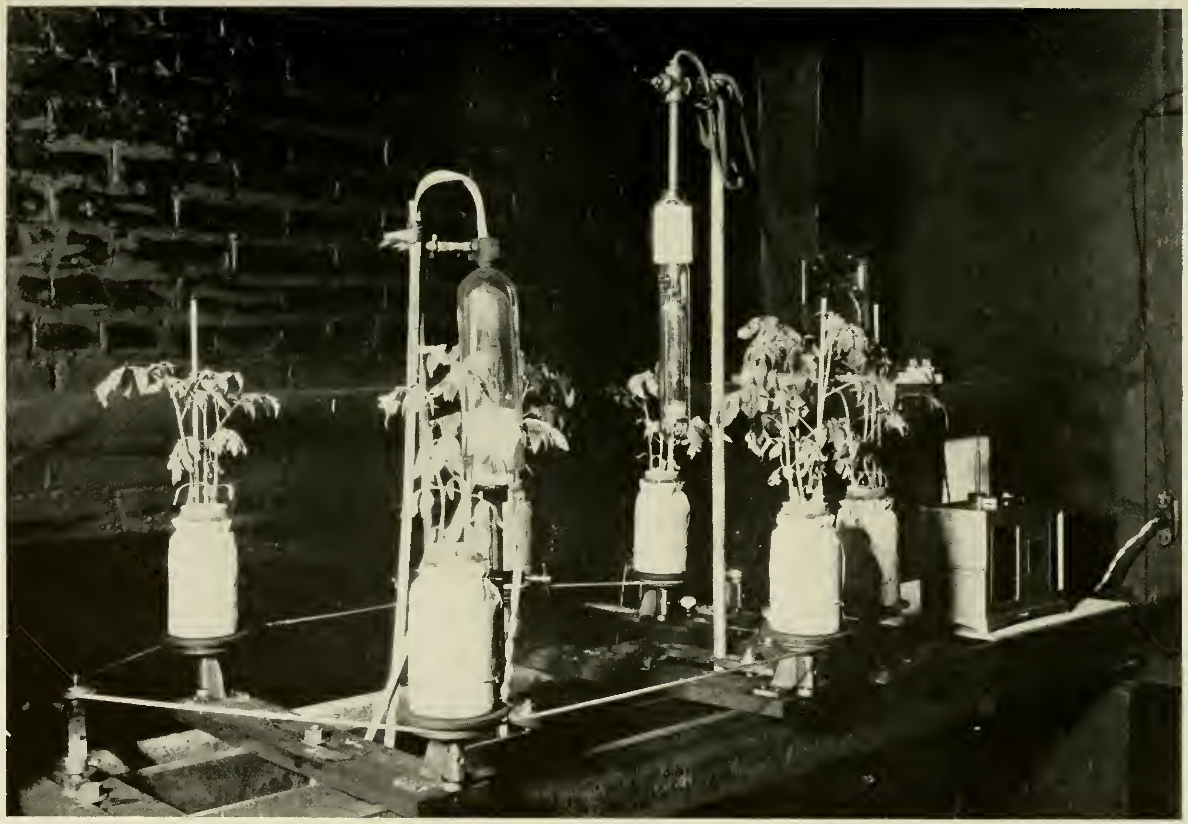
Culture	Mazda (water-cooled)	Mercury (400 watts)
1	.0071	.0048
2	.0071	.0047
3	.0140	.0046
4	.0144	.0045
5	.0137	.0010
6	.0146	.0010

GENERAL APPEARANCE OF TOMATO PLANTS IN EXPERIMENT 4, GROWN BETWEEN MERCURY AND NEON LAMPS

(For explanation, see pages 4 and 17.)

General Appearance of Plants in Experiment 6, Grown Between Mazda and Mercury Lamps

(For explanation, see pages 5 and 17.)



General Arrangement of Cultures in Experiment 8, on Rotating Tables, Placed at Different Distances from the Two Light Sources

(For explanation, see pages 10 and 18.)

GENERAL APPEARANCE OF PLANTS AT THE CONCLUSION OF EXPERIMENT 8

(For explanation, see pages 10 and 18.)