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PAPER

CRIMINALISTICS

David J. Potter,[1] *Ph.D. and Paul Duncombe,*[1] *Ph.D.*

The Effect of Electrical Lighting Power and Irradiance on Indoor-Grown Cannabis Potency and Yield

ABSTRACT: The floral development and potencies [Δ^9-tetrahydrocannabinol (THC) contents] of cannabis plants were compared when grown indoors under high-pressure sodium lamps consuming electrical power at three densities (270, 400, and 600 W/m^2). After a 3-week vegetative phase, plants were grown for 8 weeks, with lamps maintaining an artificial day length of 12 h. Foliar and floral yields were measured. Gas chromatography was used to measure the content of the psychoactive cannabinoid THC. Mean yields per unit of electrical power in each lighting regime ranged from 0.9 to 1.6 g/W, the highest being achieved in the lowest irradiance regime. The individual potencies of the separated leaf and flower materials were not affected by increasing irradiance. However, there was a corresponding increase in the overall potency of the aerial plant tissue. This was because of the plants in brighter conditions producing a higher proportion of floral material.

KEYWORDS: forensic science, cannabis, marijuana, sinsemilla, light, potency, cannabinoid, Δ^9-tetrahydrocannabinol, carbon nutrient balance, THC

In 2009, cannabis again headed the list of illicit drug markets in terms of global spread of cultivation, volume of production, and number of consumers (1). Over many millennia, *Cannabis* has adapted to grow well outdoors over a wide range of latitudes and climates (2), and consequently in many countries, the bulk of the locally produced drug would have been grown outside. However, in Canada, most Western U.S. states and Northern Europe, the climate is unfavorable, making indoor or glasshouse propagation the only reliable option. Since the 1970s, in the United States and Canada, a law enforcement crackdown and large-scale eradication efforts may have inadvertently encouraged more growers indoors (3).

In recent decades, the Western cannabis market has changed, with an increasing proportion preferring to consume only unfertilized floral parts of the female cannabis plant. This form is often called sinsemilla (from the Spanish *sin semilla*: without seeds), and most of it is grown indoors (4). In the more easily controlled indoor environment, the quality of this material is increasingly guaranteed (5).

In 2005, evidence suggested that the domestic production of cannabis in the United States was continuing to escalate, partly due to the increasing involvement of drug trafficking organizations. In Canada, similar organized crime groups were growing increasing quantities of cannabis indoors for home consumption and for smuggling to the United States (6). In the United Kingdom, organized crime groups have established so-called *cannabis factories* on a massive scale (7). In over 90% of cases, these appear to be in domestic dwellings purposely rented for cannabis growing (8,9). Within these houses, the crops are typically grown under powerful lamps that are specifically developed to encourage plant growth. These are tightly packed to produce extremely bright light levels. The high energy consumption of these lighting systems would usually be of little financial concern to the grower, as the electrical energy would be stolen (7).

Predictions of cannabis yields for court purposes have often been simply stated in terms of weight per plant. To guide such estimates, a forensic study of illicit cannabis growing operations in the Netherlands in 2006 reported an average yield of 33.7 g per plant (10). This was linked to an average planting density of 15/m^2. Another forensic study in New Zealand, in which three sparsely planted crops were grown in a hydroponic system, reported much higher yields of over 800 g per plant (11). Much of the disparity in average plant weight in these two studies would have been attributable to the marked difference in the planting density, as the yield of cannabis plants is greatly affected by the number grown per unit area (12,13). Arguably therefore, cannabis yields are more meaningfully estimated on the basis of weight per unit area. The 2006 Netherlands study (10) recommended a nominal dry floral material yield of 505 g/m^2, when valuing illicit crops this way.

Photosynthesis and growth in cannabis are strongly correlated with light intensity (14,15). Reflecting this fact, some cannabis seed suppliers and growing guides predict yields in terms of weight per watt of electrical energy consumed by the lighting system (16). Indeed, it has been claimed that "a decent grower" can be expected to achieve one gram of dry cannabis per watt of electrical lighting (17). The Netherlands study appeared to support this claim, when linking a median average yield of 505 g/m^2 to a median light fitting wattage of 510 W/m^2 (10). Light fitting power may therefore also be a meaningful factor when estimating cannabis yields.

Research has shown that over the last 10 years, the *potency* of illicit cannabis, that is, the content of the cannabinoid Δ^9-tetrahydrocannabinol (THC), has increased markedly in the

[1]GW Pharmaceuticals Ltd., Porton Down Science Park, Salisbury, Wiltshire, SP4 0JQ, U.K.

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United States (18), Canada (19), and the United Kingdom (20,21). This increase has caused concern because of a perceived link between cannabis potency and mental health problems (5,22). It has been suggested that the move to indoor growing has been part of the reason for this potency increase (23). Grown in optimized cultivation conditions under artificial lights, cloned female cannabis can produce a drug product of consistently higher potency (5).

How much of this increase in potency is specifically attributable to the lighting conditions is not clear. Lydon et al. (14) demonstrated that the THC content of some cannabis plants could be increased by irradiating them with UV-B (wave length 280–320 nm). It is notable that this wavelength, which is potentially damaging to plant ovary tissues, is absorbed by the cannabinoids. These molecules would therefore afford the plant some protection from this actinic radiation. Lydon et al. (14) postulated that cannabis plant populations having an inherited ability to increase THC production, when exposed to UV-B radiation, would have more reproductive success. The specific response to this wavelength is arguably of little relevance in most indoor growing environments, as the favored high-pressure sodium lamps emit most light energy at around 700 nm and produce minimal UV-B.

This study had two aims. First, it intended to determine whether the level of electrical power used to illuminate the flowering crop could be used to estimate the likely final yield of sinsemilla cannabis. The findings would be of value to growers of cannabis for the pharmaceutical industry as well as those assessing cannabis yields as part of court proceedings. The second aim was to discover whether the observed general increase in cannabis potency could be attributed to the use of brighter lighting regimes. In many plant species, the concentration of carbon-based secondary metabolites (such as THC in cannabis) rises if they are exposed to increased light energy (24). This is linked to a shift in the carbon nutrient balance. It was postulated that, when using increasingly bright lighting regimes to improve yield, growers have also inadvertently pushed up cannabis potency.

Materials and Methods

Cannabis Variety Selection and Propagation

Seeds of seven commonly grown cannabis varieties were acquired (*Early Pearl, Hindu Kush,* and *Super Skunk* from The Sensi Seed Bank, Rotterdam, The Netherlands; *White Widow* from Nirvana, Amsterdam, The Netherlands; *Wappa* and *White Berry* from Paradise Seeds, Amsterdam, The Netherlands; and *G1* from GW Pharmaceuticals, Salisbury, Wilts, U.K.). When the seedlings were sufficiently advanced, several cuttings were taken from each and a proportion retained under continuous lighting to maintain vegetative growth. The remainder were placed in a 12-h day length, which induced flowering, and these were propagated through to full maturation. Mimicking common commercial practice (25,26), the mature female plants were visually assessed for vigor, yield, and resin gland density, and the best performing candidate from each variety was selected. Vegetative cuttings derived from the same seedling source as the best candidate were used for all ongoing propagation.

Cuttings were raised in peat plugs under high humidity for 2 weeks. These were then placed in 5-L pots of a peat/perlite mixture, which contained sufficient controlled release fertilizer to support growth through to full maturation. The plants received uniform illumination under high-pressure sodium lamps for 24 h/day for the following 3 weeks. Being a so-called *short day* plant species, none of the varieties commenced flowering in these conditions. The established plants were then transferred to a 20-m^2 walk-in growth room, where they were maintained for 8 weeks in an artificial day length of 12 h. This regime is favored by illicit growers and typically encourages good floral development (27). Plants were hand watered as necessary throughout the test.

Within the growth room, daily average temperatures were kept at 25 ± 2°C. A constant supply of fresh air maintained ambient carbon dioxide levels of between 350 and 390 ppm. By using contrasting densities of 250 and 1000 W Philips SON-T high-pressure sodium lamps (Philips Lighting UK, Guildford, Surrey, U.K.), three distinct zones were established within which the rates of electrical power consumption were 270, 400, and 600 W/m^2. This spanned the range recommended for a flowering cannabis crop in an assortment of published and online growing guides. The majority of illicit cannabis growing operations in the Netherlands were reported to use power levels within this range (10). Five plants of each variety were placed within each of the three zones at a density of 10 plants/m^2. The irradiance levels at the surface of the plant canopy were measured using an SKE 500 hand-held light meter (Skye Instruments, Llandrindod Wells, Powys, U.K.) and found to be 80, 120, and 180 W/m^2 photosynthetically active radiation (PAR), respectively. Lamps were kept at a constant distance from the crop canopy as the plants grew. After 8 weeks in a 12-h day length, the plants were sufficiently mature to be harvested.

Plants were then cut at soil level and hung on wires to dry in a dehumidified environment at *c.* 30°C for 7 days. The floral and foliar materials were separately removed from each plant, weighed, and milled through a 2-mm mesh screen and stored at −20°C prior to analysis for cannabinoid content. Stem and root material was discarded.

Chromatographic Analysis

The analysis method used in this study was that developed by de Meijer et al. (28) for the validated identification and quantification of a range of cannabinoids.

Statistical Analysis

When assessing the effect of lighting during the flowering phase, each of the dried foliage and floral weights, as well as the foliage and floral cannabinoid weights, was compared between lighting regimes. Linear regression methodology was used, with variety as a factor and electrical power per unit area as a linear regressor. Estimates of the resulting increases in associated weights, per 100 W increase in electricity use, were derived from the fitted linear models. The possibility of a nonlinear relationship between the weights and light intensity was assessed by adding a quadratic term in light intensity to the model. There was no evidence of a quadratic relationship for any of the models fitted, and so a quadratic term was not retained in any of the fitted models. In addition, the flower to leaf weight ratio was analyzed using the same regression methodology.

Results and Discussion

Effect of Lighting Power on Yield

Increasing the power of the electrical lighting during the flowering phase had no significant effect on the mass of foliage produced or the total mass of THC within the foliage. However, as power levels were raised, plants exhibited a significantly increased floral mass (linear regression, $p < 0.0001$) and a corresponding significant

TABLE 1—*The effect of increasing electrical lighting power density on the yields per square meter of dried plant material and THC at harvest. Results are the mean of seven varieties, with five plants of each spaced at a density of 10 plants/m^2.*

Electrical Power Per Unit Area W/m^2	Flower Leaf Ratio	Dried Plant Yield			THC Yield		
		Leaf g/m^2	Flower g/m^2	Leaf + Flower g/m^2	Leaf g/m^2	Flower g/m^2	Leaf + Flower g/m^2
270	1.93	230 (±47)	422 (±102)	652 (±104)	6.2 (±2.6)	61.2 (±24.0)	67.4 (±24.0)
400	2.28	225 (±43)	497 (±118)	723 (±126)	5.8 (±2.8)	71.1 (±25.5)	77.0 (±25.1)
600	2.36	238 (±40)	544 (±88)	782 (±88)	6.5 (±2.8)	78.4 (±22.4)	84.9 (±22.7)
Significance of increase (linear regression)	$p < 0.0001$	$p = 0.19$	$p < 0.0001$	$p < 0.0001$	$p = 0.32$	$p < 0.0001$	$p < 0.0001$
Estimated increase per 100 W (95% CI)	0.12 (0.07–0.18)	2.6g (1.4–6.7)	36g (24.3–47.8)	39g (25.2–52.2)	0.51g (0.35–1.22)	5.1g (2.8–7.3)	5.2g (2.9–7.5)

THC, $\triangle^9$-tetrahydrocannabinol.

increase in flower leaf ratio ($p < 0.0001$) (Table 1). The total quantity of THC produced by the floral material showed a significant increase as power was increased ($p < 0.0001$). The total mass of THC produced by the combined foliar and floral materials similarly showed a significant increase ($p < 0.0001$).

Within each lighting zone, the yield of floral material produced was calculated in terms of mass per watt of electrical power. The results are shown in Fig. 1. Current cannabis growing guides most commonly recommend lighting regimes that use high-pressure sodium lamps and have an electrical power consumption of 400–600 W/m^2. In the 600 W/m^2 regime, yields per watt averaged 0.9 g/W. Although some commercial varieties are offered with predicted floral yields of 1.0 g/W, many have more modest predicted yields of 0.75 g/W. This study suggests that this would a reasonable minimum when estimating the indoor yield of well-grown sinsemilla cannabis crops. The minimum results of 0.8 g/W achieved here by some varieties appear to be in line with commercial expectations. When electricity lighting power was lowered from 600 to 400 W/m^2, the mean yield per unit of energy rose to 1.2 g/W and further rose to 1.6 g/W in the 270 W/m^2 regime.

The decreasing tendency for plants to convert light energy into biomass, as irradiance levels rose, was likely due to plants in the brighter regimes becoming increasingly saturated with light. In low-light conditions, plant species commonly demonstrate an initial linear rise in rate of photosynthesis, in response to increasing irradiance. However, in brighter conditions, the rate of rise slows as the chloroplasts increasingly become saturated with light (29). This has been demonstrated in cannabis, the rate of rise in photosynthetic activity being seen to slow rapidly when irradiance levels were

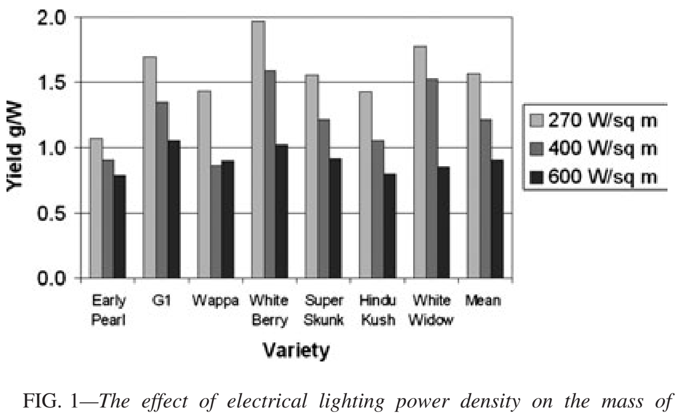

FIG. 1—*The effect of electrical lighting power density on the mass of dried floral material produced per watt of electricity. Seven cannabis varieties were compared in electrical power densities of 270, 400 and 600 W/m^2.*

increased above 100 W/m^2 PAR, and little or no further increase being observed above 300 W/m^2 PAR (14).

Giving guidance on the estimation of cannabis yields, the 2006 UNODC World Drug Report stated that "indoor yields may vary from a little under 300 grams to over 800 grams per square metre…. Overall, a yield of 500 grams per square metre per harvest seems confirmed by several sources" (30, p. 194).

In this study, in the lowest illumination regime, the floral yields of the seven varieties ranged between 280 and 470 g/m^2 (mean 422 g/m^2). In the brighter regimes, the ranges were 350–630 g/m^2 (mean 497 g/m^2) and 470–630 g/m^2 (mean 544 g/m^2), respectively. When flower and leaf materials were combined, an occasional practice of some producers yields in the brightest zone ranged from 740 to 860 g/m^2. The results of this study therefore substantiate the anecdotal yield predictions quoted in the 2006 UNODC World Drug Report (30). The predicted range of just under 300 g/m^2 to over 800 g/m^2 does appear credible. However, the results of this study suggest that if the level of illumination over the flowering crop is at the brighter end of the normal range, the predicted minimum yield of floral material should be over 470 g/m^2 for a well-grown crop.

Effect of Light Irradiance on Potency

The overall mean THC contents of leaf material in the 270, 400, and 600 W/m^2 zones were 2.64%, 2.53%, and 2.73%, respectively. A regression analysis did not indicate a significant relationship between leaf THC content and irradiance ($p = 0.42$). Similarly, there was no consistent pattern in the changes in flower potency across the varieties (Table 2). A regression analysis did not suggest a linear relationship between flower potency and irradiance ($p = 0.94$).

However, although the leaf and floral materials showed no significant potency increase because of light when analyzed separately and when the two materials from each plant were recombined, the resultant mixtures did demonstrate an upward potency trend (Table 3). This was as a consequence of plants grown under brighter lights having a significantly higher proportion of floral material, as shown in Table 1. In each variety, the floral material was four to eight times more potent than the leaf and accounted for more than 90% of the total THC produced. There was considerable variability in the pattern of potencies of these mixtures as the irradiance increased, but the potency at the high irradiance level within each variety was always larger than at the low light intensity. The linear regression model indicated a statistically significant increase in the potency of the mixtures as irradiance increased ($p = 0.031$) with an estimated increase in potency of 0.192% w/w (95% CI: 0.018–0.367% w/w) for each 100 W/m^2 power increase. Some of the observed decreasing tendency for plants to convert

TABLE 2—*The effect of increasing the electrical lighting power density on the potency (% THC content) of dried floral material at harvest.*

Electrical Power Per Unit Area W/m^2	Variety							
	Early Pearl	G1	Wappa	White Berry	Super Skunk	Hindu Kush	White Widow	Mean*
270	9.54	10.49	19.28	11.04	18.89	12.22	17.78	14.46
400	9.43	11.07	19.05	10.45	19.37	12.72	17.53	14.38
600	9.54	11.36	17.77	11.02	19.08	13.26	17.43	14.49

*There was no observed increase in mean potency—linear regression, $p > 0.05$.
THC, $\triangle^9$-tetrahydrocannabinol.

TABLE 3—*The effect of increasing the electrical lighting power density on the potency (% THC content) of combined foliar and floral material at harvest.*

Electrical Power per Unit Area W/m^2	Variety							
	Early Pearl	G1	Wappa	White Berry	Super Skunk	Hindu Kush	White Widow	Mean*
270	6.10	8.14	13.00	8.08	13.42	8.48	13.08	10.28
400	6.70	8.80	13.05	7.96	14.64	8.84	13.50	10.66
600	6.67	9.00	13.24	8.32	14.64	9.76	13.26	10.94

*The observed increase in mean potency was significant—linear regression, $p = 0.031$.
THC, Δ^9-tetrahydrocannabinol.

light energy into plant mass, as irradiance levels rose, would have been due to proportionally more energy being allocated to THC biosynthesis. The terpenoids, which include THC, demand more energy during biosynthesis than most other compounds in the plant kingdom (31).

Traditional outdoor-grown herbal cannabis material imported into the United Kingdom, and similarly produced marijuana in the United States, contains a mixture of leaf and flower materials along with seeds and some stems. Anecdotal reports suggest that some sinsemilla cannabis producers dilute their floral material with leaf before milling it, thus increasing bulk before supplying the material for sale. However, studies of cannabis potency in the United Kingdom suggested that the sinsemilla material circulating there was almost exclusively free of leaf material (20,21,23). This study suggests the observed upward potency trend for this type of material is not likely to be due to increased use of brighter lighting conditions in indoor growing facilities. The increase is perhaps the result of the achievements of plant breeders. As shown in Table 2, varieties exhibit large differences in their THC content, some offering well above average potencies. Growers may be becoming increasingly well informed about higher yielding varieties, which are available through an escalating number of retail outlets. The upward trend may also be due to an overall improvement in the general quality of cannabis horticulture, an increasing proportion of which is performed by well-organized gangs.

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Additional information and reprint requests:
David J. Potter, Ph.D.
GW Pharmaceuticals Ltd
Porton Down Science Park
Salisbury, Wilshire, SP4 0JQ
U.K.
E-mail: djp@g-pharm.com