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Project leader:	Sophie Read, University of Reading
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Key staff:	Mark Else (NIAB EMR), Carrie Twitchen (University of Reading) and Paul Hadley (University of Reading)
Location of project:	University of Reading
Industry Representative:	Richard Harnden, Berry Garden Growers Ltd, Harriet Duncalfe, Berry Garden Growers Ltd
Date project commenced:	01/10/2019

DISCLAIMER

AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

Sophie Read

PhD student

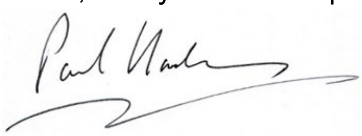
School of Agriculture, Policy and Development, University of Reading / NIAB EMR

Signature: Date: 09/01/2022

Paul Hadley

Director, Centre for Horticulture.

School of Agriculture, Policy and Development, University of Reading



Signature: Date: 11/01/2022

Report authorised by:

Carrie Twitchen

Research Fellow, Soft Fruit Technology Group, Centre for Horticulture.

School of Agriculture, Policy and Development, University of Reading

Signature: Date: 11/01/2022

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GROWER SUMMARY

Headline

Night-break lighting (NBL) reduces strawberry chill requirements promoting earlier fruiting under natural light potentially reducing LED lighting requirements. NBL increases yield and berry number of Junebearers and Everbearers. These, grown together, can maximise yields and season extension, since Junebearers produce short, high-yielding flushes and Everbearers yield for extended periods.

Background

Strawberries make up the largest proportion of the UK's soft fruit sector, which in turn is the largest category in the UK's overall fruit sector (New Food, 2018; IBISWorld, 2020). Consumption of strawberries in the UK has increased over the last 20 years with the UK having one of the highest per capita consumption rates in Europe (3 kg/yr) alongside Italy and Germany, compared to the European average (1.64 kg/yr). In recent years, new consumer demands have become apparent coinciding with increased environmental awareness, a desire for self-sufficiency and increased availability of more sustainable, locally-produced fresh produce (CBI, 2019). Over the same period, the UK strawberry industry has increased its home strawberry production by 230%, but imports have also risen by 70% showing that there is still a production gap between supply and demand (DEFRA, 2021). The current UK strawberry growing season is from March to November which has increased from a 6-week period from June-July in the 1980s. The extended season has been achieved as a result of new strawberry cultivars as well as an increase in protected horticulture with polytunnels and heated/lit glasshouses (CBI, 2019). To progress further towards complete self-sufficiency for UK strawberry production, there is a need to extend the growing season over the winter to fulfil year-round production. This involves further investigation into different cultural and environmental factors influencing strawberry plant development, including vegetative growth, fruit yield and fruit quality in order to develop optimal growing models for a range of cultivars.

Objectives of the CTP Project:

- To investigate the use of new specialist low-chill strawberry cultivars to produce out-of-season UK strawberries in winter glasshouse production.
- To explore different environmental and cultural growing conditions to develop optimal growing models for winter glasshouse production.
- To develop chilling models for major Junebearer and Everbearer cultivars.

- To carry out an economic study to balance the costs of delivering environmental conditions including lighting and heating with the financial returns from out-of-season strawberry production.

Summary

In the second year of this PhD project, a winter glasshouse experiment was set up to investigate the effect of night-break lighting (NBL) and application of gibberellic acid (GA_3) to reduce strawberry chill requirements of a specialist low-chill Junebearer (JB) and an Everbearer (EB) variety. In addition, three light regimes were incorporated, including a natural light, a low LED supplementary light intensity and a high LED supplementary light intensity regime. The plants were all maintained under a 22°C/12°C day/night temperature for 10 weeks from planting, followed by a 16°C/12°C day/night temperature prior to fruit-set until the end of the experiment. The plants were kept under a 16 hr photoperiod consisting of 12 hrs of either natural light or LED light followed by 4 hrs of low-power extension lighting. NBL reduced the time to first fruit in the natural light environment but did not have an effect in the LED-lit environment and generally increased berry yield as a result of increasing berry number. On the other hand, GA_3 delayed fruiting time and resulted in a reduced yield. Further data analysis will be conducted to review these results along with a follow-up economic assessment to estimate the financial and economic costs of the concluding optimal production models.

Financial Benefits

This report outlines the key results from work carried out in the second year of a four-year PhD project and hence, no direct financial benefits have been confirmed yet. However, the third and fourth year experimental series plans to pull together the key findings relating to optimal growing conditions for out-of-season strawberry production from the first two years of results focussing on fruit timing, yield and quality. An economic assessment will be carried out in the third year to calculate the costs of the growing conditions found to be optimal for winter strawberry production. This will then contribute to a final year experiment which will bring all the optimal environmental and cultural conditions together into a single model. The economic assessment is designed to optimise the energy requirements for artificial lighting, heating and other environmental conditions needed to fill the production gap with a strong emphasis on sustainable production.

Action Points

There are no grower action points at this early stage of the project.

SCIENCE SECTION

Introduction

The UK has one of the highest per capita consumption rates of strawberries in Europe (3kg/yr) alongside Italy and Germany compared to the European average (1.64kg/yr). UK production of home-produced strawberries has increased by 230% over the last twenty years, reaching a record of 124,500 tonnes in 2019 helping to meet the increased demand. Despite this, the UK is still the second biggest European importer after Germany with imports exceeding a value of €200 million. To date, increased production, has been largely achieved through season extension through the development of polytunnels and glasshouses providing increased protection against the weather (British Summer Fruits, 2017) and increased Class 1% yield (IBISWorld, 2020). This has enabled the season to be extended from 6 weeks in June to July in 1990, to 9 months now, between March and November. However, further investigation could lead to the development of optimal growing models to fill the current production gap between November and February (British Summer Fruits, 2017) and hence reduce UK strawberry imports.

Most plants become dormant in the winter to protect the flower buds initiated in the autumn from the cold winter climate and hard frosts (Sønsteby & Heide, 2006). Dormancy is generally induced by short days and decreasing temperatures seen in the late autumn which occur after the initiation of flower bud primordia in the early autumn (Jonkers, 1965). The deepest dormancy state is reached in mid-November (Lieten, 1997; Sønsteby & Heide, 2006). Whilst dormant, growth of above ground vegetative (leaves and petioles) and reproductive components (runners and flowers) is significantly reduced. Strawberry plants, differently to other flowering plants, go into a semi-dormant state which means that even when 'dormant' they still undergo some low-level productive activity. This typically means that after a short exposure to dormancy-inducing conditions, this reduced growth can be reversed by exposure to long days in a heated environment (Guttridge, 1985; Sønsteby & Heide, 2006). Sønsteby & Heide (2006) found that when the Junebearers, 'Elsanta' and 'Korona', were exposed to short days and temperatures between 9-27°C for 5 weeks, they could return to their normal growth development with the return of long days. However, when exposed to these conditions for 10-15 weeks, the plants required a period of chilling between -2 and 6°C to allow for the re-establishment of full growth potential.

Despite this chilling requirement to break dormancy and allow the full growth potential of strawberry plants to be re-established, extended chilling duration increases plant stress. Increased plant stress can have negative effects including reduced plant vigour and reproductive capacity of the plant (Lieten, 1997). Studies have shown this stress to be caused by a reduction of sugars in plants exposed to extended chilling periods leading to earlier flowering and increased flower abortion rates and hence increased fruit malformation. This subsequently leads to loss of marketable yields for growers (Lieten, Kinet & Bernier, 1995). Therefore, research has focussed on finding alternative methods for breaking dormancy to reduce the requirement for chilling. This coincides with efforts to increase the growing season of the strawberry as has been achieved in Norway, as reduced chill means that plants can be forced earlier in the winter season under favourable conditions (Sønsteby & Heide, 2006).

One method of reducing chill requirement, is the use of GA_3. This is a natural endogenous growth hormone produced by plants that can also be applied exogenously. Multiple studies have shown that GA_3 can be effective in imitating the effects of chill in terms of reducing the time to flowering, but it also has negative effects in reducing the marketable yield as a consequence of increased flower abortion and fruit malformation (Tehranifar & Battey, 1997; Paroussi *et al.*, 2002; Sharma & Singh, 2009; Ikram, Qureshi & Khalid, 2016). Generally, application of 50ppm GA_3 has been found to be the most effective concentration for achieving early yields, with minimal negative impacts on marketable fruit yields (Tehranifar & Battey, 1997; Paroussi *et al.*, 2002). It has been suggested that the effects of GA_3 can be enhanced further when combined with a NBL treatment (Tafazoli & Vince-Prue, 1978). A NBL practice typically used in strawberry is low level incandescent lighting at 10 W/m^{-2} hourly for 15 minutes at a time between 11pm and 7am (Lieten, 1997; Van Delm *et al.*, 2013). Lieten (1997) found that 45-55 days of NBL made up for the lack of chill seen in 'Elsanta' plants with increased vegetative and reproductive growth. However, further research is needed to examine the potential of NBL in promoting early flowering and fruiting, with a focus on the timing of the NBL treatment (Van Delm *et al.*, 2013).

Light intensity is another environmental factor that has been shown to have a significant effect on strawberry yield and quality. Choi, Moon & Kang (2015) conducted a study comparing strawberry plants grown in a growth chamber with only artificial lighting against strawberry plants grown in a plastic greenhouse exposed to both ambient and artificial lighting. Plants in the plastic greenhouse produced a significantly greater yield than in the growth chamber. This was attributed to the higher light intensity from the combined ambient and artificial lighting. Further effects of increased light intensity include increased vegetative growth (Van Delm *et al.*, 2016) and increased brix (Vlachonasios *et al.*, 1995; Hidaka *et al.*, 2013). However, there is scope for further research focussing on the specific timing of higher light intensities to maximise high yields and high quality.

Therefore, the main aim of this study was to investigate the potential use of GA_3 and NBL to reduce the chilling requirements of both Junebearer and Everbearer strawberry varieties to promote early strawberry production in combination with different light intensity regimes to help maximise overall strawberry yield and quality. The energy efficiency of the lighting regime will also be studied to develop a production model that balances the benefits of increased early yields with cost of production. A secondary aim of the study was to explore different concentrations and number of applications of GA_3 to confirm whether 50ppm is optimal as according to previous studies (Tehranifar & Battey, 1997; Paroussi *et al.*, 2002).

Materials and methods

<u>Growing Facility</u>

The primary experiment (experiment 1a) was carried out in a glasshouse with two individually temperature-controlled compartments at the University of Reading's Crops and Environment Laboratory. Each compartment was fitted with two trolleys set under LED lamps which were programmed to be automatically wheeled into and out of a light-tight photoperiod extension compartment (garage) at set times. Two of these garages were fitted with additional night-break lighting facilities (NBL). Additional benches in the glasshouse under natural daylight conditions were used for control plants and a secondary experiment (experiment 1b). These plants were under timer-controlled Tungsten lights for photoperiod extension and had the facility for NBL to be applied.

<u>Plant Material</u>

A commercial Junebearer (JB) and an Everbearer (EB) variety were sourced from Driscoll's Plants BV on 11/09/2020. For experiment 1a, tray plants of each the JB and EB were planted on 17/09/2020 in 2 L black pots containing 90:10 mix of coir (Sinclair) and perlite. Additional tray plants of both varieties were put into cold storage at 2±2°C on 23/09/2020 and were taken out of cold storage on 01/10/2020 having accumulated 187 chill units and planted into 2 L black pots containing the same growing medium. These plants were used as controls to enable comparison between chilled and non-chilled plants. For experiment 1b, 48 JB tray plants were planted on 17/09/2020 in 2 L black pots containing 90:10 mix of coir (Melcourt) and perlite.

<u>Experimental Treatments</u>

For experiment 1a, 35 plants of both the JB and the EB variety were positioned on the 4 trolleys, along with 18 control plants of each cultivar on the bench on 17/09/2020. The plants were maintained under natural lighting and daylength and 16°C/12°C day/night temperature for 2 weeks, before increasing the temperature to 22°C/12°C day/night temperature on 01/10/2020 whilst plants on the trolleys were maintained at a controlled daylength of 12 hrs LED lighting (PPFD 130 µmol m^2 s^{-1} from 6am-6pm) and +4 hrs photoperiod extension (using LED lamps mounted in the garages) from 06/10/2020. The temperature and photoperiod conditions were selected based on the results from the first-year experiment. Half of the plants of each variety on each trolley were sprayed with 50ppm GA_3 on 27/10/2020. NBL (for 15 minutes every hour from 10pm until 4am (10 W/m^{-2}) using tungsten filament lamps mounted in two of the garages) was started on 20/11/2020 and ran for 7 weeks until 08/01/2020. Seven weeks after planting, two separate LED lighting regimes were introduced with high light intensity (260 µmol m^2 s^{-1}) and a low light intensity (130 µmol m^2 s^{-1}) (appendix 1). Ten weeks after the initial planting, on 24/11/2020, the daytime temperature was reduced to 16°C to promote increased fruit quality and yield whilst the night-time temperature remained constant at 12°C.

Control plants were arranged alternately 'JB, EB' in 4 groups of 12 plants. Three groups were positioned on the bench in one glasshouse compartment with one group receiving no additional treatment, one group having been chilled and one group having received the GA_3 application on 27/10/2020. A fourth group was set up on the bench in the second glasshouse compartment with an additional Tungsten filament lamp linked to a timer to provide NBL from W/C 20/11/2020 – 08/01/2021. The +4hrs photoperiod extension for these plants commenced 20/11/2020.

For experiment 1b, 48 JB plants were set out on a bench in 8 groups of 6 plants. Six groups were sprayed with three different concentrations of GA_3 (25ppm, 50ppm and 75ppm; see appendix 2 for solution details) and either one or two GA_3 applications (see appendix 3 for application timings). Two groups were the control groups and either sprayed once or twice with water, Tween 20 and 0.8% ethanol solution (equivalent to the volume of GA_3 applied).

Plant Husbandry

The plants were fertigated through drip irrigation using a commercial strawberry mix (Strawberry Special, Solufeed Ltd., Barnham, UK) with potassium added at fruit set (Solupotassse, Solufeed Ltd., Barnham, UK). EC and pH were maintained at 1.8 mS/cm and 5.5 respectively and the daily run-off was maintained at 10-20%. Dead leaves, weeds and runners were removed regularly by hand and spraying for control of grey mould *(Botrytis cinerea)* and powdery mildew was undertaken weekly. Biological control was added as necessary according to standard commercial practice for the control of white fly *(Trialeurodes vaporariorum)*, two-spotted spider mite *(Tetranychus urticae)* and various thrip and aphid species (Bioline, Little Clacton, UK).

Data Collection

The number of days from planting to first flower and first fruit were recorded. Ripe fruit were picked twice weekly during the main fruiting period and were classified as either: Class 1, Class 2, waste or unset. Class 1 was defined as all berries that had a 22mm or greater diameter at the shoulder and were intact without disease or pest damage, whilst Class 2 were damage free, but had a shoulder diameter below 22mm (United Nations, 2017). Weekly fruit totals were recorded. Additionally, growth measurements (petiole length and nº, truss length and nº, leaf nº and crown diameter) and chlorophyll measurements were taken for marked plants for each treatment at three-week intervals. A series of general linear models (ANOVA) using GenStat (20^{th} Edition, VSN International, Hemel Hempsted, UK) were generated to analyse the influence of GA_3, NBL light intensity treatments and cultivar on various factors including time to flowering and fruiting, fruit yield class percentages and berry weight. Further analysis is planned to look at the influence of these factors on overall plant growth and development.

Results

Experiment 1a

In general, the JB variety fruited significantly earlier than the EB variety in natural light for all treatments apart from with NBL ($p=0.004$). NBL was the most effective treatment for reducing time to reach first fruit with a 5-week and 14-week earlier first pick under NBL compared to the control for the JB and EB respectively. There was no significant effect of GA_3 in the natural light environment, although it did result in a greater variability in time to first ripe fruit between plants exposed to the same environmental conditions. There was also no significant effect of chill for either variety (Figure 1).

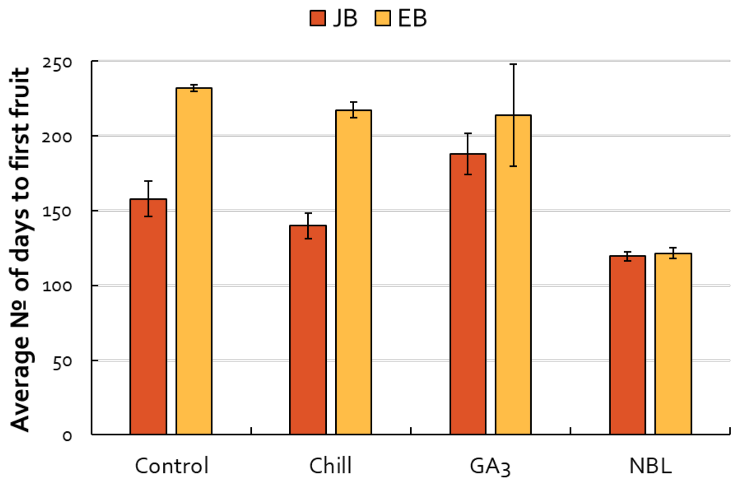

Figure 1. Effect of chilling, GA_3 application and NBL on the average number of days to reach first ripe fruit of the JB and EB in the natural light environment.

In contrast, when the JB and EB varieties were exposed to 12 hrs of LED lighting, NBL did not have a significant effect on the average number of days to reach first fruit. However, the lighting environment did have a significant effect ($p<0.001$). The JB variety reached first ripe fruit ~7 weeks earlier in the LED-lit environment compared to the natural light environment, similarly, the EB variety reached first ripe fruit ~19 weeks earlier. Additionally, the EB variety in the LED-lit environment reached first fruit 2 weeks earlier than the JB variety ($p<0.001$) (Figure 2).

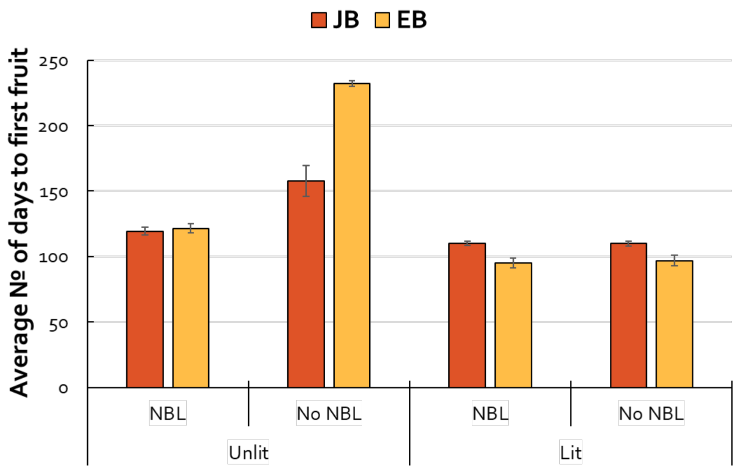

Figure 2. Effect of NBL in the natural light environment versus LED-lit environment on the average number of days to first ripe fruit on the JB and EB.

Where LED lighting was applied, the application of 50ppm GA_3 significantly delayed the time to first ripe fruit in both the JB ($p<0.001$) and the EB variety ($p=0.002$), by an average of 9 days (Figure 3).

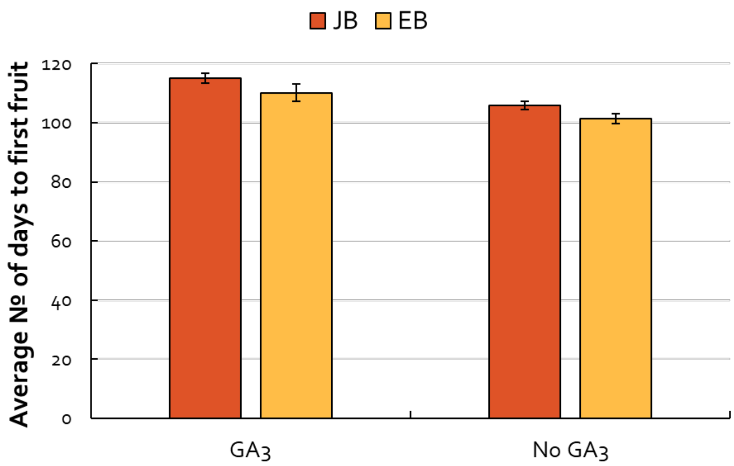

Figure 3. Effect of 50ppm GA_3 on the average number of days to first ripe fruit of the JB and EB in the LED-lit environment.

In general, NBL increased the total yield of both the JB and the EB variety. In the LED-lit environment, NBL resulted in a 17% increase ($p=0.028$) and a 20% increase ($p=0.035$) in average yield for the JB and EB variety respectively. In the natural light environment, the EB variety yielded 56% higher with NBL, compared to without NBL, although the JB variety yielded 20% less. However, the latter result needs further investigation, confirmed by the also surprising result that the JB variety appeared to yield more than under LED lighting. Under NBL, the JB variety yielded 9% greater in the LED-lit versus natural light environment, with no effect on the EB variety, whereas the opposite was seen when no NBL was applied with the EB yielding 30% more in the LED-lit compared to the natural light environment with no effect on the JB variety (Figure 4).

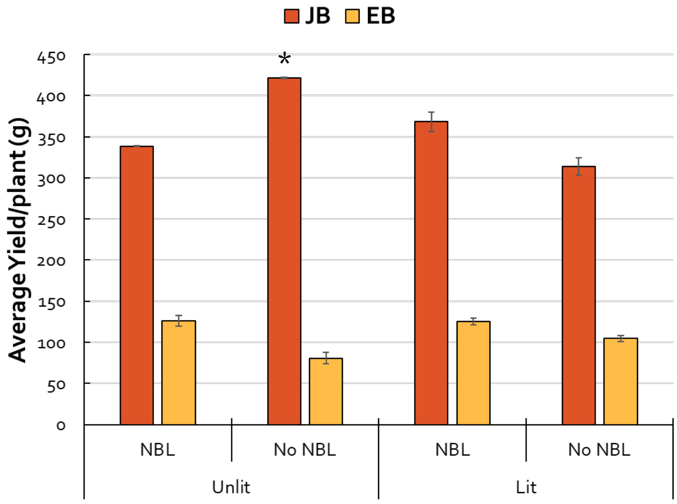

Figure 4. Effect of chilling, GA_3 application and NBL on the average yield per plant of the JB and EB in the natural light environment and the LED-lit environment (* = anomalous result).

GA_3 significantly reduced the yield of both the JB (p=0.052) and EB variety (p=0.084) in the natural light environment and in the LED-lit environment (p<0.001). In the natural light environment, the yield decreased by 105% and 93% for the JB and EB variety respectively when compared to no GA_3 application whilst in the LED-lit environment the yield declined by 68% and 38%. Without GA_3, the JB and EB variety yielded 2% and 65% greater in the LED-lit compared to the natural light environment respectively (Figure 5).

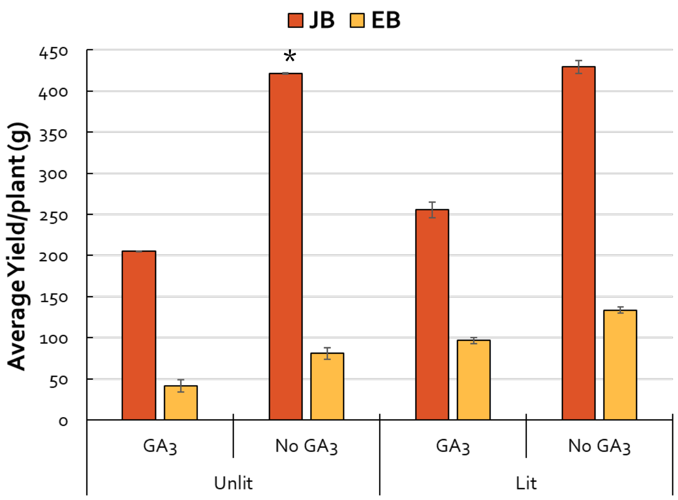

Figure 5. Effect of GA_3 on the average yield per plant of the JB and EB in the natural light environment and the LED-lit environment (* = anomalous result).

In the natural light environment, NBL increased the berry number for the EB variety by 200% (p=0.035) but resulted in a 7% decrease in the JB variety. In the LED-lit environment, NBL resulted in a 17% (p=0.017) and 13% increased berry number for the JB and the EB variety respectively, although the latter was not significant. Similar to the total yield results, under the NBL, a 32% increased berry number was produced by the JB variety in the LED-lit environment compared to the natural light environment, whilst there was no effect on the EB variety. Again, the opposite trend was seen without NBL, where a 117% increased berry number was produced by the EB variety in the LED-lit environment (Figure 6).

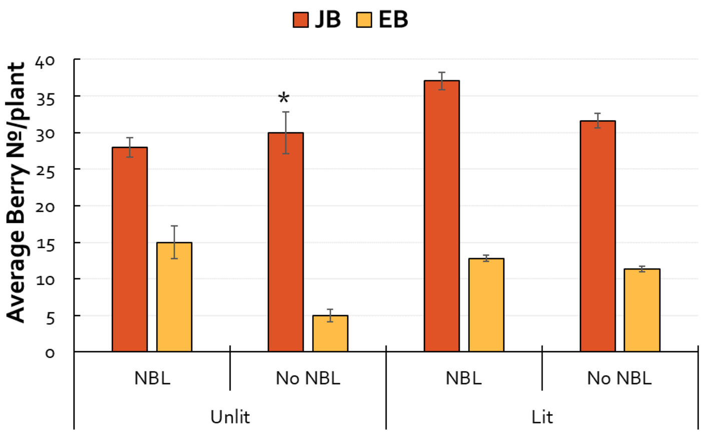

Figure 6. Effect of NBL on the average berry number per plant of the JB and EB in the natural light environment and the LED-lit environment (* = anomalous result).

GA_3 reduced the average berry number of both the JB and the EB variety in the natural light and LED-lit environment. In the natural light environment, the GA_3 resulted in a 51% decrease (p=0.101) in average berry number for the JB variety and a 40% decrease for the EB variety (p=0.035) compared to a 44% (p<0.001) and 28% (p<0.001) for the JB and EB variety respectively in the LED-lit environment. Additionally, without GA_3, in the LED-lit environment the JB produced an average 47% greater berry number and the EB a 180% increased berry number compared to in the natural light environment (Figure 7) (see appendix 4 for photos of plants under optimal and least optimal treatment combinations).

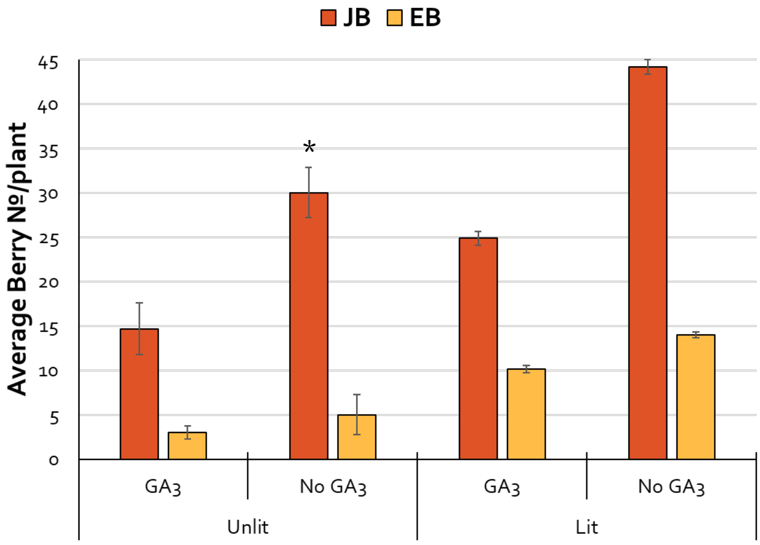

Figure 7. Effect of GA_3 on the average berry number per plant of the JB and EB in the natural light environment and the LED-lit environments (* = anomalous result).

In the LED-lit environment, there was no significant effect of either NBL or GA_3 on average berry weight. There was also no significant effect of cultivar with the JB variety producing only a 2% greater average berry weight than the EB variety (data not shown). This contrasts with the natural light environment, where the EB variety produced a 37% greater average berry weight than the JB variety. Furthermore, in the natural light environment there was a significant effect of GA_3 on increasing the average berry weight for the JB variety ($p=0.046$), but this cannot be confirmed for the EB variety due to large variation between the replicates (Figure 8).

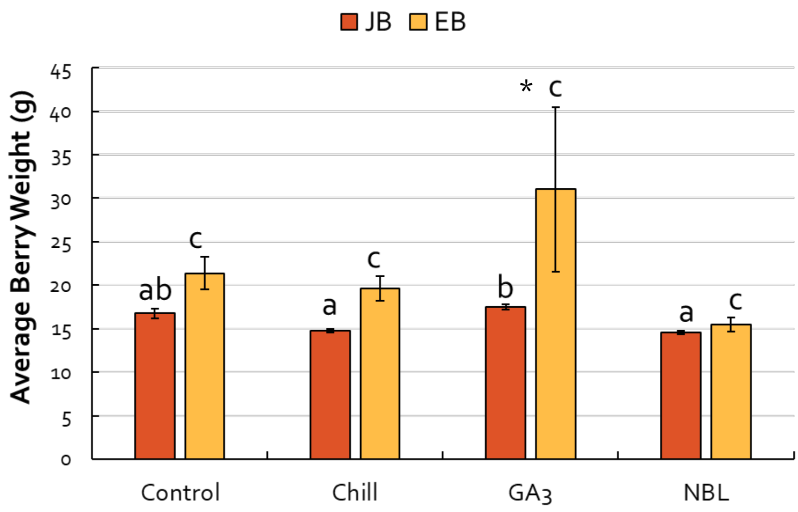

Figure 8. Effect of GA_3, NBL and chill on the average berry weight (g/berry) of the JB and EB in the natural light environment (* = anomalous result).

Experiment 1b

The time to first flower was significantly longer with the 'no spray' control compared to all other treatments including the spray water control ($p<0.001$) where there were no significant differences between treatments. There was no significant difference between 1 application of GA_3 at 25ppm or 50ppm and the controls for the time to first ripe fruit. However, there was a significant delay in time to the first ripe fruit when 75ppm GA_3 was applied or when any of the three concentrations were applied twice ($p<0.001$). One application of 50ppm GA_3 was the most effective in reducing the average number of days to fruiting, although this was not significantly different to the 25ppm treatment (Figure 9) (see appendix 5 for photos of plants under different GA_3 treatments).

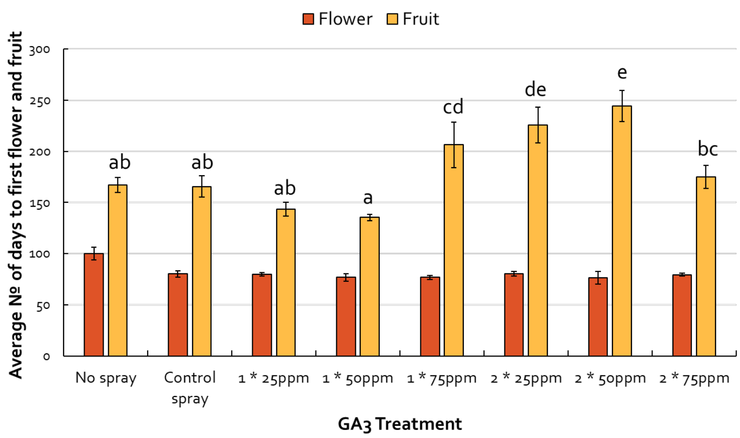

Figure 9. Effect of different GA_3 applications (frequency & concentration) versus 'water spray' and 'no spray' controls on the average number of days to reach first flower and ripe fruit of the JB.

Discussion

The results demonstrated that NBL promoted earlier fruiting in a natural light environment, which is in agreement with Van Delm *et al.,* (2013), although they found that NBL only had a significant impact on the second crop cycle. This was due to the first crop flowers having already been initiated before the NBL was started (Van Delm *et al.*, 2013). These results suggest that there is potential for NBL to be successfully incorporated into a season-extending growing model using Everbearers which fruit more than once in a year. Contrastingly, the results show that there was no significant effect of NBL in the LED-lit environment. These results suggest that whilst there is no benefit of NBL when high intensity LED lighting is in place for promoting earlier fruiting, there is the potential that NBL could be used to supplement some of this high intensity LED lighting. The use of NBL in place of LED lighting early in the plant development cycle could be particularly beneficial as it is currently uneconomical to provide full LED lighting when the leaf area of the plants is small. This could help contribute to the development of a sustainable and economical optimal growing model for winter production.

Furthermore, these results support previous findings that NBL results in increased strawberry yields. NBL contributed to increased yield of both the JB and the EB variety in the LED-lit environment and the EB in the natural light environment. The decreased yield seen with the JB variety in this environment needs further investigation as it is likely to be the result of anomalous data. The observed yield increases seen with the EB support Van Delm et al's (2013) results. Lieten (1997) showed that 35 days of NBL successfully supplemented the lack of chill for the JB variety, 'Elsanta', resulting in increased yield. This is partially supported by the results from this experiment in the LED-lit environment, but the potential anomalous data means that this cannot be confirmed in the natural light environment. Therefore, a future experiment is planned to repeat the use of NBL under a natural light environment to clarify these findings.

The results show that the increased yield from NBL seen in both the natural and LED-lit environments were due to increased berry number as opposed to berry weight. There was no significant effect of NBL on average berry weight in either environment. However, Lieten (1997) found that his optimal NBL treatment resulted in both increased berry yield and weight. These discrepancies could be due to the differing duration or timing of the NBL used as well as a potential cultivar difference. The effect of NBL on average berry weight will be re-examined in the next experiment incorporating an earlier NBL treatment. Under NBL, the JB variety produced a significantly greater yield and total berry number in the LED-lit compared to the natural light environment. Contrastingly, the EB variety produced these significant increases in the LED-lit environment in the absence of NBL. The results from this experiment build on previous experiments by showing how different cultivars respond differently to NBL in different lighting environments (Lieten, 1997; van Delm *et al.*, 2013).

In contrast to the positive effects of NBL, this experiment suggests a negative effect of GA_3 on time to fruiting compared to previous studies, although a direct comparison cannot be accurately made since most other studies focussed on time to flowering and not fruiting (Jonkers, 1965; Tafazoli & Vince-Prue, 1978; Tehranifar & Battey, 1997; Paroussi *et al.*, 2002). Here, application of GA_3 delayed time to fruiting by an average of 9 days, so it could be assumed that flowering would also be delayed. However, the only significant difference seen in time to flowering in this experiment was between the ‘no spray’ control and all other treatments including the ‘water spray’ control. This significant difference does not confirm any possible effect of GA_3 due to the late application of GA_3 after the plants had already initiated flowers. Previous studies that have applied GA_3 two weeks after planting have shown that GA_3 accelerates flowering with reduced time to inflorescence emergence (Tehranifar & Battey, 1997; Lotfi *et al.*, 2014). The present results suggest that there might be a different effect of GA_3 on time to flowering and fruiting which could be as a result of the increased flower abortion and fruit malformation, effects commonly seen with GA_3 (Tehranifar & Battey, 1997; Paroussi *et al.*, 2002; Sharma & Singh, 2009; Ikram, Qureshi & Khalid, 2016). To confirm this, a further investigation needs to be carried out with earlier application of GA_3 to match previous experiments and then continued to enable analysis of the effect on time to fruiting. In this study, the effect of GA_3 was not significant, but this could be because it took place in a natural light environment and GA_3 has been shown to have significant interactions with other environmental factors such as heating and lighting; these factors might have influenced the results in the previous studies (Paroussi *et al.*, 2002).

The reported effects of GA_3 on yield parameters in strawberry production are mixed with some studies suggesting a positive effect with a 75ppm treatment including highest flower bud, flower and fruit number and fruit weight and yield (Uddin *et al.*, 2012). In comparison, other studies have reported a reduced marketable yield (Tehranifar & Battey, 1997; Ikram, Qureshi & Khalid, 2016). This is due to the increased production of malformed berries that could possibly be explained by the treatment contributing to increased runner production, reducing the nutrient availability to the fruit and thus, resulting in a reduced quality. In this experiment, the latter findings were confirmed with GA_3 significantly reducing the total yield and berry number of both the JB and EB variety. These contrasting results from different studies highlight the importance of further work looking at the timing of the GA_3 application which has been suggested to be critical for the overall impact of GA_3 on fruit production (Tafazoli & Vince-Prue, 1978; Tehranifar & Battey, 1997).

The lighting environment was found to have a significant impact on both time to fruiting and total berry yield supporting previous research showing that increasing light intensity enhances flower development (Wang *et al.*, 2020). The LED-lit environment generally resulted in earlier fruiting and increased total berry yield and berry number. The LED lights provide a higher photosynthetic photon flux density (PPFD) compared to natural light. A higher PPFD increases photosynthesis resulting in accelerated and overall greater vegetative and reproductive plant growth (Sung & Chen, 1991; Hidaka *et al.*, 2013). Despite these findings suggesting that artificial LED lighting has the potential for supplementing solar radiation for out-of-season production, further consideration needs to be given to the economics and environmental sustainability of using these energy intensive resources. Further analysis will be carried out with the data to investigate whether there is a significant difference between the low and high light intensity regimes used in terms of time to fruiting and overall yields. This analysis could support Yoneda et al's (2020) study that found that there were few significant differences for strawberry production between the use of LED lighting for the whole strawberry cultivation period versus just the fruit development period. Their findings suggest that a shortened supplementary lighting period could be beneficial for extending out-of-season production whilst also minimising the energy and cost outputs of doing this.

Conclusions

From the analysis so far, the following findings have been observed:

Cultivar

- The JB variety reached first pick earlier in the natural light environment, whereas the EB variety reached first pick earlier in the LED-lit environment suggesting that cultivars should be chosen according to the lighting environment selected when trying to optimise the optimal economic and environmental costs associated with a growing system.
- The JB variety produced an overall greater yield than the EB during the experimental period, suggesting that JBs are likely to be the focus for increasing out-of-season production.

NBL

- NBL promoted earlier fruiting in the natural light environment and generally higher yield in both environments suggesting the potential for NBL to be used to supplement LED lighting, reducing energy usage of a growing system.

- Further experimental work will be conducted to confirm the effects of NBL on yield as well as investigating whether an earlier NBL treatment could promote even earlier fruiting and greater yields.

GA_3

- GA_3 did not successfully supplement strawberry chill requirements with no apparent benefit seen relating to earlier fruiting or increased yields.
- One application of 50ppm GA_3 was the most effective GA_3 treatment trialled in reducing time to fruiting.
- A future experiment is planned to investigate different timings of 50ppm GA_3 application to see if it was the application timing that contributed to the unexpected results based on previous literature.

Light Intensity

- LED lighting promoted earlier fruiting and generally increased total yield although future experimental work will justify this due to the probable anomalous JB data in the natural light environment.
- Further analysis of the results will compare the low and high light intensity regimes to see if reducing the intensity or duration of LED lighting can assist with the development of optimal sustainable and economic production models.

Knowledge and Technology Transfer

The student attended and presented at:

- 9th ISS Strawberry Symposium – ISS 2021 (online), 1st-5th May 2021 – Poster Presentation
- Crops Group Seminar, University of Reading, 6th July 2021
- CTP Student Presentation Summer Event (online), 6th-7th July 2021
- PhD Crop Symposium, University of Reading, 2nd November 2021
- Berry Gardens' Annual Research & Agronomy Conference, 11th November 2021
- AHDB Soft Fruit Technical Day (online), 16th November 2021
- RHS PhD and Fellowship Symposium (online), 6th January 2022

Awards Received:

- The Marsh Charitable Trust Award for Horticultural Science

Glossary

Key Word	Definition
Chilling requirement	The number of accumulated hours needed in a specific temperature range by a plant to break dormancy i.e. between -2 and 7 °C for strawberries.
Everbearer (EB)	Typically initiates flowers under long day conditions and characteristically produces two to three crop flushes per year.
Gibberellic Acid (GA_3)	A natural endogenous plant growth hormone that stimulates vegetative growth and development.
Junebearer (JB)	Initiates flowers under short day conditions (less than 12 hrs).
Night-break lighting (NBL)	Long nights are interrupted by intermittent short periods of artificial lighting, traditionally incandescent lamps.
Photosynthetic photon flux density (PPFD)	The number of light photons that hits a surface e.g. plant canopy, in one second. Measured in Micromoles (μmols).

References

British Summer Fruits. (2017). The Impact Of Brexit On The UK Soft Fruit Industry, British Summer Fruits Seasonal Labour Report. [pdf] Available at: https://www.britishsummerfruits.co.uk/uploads/files/news/The%20Impact%20of%20Brexit%20on%20the%20UK%20Soft%20Fruit%20Industry%20-%20The%20Anderson%20Report.pdf (Accessed: 11 August 2021).

CBI. (2019). Exporting fresh strawberries to Europe | CBI. [online] Available at: https://www.cbi.eu/market-information/fresh-fruit-vegetables/fresh-strawberries (Accessed: 3 July 2021).

DEFRA. (2021). Horticulture Statistics 2020. [pdf] Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1003935/hort-report-20jul21.pdf (Accessed 29 August 2021).

Guttridge, C. (1985). Handbook of Flowering. 3rd ed. Boca Raton: CRC Press.

Hidaka, K., Dan, K., Imamura, I., Miyoshi, Y., Takayama, T., Sameshima, K., Kitano, M. and Okimura, M. (2013). Effect of supplemental lighting from different light sources on growth and yield of strawberry. Environmental Control in Biology 51(1):41–47.

IBISWorld. (2020). Fruit Growing in the UK. [online] Available at: https://www.ibisworld.com/united-kingdom/market-research-reports/fruit-growing-industry/ (Accessed 22 June 2020).

Ikram, S., Qureshi, K.M. and Khalid, N. (2016). Flowering and fruiting responses of strawberry to growth hormone and chilling grown under tunnel conditions. Pakistan Journal of Agricultural Sciences 53(4):911–916.

Jamal-Uddin, A.F.M., Hossan, M.J., Islam, M.S., Ahsan, M.K. and Mehraj, H. (2012). Strawberry growth and yield responses to gibberellic acid. J. Expt. Biosci. 3(2):51–56.

Jonkers, H. (1965). On the flower formation, the dormancy and the early forcing of strawberries. Mededel Landbouwhogesch Wageningen 65(265):1–59.

Lieten, F. (1997). Effects of chilling and night-break treatment on greenhouse production of “elsanta”. Acta Horticulturae 633–640.

Lieten, F., Kinet, J.M. and Bernier, G. (1995). Effect of prolonged cold storage on the production capacity of strawberry plants. Scientia Horticulturae 60(3–4):213–219.

Lotfi, A., Karami, F., Ghargani, A. and Eshghi, S. (2014). Effect of dormancy-breaking chemicals on overcoming winter rest of strawberry. Acta Horticulturae 1049:431–433.

Paroussi, G., Voyiatzis, D.G., Paroussis, E. and Drogoudi, P.D. (2002). Growth, flowering and yield responses to GA3 of strawberry grown under different environmental conditions. Scientia Horticulturae 96(1–4):103–113.

Sharma, R.R. and Singh, R. (2009). Gibberellic acid influences the production of malformed and button berries, and fruit yield and quality in strawberry (Fragaria × ananassa Duch.). Scientia Horticulturae 119(4):430–433.

Sønsteby, A. and Heide, O.M. (2006). Dormancy relations and flowering of the strawberry cultivars Korona and Elsanta as influenced by photoperiod and temperature. Scientia Horticulturae 110(1):57–67.

Sung, F.J.M. and Chen, J.J. (1991). Gas exchange rate and yield response of strawberry to carbon dioxide enrichment. Scientia Horticulturae 48(3–4):241–251.

Tafazoli, E. and Vince-Prue, D. (1978). A Comparison of the Effects of Long Days and Exogenous Growth Regulators on Growth and Flowering in Strawberry, Fragaria χ Ananassa Duch. Journal of Horticultural Science 53(4):255–259.

Tehranifar, A. and Battey, N.H. (1997). Comparison of the effects of GA3 and chilling on vegetative vigour and fruit set in strawberry. Acta Horticulturae 627–631.

United Nations. (2017). Unece Standard Ffv-35 Strawberries. [pdf] Available at: http://www.unece.org/fileadmin/DAM/trade/agr/standard/fresh/FFV-Std/English/35Strawberries_2010.pdf. (Accessed 23 August 2021).

Van Delm, T., Melis, P., Stoffels, K., Vanderbruggen. R. and Baets, W. (2016). Advancing the strawberry season in Belgian glasshouses with supplemental assimilation lighting. Acta Horticulturae 1134:147–153.

Van Delm, T., Melis, P., Stoffels, K. and Baets, W. (2013). Pre-Harvest Night-Interruption on Everbearing Cultivars in Out-of-Soil Strawberry Cultivation in Belgium. International Journal of Fruit Science 13(1–2): 217–226.

Vlachonasios, C., Vasilakakis, M., Dogras, C. and Mastrokostas, M. (1995). Out of season glasshouse strawberry production in North Greece. Acta Horticulturae 379.

Wang, R., Eguchi, E., Gui, Y. and Iwasaki, Y. (2020). Evaluating the effect of light intensity on flower development uniformity in strawberry (Fragaria × ananassa) under early induction conditions in forcing culture', HortScience 55(5):670–675.

Appendices

Appendix 1. Summary of high and low LED LI regimes used in experiment 1a (Light 1 = high LI, Light 2 = low LI).

Light 1	7 weeks 12hrs LED lights 130 µmol m^2 s^{-1} 13 weeks 12hrs LED lights 260 µmol m^2 s^{-1} 4 weeks LED lights 130 µmol m^2 s^{-1} 10 weeks 12hrs natural light
Light 2	13 weeks 12hrs LED lights 130 µmol m^2 s^{-1} 4 weeks 12hrs LED lights 260 µmol m^2 s^{-1} 7 weeks 12hrs LED lights 130 µmol m^2 s^{-1} 10 weeks 12hrs natural light

Appendix 2. GA_3 solution components.

	Deionised Water (l)	Tween 20 (ml)	0.8% ethanol (ml)	GA_3 (g)
Water Control	1	1	8	
25ppm	1	1	8	0.025g
50ppm	1	1	8	0.05
75ppm	1	1	8	0.075

Appendix 3. Summary of experiment 1b GA_3 treatments.

Block	Treatment	GA spray 1	GA spray 2	Water spray 1	Water spray 2
1	1 * Water Control			27/10/2020	
2	2 * Water Control			27/10/2020	26/11/2020
3	1 * 25ppm GA spray	27/10/2020			
4	1 * 50ppm GA spray	27/10/2020			
5	1 * 75ppm GA spray	27/10/2020			
6	2 * 25ppm GA spray	27/10/2020	26/11/2020		
7	2 * 50ppm GA spray	27/10/2020	26/11/2020		
8	2 * 75ppm GA spray	27/10/2020	26/11/2020		

Appendix 4. Photos showing the JB and EB varieties under optimal conditions (row 1) versus least optimal conditions (row 2) for supplementing chill and maximising berry yield.

Appendix 5. Photos of plants sprayed with different GA_3 treatments 10 weeks after the first GA_3 application and 6 weeks after the second GA_3 application.