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Date project commenced:	1 September 2018
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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.

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Contents

1 Grower Summary

1.1 Headline

- Both blue and opaque plastic may significantly bring forward the harvestable window for green-pull rhubarb, while offering significant enhancement of marketable qualities.

1.2 Background and expected deliverables

Rhubarb is a high value crop grown over 500 ha in the UK, producing 21,000 tonnes in 2018. The marketed product, the leaf petioles with a strong red pigmentation (or 'sticks'), are harvested from perennial crowns in the spring. Desirable traits include a long and slender habit with a snappy, non-fibrous texture. Forced and green pull rhubarb is often considered a separate product.

Conventional rhubarb is harvested from crowns grown in the open field from Feb/March into early summer, but this tends to be of lower value due to thicker petioles with prominent fibres and significant greening. Customer demand (in terms of both early season supply and high quality petioles) can be more directly met with forced rhubarb whereby mature crowns are lifted in the early spring and kept in near-complete darkness with controlled temperatures. The lack of light curtails normal petiole development, causing petioles to rapidly elongate without developing any significant leaf. The lack of light also prevents the petioles from greening up, giving a strong red colour and strong flavour. This produces a product of optimum quality which can be marketed 3 – 4 months before green-pull rhubarb is ready for harvest.

However, crowns are exhausted by this forcing and must be replaced with fresh crowns the following season. Forcing sheds can be expensive facilities to maintain, particularly as they cannot easily be repurposed for the rest of the year. When combined with the significant labour costs of lifting, overall production costs can be increased by £11k/ha, although forced rhubarb can be worth 5 – 6 times more than that of green pull rhubarb due to the greater market quality and early season supply.

Labour remains one of the greatest costs of production across horticulture. This cost has been overcome by increased automation in many crops, particularly during harvesting. However, in the case of rhubarb, harvesting still has to be done by hand, particularly in selective pulls where only harvestable petioles are taken leaving immature sticks in the ground for later harvests. As a result, rhubarb growers have not gained the cost savings during harvest that are achieved by growers of other field crops. They must therefore consider alternative methods to increase profitability of rhubarb production to remain competitive, especially on sites where they have no access to forcing sheds.

Forcing rhubarb is physiologically achieved in several ways. A slightly warmer constant temperature promotes the crowns to break dormancy sooner, producing earlier growth than in the field. The almost complete lack of light stalls normal leaf development (leaf expansion and chlorophyll production) as the crown channels energy into elongating the petioles as they search for light. The absence of light also prevents chlorophyll from being formed so the petioles do not begin to produce green pigment. There is also much less development of the leaf blade and it is likely that more of the crown's energy reserves will be channelled into the elongating petiole rather than being invested in the developing leaf.

Growers would benefit significantly if field-grown crops could be forced as well as those in sheds. This may offer increased produce value whilst avoiding the additional costs of forced rhubarb production in sheds. Whilst complete forcing is unlikely to be achieved in the field, it is possible that some form of intermediate forcing could be carried out by the cultivation of crowns under plastic where the use of plastic coatings could enable light manipulation. The exclusion of light, or distortion of the red to far red light ratio (which plants use as a developmental signal) could be used to achieve greater elongation of petioles, giving greater stick length at harvest. Enriched proportions of blue or red light may also increase pigmentation in the petioles, giving a brighter red colour at harvest. Lastly, plastic use is likely to create a warmer microclimate, encouraging crowns to break dormancy earlier and achieve faster rates of growth, providing early harvests.

Modification of the light spectrum can be achieved through the use of photoselective plastics in the field. These are carefully formulated polyethylene covers which can be placed over the crop in low tunnels and selectively absorb or transmit different wavelengths to produce a spectrum that is either enriched or depleted in certain regions to influence plant morphology and growth responses of the crop. Of particular interest here is the distortion of the red to far red light ratio. Plants use the ratio between red and far red light to sense whether they are growing in shade or in full sun – plants growing in shade will elongate further and faster as they seek to outcompete surrounding plants and reach stronger light, giving longer stems and petioles than would be seen in the open sun. This is a similar effect to that seen in the elongated petioles harvested from forced plants, so it is possible that manipulation of the red to far red ratio could be used to produce petioles of a greater length.

Different species will respond to this treatment in different ways, while non-target effects such as microclimate modification can have further impact on the growth of the crop or other aspects such as disease development. The use of such an approach in rhubarb may allow field-grown crops to be manipulated so as to improve the value of the harvested petiole by producing a product that is intermediary between forced and field-grown rhubarb either in terms of harvest window or quality.

Using this novel approach, this project was established to test whether the use of photo-selective plastics could be used to increase the profitability of field grown rhubarb. The work set out to meet the following five objectives:

1. To develop and trial a functional prototype photo-selective film polytunnel for effective rhubarb field forcing.
2. To compare different forcing strategies for their effect in crop yield and post-harvest crown condition, whilst testing their relative economic benefits.
3. To quantify the effect of rhubarb field film-forcing in marketable stem characteristics, e.g. colour, texture, sugars.
4. To assess the effectiveness of photo-selective protection in controlling rhubarb pests and diseases.
5. To generate grower guidelines for the implementation of photo-selective plastic technology.

1.3 Summary of the project

Approach

A literature review identified target spectral modifications that could be of benefit in rhubarb, such as those likely to promote pigmentation of petiole elongation. These were also linked with available commercial products that could be used to achieve these in a field setting. Two products were identified that enriched the blue and green portion of the spectrum by reducing red light transmission. It was considered that these had strong potential to achieve the desired effects on marketable product quality, particularly petiole elongation. Alongside the blue and green plastics, an opaque plastic was identified to replicate the commercial practice of field-forcing, whereby crowns are left in the ground but covered with light-excluding plastic in near-forcing conditions. As this plastic was available in two orientations (white out and black out), both forms were used separately to test whether the outer material had an impact on the achieved microclimate as a result of difference in absorbance/irradiance of heat. The two photo-selective plastics and two opaque plastics were to be compared against a clear plastic control which allowed high levels of light transmission to test whether any observed effects were due to light manipulation or due to changes in the microclimate alone. These five treatments were compared against field grown conventional green-pull rhubarb.

These plastics were used to skin small polytunnels over a 5-year old Timperley Early crop at Barfoots Farm, Romsey, Hampshire. At the end of February 2020, strong storm damage prevented earlier installation, but the tunnels were erected on 2nd March. Three tunnels each with a footprint of 1x4.8m were skinned with each plastic treatment, and were sealed at each end (**Figure i**). The crop was flailed before tunnel construction to ensure a consistent age between treatments and subject to standard pest/nutrient management approaches. The first harvest was taken on 18th March 2020, with subsequent pulls made on 26th March and 6th April. The first and second harvests were selective with only marketable petioles pulled, while the last harvest was entire. While it would have been beneficial to carry out later harvests, these were precluded by the onset of the covid-19 outbreak.

Figure i. Photograph of the trial area showing tunnels skinned with plastic treatments.

The petioles cut at each harvest were subject to a range of assessments. Gross and marketable yield after the discard of out of specification petioles (e.g. twisting, length) was recorded, along with the proportion of investment in the developing leaf. Petiole length, width and depth were recorded, along with the texture as indicated by a shore firmness meter. The colour of the petiole was mathematically determined at the top, middle and bottom points of a selection of petioles using a chromameter to quantify the strength of red or green pigmentation. These methods allowed for an appraisal of the quality produced from each treatment alongside bulk yield. The spectral qualities of the plastics were assessed before and after use to identify any degradation that might adversely affect the lifespan of new materials used in the field. These measurements were tailored to provide a holistic evidence base relating to the use of plastics in field rhubarb production.

1.4 Results

Marketable yield per crown was significantly reduced in the open field control relative to the plastic treatments – 423g/crown was seen in the open field control compared with 892 – 1,117g/crown in the plastic treatments (**Figure ii**). The bulk of the harvest was seen in the first harvest of the plastic treatments, while individual picks were relatively low between each harvest of the open field control. The blue and black plastic treatments gave the greatest marketable yield outputs (1,117g/crown and 1,088g/crown respectively) compared with the clear plastic which only achieved 892g/crown. Relative to gross yield, the plastic treatments achieved a much higher proportion of marketable yield (68 – 79%) than the open field control which achieved only 44% marketable yield.

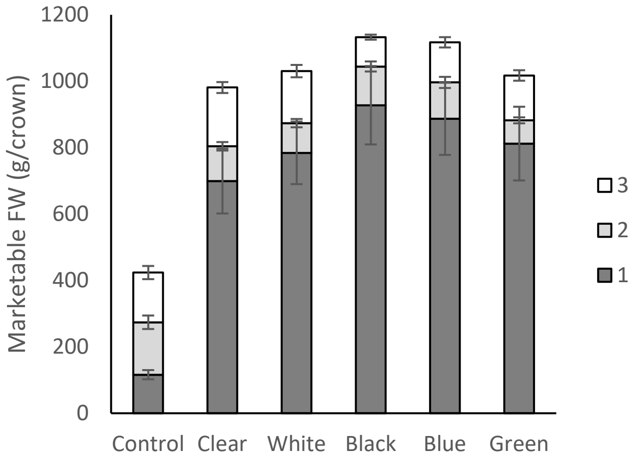

Figure ii. Marketable yield outputs for the first, second and third harvests, averaged per crown. Marketable yield from the control plots were significantly lower than those achieved in the plastic treatments, although there was no significant difference within the plastic treatments.

The limited duration of the trial has not allowed examination of the impact on yield across a complete season, but the use of plastics has significantly advanced the timing of harvestable yield compared with the open-field control. The uniform response between the clear, coloured and opaque plastics indicates that the early yield uplift is likely to be independent of light effects – most likely a warming of the microclimate increasing the rate at which crowns break dormancy and giving greater rates of growth.

However, significant differences were seen in the quality of petioles recovered from each treatment. Average petiole length in the petioles harvested from the black and white opaque plastics (34.3 and 35.23cm respectively) were significantly longer than those seen in the clear plastics and the open field control (29.2 and 28.6cm), while being significantly narrower (**Figure iii**). Petiole colour was also affected by the use of plastic treatments. The opaque plastics brought out the strongest pigmentation, giving deep red colour throughout the petiole. The other treatments showed partial greening, although this was limited only to the upper third of each petiole. The greening on the blue and green treatments was more significant than the clear and open-field control, but was limited to the upper third and did not lead to any loss of marketability (**Figure iv**).

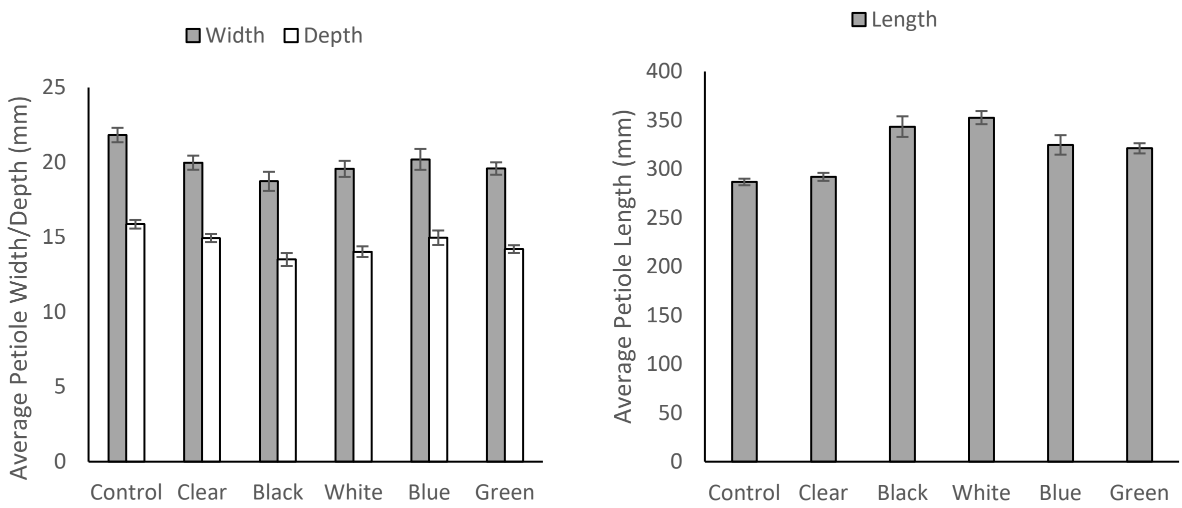

Figure iii. Average petiole length, width and depth as recorded across the trial.

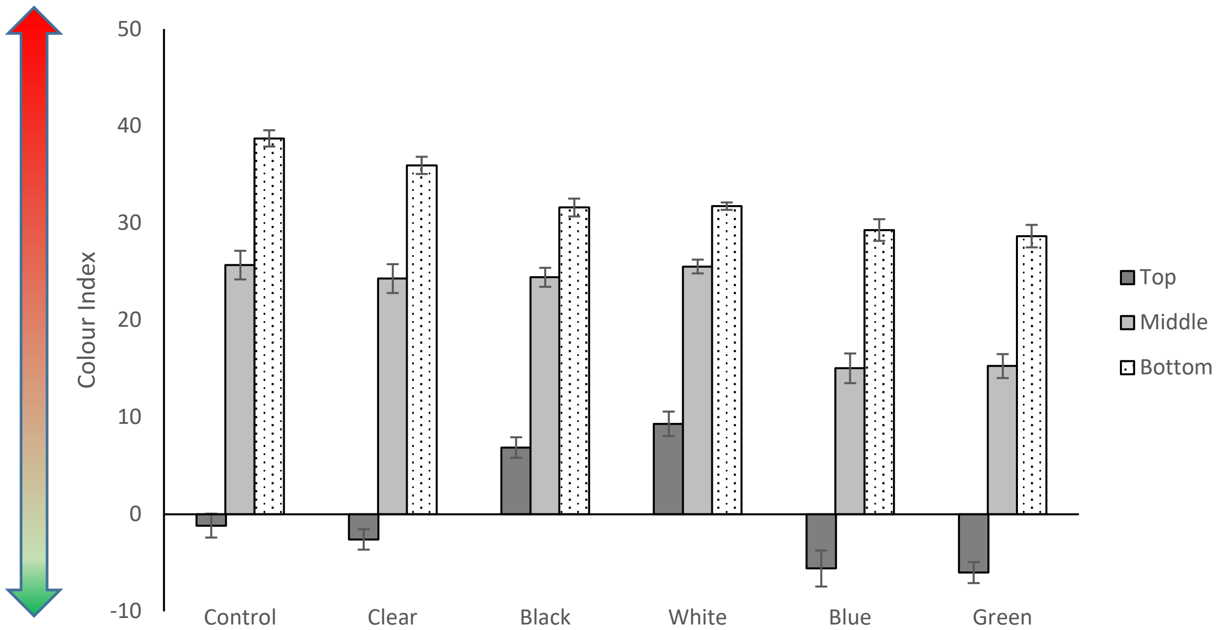

Figure iv. Petiole colour index measured at the top, middle and bottom petiole position. A more positive colour index indicates increasing red. Lower (or negative) colour index value indicates a stronger green colour.

Taken collectively, the use of plastics can be seen not only to advance early yields but also (in the case of blue, green and opaque plastics) increase the value of marketable quality. It is noteworthy that comparable effects on petiole length can be achieved with the opaque plastic treatment as the green and blue plastics. In opaque plastics, the elongated petioles are likely as a result of the crop growing in the search for light. In the blue/green plastics, a distortion of the red to far red ratio caused by the spectral modification is likely to be having a similar effect, leading to elongation of the petioles giving the increased length recorded here.

Within a single year of production, the ability of either plastic to give the quality benefits may lead to a plastic choice on price alone – the comparatively cheaper value of opaque plastic may promote its use over the green/blue plastics. However, the blue plastic allows for significant transmission of photosynthetically active radiation through to the crop, unlike the complete absence seen in the opaque treatments. The availability of light (whilst still achieving the desired uplift in quality and yield outputs) means that an additional resource is available to the crop – rather than relying solely on the reserves of the crown. The blue light enhanced treated petioles may be able to produce a significant quantity of sugars to support their growth – this is hypothetical at this stage but would be worth examining by tracking productivity of the treated crowns over several seasons. This may avoid exhausting the crown, promoting greater yields within a season or giving greater yields in the following season. While we have been unable to test this aspect in the current project, there is strong potential for this treatment to have longer-term benefits for growers seeking to increase the productivity of their crops in the early season.

The low yield of the open-field control is likely to be the result of the time at which harvests were taken rather than indicative of a reduced whole-season yield. Field production is normally in mid- to late spring, so the harvest window used in this trial is likely to have missed the main periods of productivity for open field production. As we have been unable to assess productivity over a complete season we are unable to fully explore the impacts of plastic on total yield output. However, we have been able to demonstrate that the use of plastics can significantly advance the timing of the harvest. The results of this trial indicate that around 15 tonnes/ha could be achieved with plastic use in March/April this year, compared with 6 tonnes/ha in the open field control. Assuming Timperley Early may yield around 44 tonnes/ha (based on Stockbridge House trials data), this means that plastic treatment could be used to achieve 34% of total yield in March compared with only 14% in open field plastic in the same period.

Main conclusions

- Rhubarb production in the UK is worth over £17m annually with high customer demand despite it being a niche crop. Rhubarb is a labour-intensive crop requiring harvesting by hand, and this has made rhubarb production difficult to automate. Growers must consider other routes to drive profitability of their production.
- Forced rhubarb grown in near-total darkness can achieve prices 6 times that of green pull rhubarb due to greater quality and earlier harvesting, although this carries greater labour costs from lifting and requires specific facilities whilst exhausting the crowns, preventing regrowth.

- Plastics which either block light completely, or modify the spectrum of light reaching the crop, are available as coverings for field rhubarb production. As light is responsible for the difference between forced and field grown rhubarb, this project examined whether plastic use could enhance the profitability of field grown rhubarb.
- Growing crowns under plastic in the field can address the gap between forced and green pull rhubarb. In this project plastic use increased marketable yield by 2.1 – 2.6 times that of open field harvested rhubarb in March, giving around 17 tonnes/ha compared with 6 tonnes/ha, assuming 15k crowns/ha.
- The work has shown that both opaque plastics and blue/green plastics can bring forward the harvest window for field-grown rhubarb by adjusting the quality of the light reaching the crop. Opaque plastics are likely to be around 20% cheaper to use, but blue plastic may allow the crops to produce some new sugars in the spring, lessening the exhaustive effect of early field-forcing.

1.5 Financial benefits

Based on the figures above, the use of plastic in open-field rhubarb production could bring forward roughly 20% of the total yield to the early part of the season. Based on trends in market value (**Figure 1 of the Science Section of this report**) there is a decline in wholesale rhubarb value of c. 30% between March and April. This means that produce harvested earlier will be of greater market value if harvested in March rather than later in the season. Assuming an initial value of £1/kg value to the grower, and that similar declines are seen later in the season, this would be equivalent to £9,000/ha in March compared with £6,300 in April. Plastic at a cost of 80p/m^2, alongside other costs such as tunnel hoops and labour inputs for construction would increase the cost of production (although the reuse of plastic over a 5-year period may reduce this). While the most cost efficient use of plastic may be achieved with opaque plastic, such treatment is liable to exhaust the crowns and reduce yield in subsequent years. However, the use of blue plastic may allow yield benefits (both in terms of productivity and quality) to be gained without exhausting the crowns as discussed above.

1.6 Summary

The use of plastics can drive productivity in field-grown rhubarb through a variety of ways. Light manipulation can positively affect quality of rhubarb achievable in the field. Opaque plastic offers longer sticks with greater pigmentation, while blue/green plastics offer long sticks without having as draining an effect on the crown, potentially increasing later harvests. Plastic use will also create a warmer microclimate around the crowns which can significantly advance harvests, making produce available earlier in the season.

While we have demonstrated that it is possible to increase the value of field-crown rhubarb it is considered that the likely costs and labour inputs required (particularly at a time when field access may be difficult) it is unlikely that large scale application of plastics would be seen. However, when applied on the small scale this may enable growers to bring forward a portion of their productivity to address the gap between forced and green-pull rhubarb, better enabling them to match customer demand whilst meeting greater market value early in the season.

1.7 Action points for growers

- Consider plastic coverings as a method for adjusting the period of productivity of field grown rhubarb. Both blue and opaque plastic may significantly bring forward the harvestable window for green-pull rhubarb, while offering significant enhancement of marketable qualities.
- Blue plastic use may offer greater benefits than opaque plastic between seasons by allowing the crop to generate new sugars for growth during the season rather than entirely relying on the crown for resources, whilst still producing petioles of improved quality.

2 Science Section

2.1 Introduction

Rhubarb is harvested as the petioles of *Rheum rhubarbarum* which emerge from perennial crowns in early spring. While it is a niche crop occupying only 516 ha producing 21,000 tonnes/year in the UK it is a high value crop farm gate value of £17m (Defra Horticulture Statistics, 2019). The industry has contracted significantly over the last 30 years, despite strong growth in customer demand and product value. Rhubarb is a perennial crop harvested by hand, and it has proven difficult to automate requiring high labour inputs relative to other field crop crops. To better match consumer demand, growers must be supported in developing methods of increasing yield quality and value.

Rhubarb production follows two general approaches: crowns can either be reared in the open field with petioles pulled over several harvests as the crop naturally breaks ground. Alternatively, crowns can be lifted and placed in forcing sheds in near total darkness and controlled temperatures. Forcing rhubarb brings forward produce availability by two to three months, giving an early harvest window to match peak demand. Forced rhubarb is typified by longer, slender petioles which deed red pigmentation that develops as a result of growth without light. The enhanced quality and early harvests of forced rhubarb offers a significantly greater market value of around six times that of field grown rhubarb, particularly of Yorkshire forced rhubarb that has been awarded Protected Designation of Origin status – wholesale prices are given in **Figure 1** and while supermarket sales are likely to differ general trends in price will be comparable. This uplift in price is likely to be due to a combination of the significant differences in quality for the forced rhubarb (as discussed below) as well as early-season supply.

However, the additional labour costs of lifting crowns, coupled with maintaining temperatures in the forcing sheds increases costs by approximately £11k/ha. Forcing sheds are specialist facilities are generally left empty for the rest of the year, requiring growers to maintain facilities that cannot be used for other purposes. Lastly, forcing rhubarb exhausts the crowns with the result that they must be disposed of after harvest and replaced with field-matured crowns that have been grown without harvest for 2 – 3 years the next season compared with field grown crowns that will continue to yield produce for 5+ years after establishment. These aspects have limited the proliferation of forced rhubarb production in the UK: in 2019 8,000 tonnes of forced rhubarb were produced compared with 13,000 tonnes of field-pull rhubarb.

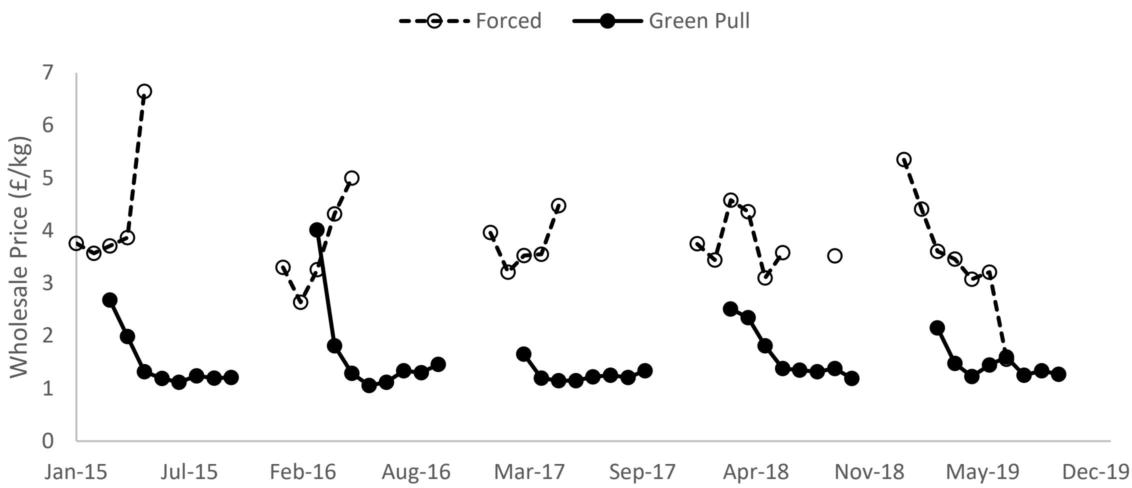

Figure 1. Wholesale market prices for UK-grown rhubarb 2015 – 2019. Data modified from www.statista.com/statistics/467080/outdoor-rhubarb-wholesale-price-average-united-kingdom-uk/ and www.statista.com/statistics/467077/forced-rhubarb-wholesale-price-average-united-kingdom-uk/ - accessed 1/6/20.

There is a perceived need by UK growers for ways to enhance the profitability of field rhubarb production to address the gap between the profitability of field and forced grown rhubarb. The higher market value of forced rhubarb is due to two key aspects: firstly, earlier production than field grown rhubarb offers earlier marketing opportunities to offset lower quality imports. Secondly, and more significantly, customer-valued criteria such as colour, flavour and texture are greatly enhanced in forced rhubarb (**Figure 2**). Natural development of field-pull rhubarb in light results in short, fibrous petioles which progressively turn green as the leaf blade develops and begins to photosynthesise, although the ability to green up and synthesise sugars provides a second source of sugars for the developing plant. This means that the crown is not exhausted and can remain in the ground for harvests in following years. However, the lower quality of green pull rhubarb means that it achieves lower market value.

Figure 2. Forced (top) compared with field grown (bottom) rhubarb. Forced rhubarb is typified by longer, slender petioles with a sweeter flavour and softer texture.

2.2 Background

Rhubarb is perhaps unique in that two very different products, with significantly different costs of production and market value, can be produced from an overwintered crown. Growers are seeking to improve the profitability of their rhubarb production. Increasing the proportion of forced rhubarb will require greater capital investment (e.g. increased forcing shed area) and labour requirements which may be difficult to meet given the increasing difficulties facing the wider horticulture sector. As an alternative to lifting crowns, it is desirable that the marketable quality and/or timing of harvests of field grown rhubarb be enhanced. There has been a limited application of field forcing of rhubarb – low tunnels covered with opaque plastic are placed over rows to provide darkness leading to production similar to forced rhubarb without the additional labour inputs of crown lifting. However, variable temperatures under the plastic can lead to an increased proportion of twisting (leading to increased proportion of unmarketable produce) while high humidifies can lead to increased pest/disease damage. The process also exhausts the crowns, requiring replanting for the following season.

An attempt at reconciling these aspects, the use of photoselective plastics was identified as a potential method of enhancing the profitability of field grown rhubarb. Light is the primary mechanism that drives the distinction between forced and field-pull rhubarb through its presence or its exclusion. Therefore, the manipulation of light reaching the emerging petioles may be used to impact their development to further enhance the profitability of production, either by direct manipulation of the produce quality or by bringing forward harvest to earlier in the season. This project was established to develop to test the potential for plastic use to improve the profitability of field-grown rhubarb relative to conventional production.

2.3 Project Objectives

1. To develop and trial a functional prototype photoselective film polytunnel for effective rhubarb field forcing.
2. To compare different forcing strategies for their effect in crop yield and postharvest crown condition and test their relative economic benefits.
3. To quantify the effect of rhubarb field film-forcing in marketable stem characteristics, e.g. colour, texture, sugars.
4. To assess the effectiveness of photoselective protection in controlling rhubarb pests and disease.
5. To generate grower guidelines for the implementation of photoselective plastic technology.

2.4 Literature Review

2.4.1 Light and Rhubarb Development

Like all crop production, light provision has a significant impact on rhubarb production. Unlike other crops, however, rhubarb production focuses on two alternative types of production which depend on light in different ways. Firstly, typical field production is focused on optimising light interception by growing leaves – planting density and weed development is controlled to ensure adequate light reaches the leaves to allow strong petiole and crown development and to promote good regrowth in the following season. Alternatively, crowns are lifted from the field and are transferred to forcing sheds where they are kept in near absolute darkness. The exclusion of light promotes the onset of etiolation in developing leaves (Williams, 1956) to give a crop of optimum quality and value. Leaves do not expand, remaining stunted with no chlorophyll development. Etiolation promotes petiole growth as leaves seek to outgrow the darkness, producing long, thin petioles with little fiberisation as there is only limited leaf mass for the petiole to support. The absence of light also promotes the development of deep red pigmentation, chiefly due to the production of anthocyanins (see below). The lack of chlorophyll development prevents greening of the petioles, further enhancing the pigmentation of the stem. This treatment produces a product of maximum quality – long, thin tender petioles with a strong colour which can be marketed at high value. However, this carries additional costs of labour, required to lift the crowns, maintaining suitable temperatures in forcing sheds and maintaining facilities which are only used for narrow periods of the season. Therefore, there is a requirement to improve the quality of field-grown rhubarb to increase its market value without incurring the higher level of costs associated with forcing. As the growth and development of the rhubarb crop is intrinsically linked with light, there is strong potential for this to be achieved through careful manipulation of the growing environment of field grown rhubarb.

2.4.2 Light Quality

Light is a fundamental resource for plants, and as such, is the predominant factor in determining the how yield quality and volume is realised from the biological potential of the crop. Solar radiation provides a range of wavelengths from UV-A, through the visual spectrum to far red light (**Figure 2**). Only a portion of the spectrum is used for photosynthesis, represented by photosynthetically active radiation (PAR) between 400 – 700nm. Photons within this range are capable of being absorbed by photosynthetic pigments, allowing the conversion of light to chemical energy, resulting in the uptake of CO_2 and production of sugars. The fundamental requirement for light in plants means that it exerts a significant effect on plant development. The direction, intensity, and quality of light all have potential to impact growth. The relative intensity of UV/blue light to red is used to inform plant growth, as is the ratio between red and far red light with different intensity ranges, leading to a series of common developmental responses in plants. It is these responses that offer the potential to enhance the quality of field grown rhubarb, and these are reviewed below.

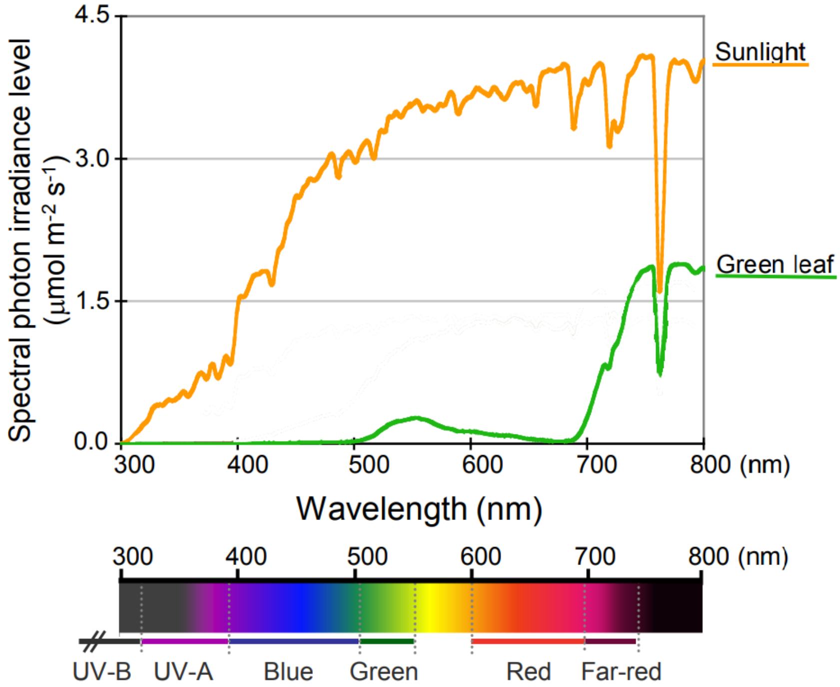

Figure 3. Spectral composition of unfiltered sunlight (yellow) and shaded light under a green leaf canopy (green). Wavelengths are not transmitted proportionately through green foliage – blue (400 – 500nm) and red (600 – 700nm) are absorbed for photosynthesis, leading to a higher green and far red proportion under the canopy layer. Figure adapted from Kami *et al*. (2010).

2.4.3 Enhancing the Quality of Field Grown Rhubarb

As the benefits of forced rhubarb are driven by light responses in the crop, it is considered that there is a potential to enhance the value of field grown rhubarb using photomanipulative techniques. While traits of forced rhubarb are likely to be only achieved in complete darkness, many of the key traits (petiole colour, length, thickness, sugar/content/flavour) are likely to be modifiable through careful manipulation of light quality. A variety of methods are available to growers for the manipulation of light quality in the growing environment. Supplementary methods (typically light emitting diodes or LEDs) can be used to provide a very precise spectra for growing crops, but the high economic costs of using LEDs (coupled with the relatively short period of utilisation in the rhubarb growing season) is likely to preclude their use on grower holdings. As an alternative, subtractive methods – wavelength attenuation whereby some wavelengths are reduced by absorbance increasing the relative proportions of others - can be used to modify the light spectrum that a growing crop is exposed to. In this instance, the crop is grown under plastic or glass containing chemicals which selectively transmit different parts of the spectral creating a specific spectral mix. Photoselective plastics are the most common material used for this and offer a cost efficient way of creating a modified environment for a growing crop.

It is the purpose of this project to trial the use of photoselective plastics in the field to improve the quality of field grown rhubarb. Through manipulation of the growing environment, it may be possible to enhance marketable value of field grown rhubarb, helping growers to bridge the gap between forced and conventionally grown rhubarb. The optimal spectral recipe for field forced rhubarb will require direct experimental analysis. The niche nature of rhubarb as a crop means that little evidence has been published relating the potential for light manipulation in rhubarb. However, the crop responses that we seek to exploit are well documented in other plant species, and it is our intention to use the conserved nature of light responses to promote quality enhancement in rhubarb.

Photoselective plastics cannot produce the purity of spectra seen in LED lighting – the limits of photochemical absorbance mean that it is difficult to achieve spectra which are highly specific to given wavelengths. As a result, it is more appropriate to talk about modification of regions rather than specific wavelengths. Besides the visible spectrum represented by red, green, and blue regions, light outside of this range (UV and far red) can be selected for or against in photoselective plastics. Discussed below are the potential benefits of modifying these sections in the production of rhubarb as justification for the ranges selected for field trials. Besides modification of the spectrum, use of plastic polytunnels will alter other aspects of the growing environment such as temperature and humidity, and this may prove beneficial by promoting crop development allowing for earlier harvest. Use of plastics to modify the physical environment (including spectral modification) also has the potential to alter pest/disease interaction, and this will be monitored accordingly to ensure the benefits of this approach can be fully exploited.

2.4.4 UV and Blue Light

Short wavelength radiation, in the blue end of the visible spectrum moving into UV, carries the greatest energy of the visible spectrum. Blue light is actively absorbed for photosynthesis with peak absorbance at 430nm (chlorophyll a) and 453nm (chlorophyll b), but exposure to shorter wavelength, higher energy radiation can place an oxidative stress on a plant. Under normal circumstances, this intensity of UV light is normally seen only at high altitudes, but this has been shown to alter the biochemical profile of rhubarb (Sun *et al*., 2016; Yong-gang *et al*., 2017). However, plastics have been developed which allow the transmission of UV light, creating the potential for increasing the proportion of UV radiation relative to other sections of the spectrum.

Anthocyanins (the chemicals responsible for the red/purple pigmentation in rhubarb petioles) serve a photoprotective function, reducing inhibition and bleaching of chlorophyll under high light stress or photoxidative stress (Steyn *et al.*, 2002). Anthocyanin synthesis is also impacted by light quality, with blue light stimulating anthocyanin synthesis more than red or far red light (Chen *et al.*, 2006), and blue light in the 470nm range has been effectively used to enhance anthocyanin concentration in apple (Saure, 1990), bayberry (Shi *et al.*, 2014) and lettuce (Li & Kubota, 2009). While growth under blue light alone is likely to limited growth, adjusting the red:blue ratio may potentially drive increased anthocyanin biosynthesis. A red:blue ratio of 3:2 was found to lead to a 7x enhancement of anthocyanin content in lettuce without retarding growth (Lee *et al.*, 2010). Rhubarb grown under incandescent light filtered to give a spectral range of 400 – 490 nm gave similar pigmentation to dark-grown rhubarb, while other spectral ranges gave a weaker colour, showing green development in the petiole. The blue lit crop showed small but significant increases in dissolved soluble solids of 25% (refractometer readings used as a proxy for sugar content) compared with the dark-forced crop, a 13% increase in petiole number and 15% increase in petiole weight with blue lighting, implying that additional yield benefits may be realised from spectral modifications (Chipman & Hope, 1964).

Besides blue light, UV wavelengths may also enhance pigment development. For example, UV-B exposure in apple (Arakawa, 1985) and in lettuce (Li & Kubota, 2009) enhanced anthocyanin biosynthesis, in keeping with the hypothesis that anthocyanins play a role in photoprotection. UV wavelengths are typically blocked by plastic, but some UV transmissible plastics are becoming available for horticulture as the physiological benefits of UV exposure crops are identified.

Therefore, it is proposed that plastics which are selective for the blue portion of the spectrum, potentially with UV transmission, will be worth trialling on field grown rhubarb from the perspective of enhancing petiole colour and flavour. Previous work has supported this directly in rhubarb (Chipman & Hope, 1964), and so trialling this in the field would represent a translation of this into coomercial field settings.

2.4.5 Simulating Shade – Red/Far Red Light

Two sections of the light spectrum interact to exert a significant level of control on plants – red light (R) between 600 – 700nm, and far red light (FR) between 700 – 850nm. Red light is absorbed for photosynthesis at 662nm (chlorophyll a) and 642nm (chlorophyll b). Red light between 650 – 670nm is also absorbed by the P_r isoform of the phytochrome photoreceptor. Upon red light absorption, the P_r isoform is converted to the P_{fr} isoform, which shows an absorbance peak in the far-red region between 705-750nm. The P_{fr} isoform is physiologically active (exerting a developmental influence on the plant) but can be converted back to the P_{fr}

isoform through the absorption of far red light, and the proportion between the two isoforms provides information to the plan relating to the light quality of its growing environment. The proportion of P_r to P_{fr} is determined by the relative intensities of red (R) light to far red (FR) light. The proportion between the relative intensities of these wavelengths (often described as the R:FR ratio) can have profound effects on how plants respond to light from vegetative growth to timing of flowering, breaking dormancy etc, although it is the vegetative effects that are of relevance in this instance.

The R:FR ratio of sunlight is typically around 1.0. Red light will be absorbed by leaf material as the energy is captured for photosynthesis, while the longer wavelength far red light will be transmitted or reflected off the leaf surface. This means that a green leaf canopy will not equally transmit light to lower canopy leaf layers, altering the spectrum of light underneath to be enriched in far red light while depleted in red light, giving a low R:FR ratio (Figure 3).

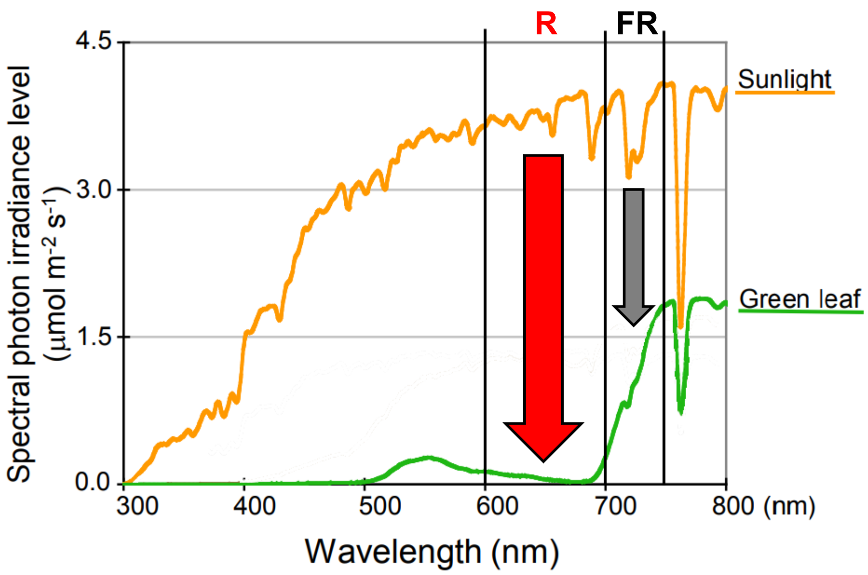

Figure 4. The effect of the canopy layer on spectral composition. While all wavelengths are reduced by transmission through the green leaf layer, the reduction is not proportionate. Red light is absorbed for photosynthesis, while far red light is transmitted. This gives a low R:FR ratio in the transmitted spectrum. Figure adapted from Kami *et al*. (2010).

When a low R:FR ratio is encountered, this indicated to the plant that it is growing in the shade of a canopy rather than full sun, leading to a range of responses as the plant seeks to either outgrowth the shade, or adapt its morphology and physiology to maximise its utilisation of the limited amount of light available to it. While there is some variation between species relating to their tolerance of shaded conditions, the shade response shares a number of common themes between different plant groups.

In shaded conditions, leaves typically become thinner, supported by stems and petioles which become thinner and elongate further as the plant attempts to outgrow the shade, and this has been demonstrated in a range of plants including *Impatiens* (Whitelam & Johnson, 1982) and pumpkin (Holmes & Smith, 1977). In addition to elongation, apical dominance is typical reinforced to reduce branching and channel growth into a central stem trying to outgrow the canopy layer, although this is also variable between species (Casal & Smith, 1989; Franklin, 2008).

Manipulation of the shade response has been demonstrated in several horticultural crops, although this has typically been through reducing the proportion of FR to simulate full sun. Promoting a high R:FR ratio (either by supplementation with red light or the use of FR absorbing plastics) to promote short, compact plants with increased branching by triggering a reverse of the shade response in plants. This has been shown to be beneficial in ornamental horticulture, e.g. *Petunia* and *Impatiens* (Fletcher *et al*., 2005), and has been used to enhance the concentration of nutritional value of various crops (e.g. antioxidant concentrations), as key indicators of market quality (Samuoliene *et al*., 2012).

In the instance of rhubarb, the reverse of this effect has the potential to improve market quality – by reducing the proportion of red light, giving a low R:FR ratio, shade will be simulated potentially promoting the development of long, thin petioles in the developing leaves rather than thick petioles, associated with increased fibre content and of a lower quality. Therefore, the cultivation of rhubarb in a low R:FR ratio spectrum is considered to have strong potential to improve marketability of field grown rhubarb. While there is no specific information available for the effect of a low R:FR ratio in rhubarb, the highly conserved nature of these responses supports trialling this in the field. Furthermore, manipulation of the R:FR ratio is widely practiced in other sectors (e.g. ornamentals) so the technology is readily available for adaption for use in rhubarb cultivation.

2.4.6 Green Light

Besides the changes to the R:FR ratio caused by canopy cover, the proportion of green light is also significantly enriched (**Figure 3**) as a result of the depletion of red and blue light by photosynthesis. While the effects of green light (500 – 580nm) are less well understood than changes in R:FR ratio, there is a body of evidence which suggests that green light exposure triggers similar shade responses, and can act in a synergistic fashion with increased far red intensity (Klein, 1992). For instance, shade responses in *Arabidopsis* lead to an increase in petiole length typical of shade avoidance (Zhang *et al,* 2011) and green light illumination in lettuce gave greater stem and petiole elongation compared with fluorescent light (Mizuno & Amaki, 2005). The green region of the spectrum may not exert a significant influence in its own right, but in combination with the manipulation of the R:FR ratio it may further enhance the shade simulation.

2.5 Photoselective Plastics

Modified spectra can be chiefly achieved through two routes – addition or subtraction. LED lighting technology has provided growers with a precise way of providing crops with a precise spectra for growth, and this seen increasing uptake in the protected edibles sector. For rhubarb, this approach is unlikely to be financially viable given the scale of application required. A much more viable alternative is the use of photoselective plastics – these have been developed to provide a modified spectrum over an enclosed crop by selectively absorbing or transmitting different wavelengths of sunlight. This means that a modified spectrum can be provided to a crop in a relatively simple and cost-efficient fashion. The technology has seen variable uptake across the sector but has been particularly adopted by ornamental growers to provide novel ways of control plant growth. A limitation to their uptake is the need for specific evidence as to how the crop will respond to the modified spectra to support its use.

Given the availability of photoselective plastics that are already used in the horticulture sector, it was considered a viable approach to test the impacts of photoselective plastics of a commercial rhubarb crop. The use of poly tunnels already sees limited use in rhubarb production – opaque plastics are used for field forcing by providing a light-proof cover over field-grown crowns to provide an environment comparable to force sheds. As the infrastructure is available for using polytunnels in rhubarb this provides an easy route testing the potential for photoselective plastics to increase the productivity of field rhubarb production. As part of the review activities above, commonly available horticultural plastics were identified and reviewed against their potential to be included in this trial. Two key plastics were identified as being of interest: “Sunsmart Green” and “Sunsmart Blue”.

Blue enrichment in the 400 – 500nm range is considered a key region to target to promote the development of anthocyanins and improve the pigmentation of rhubarb stems. Two plastics have been identified which enhance this section of the spectrum. “Smart Blue” from XL Horticulture shows peak transmission between 400 – 500nm (c. 80%) compared with 20% transmission in the UV and c. 30% transmission in the R/FR region (**Figure 4**). This still has some green/red transmission, and these have been shown to be antagonistic to anthocyanin production.

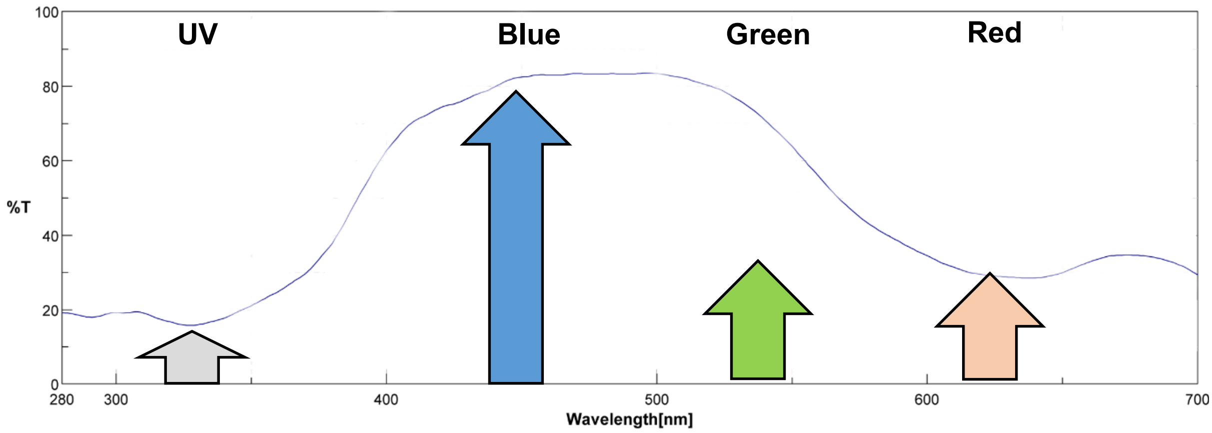

Figure 5. Transmission spectra for "Smart Blue" (XL Horticulture). High blue transmission is paired with a reduction in the red, green and UV sections.

The plastics identified for trialling blue enrichment do not address the potential for R:FR modification to induce a shade response. To address this end of the spectrum, “Smart Green” from XL Horticulture will be trialled. This shows a peak in transmission around 500 nm, with a reduction in the blue (400 – 500nm) and red (600 – 700nm) (**Figure 5**). In addition, “Smart Green” shows a greater reduction in red compared with far red, giving a low R:FR ratio to further promote the simulation of shade. This plastic also allows significant transmission in the UV range, potentially allowing promotion of anthocyanin development which is normally impaired in shaded conditions.

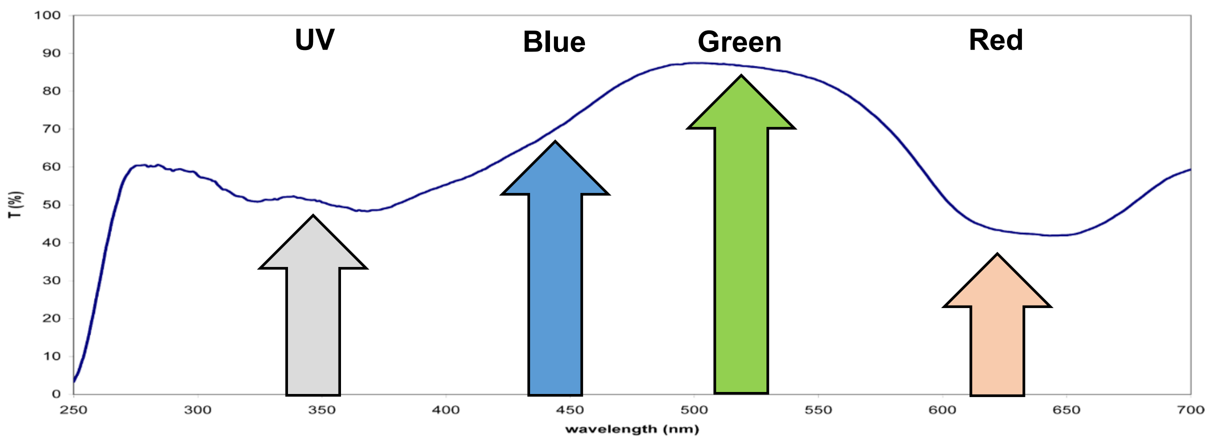

Figure 6. Transmission spectra for "Smart Green" (XL Horticulture). High green transmission with a low R:FR ratio will be used to simulate shaded conditions.

In addition to these two plastics, it was considered important to include three further plastic combinations: “Sunmaster Clear” (a conventional clear, colourless plastics) and “Total Block Black/White” (an opaque plastic that blocks nearly all light transmission. These plastics will allow the testing of additional aspects besides spectral modification. The use of a clear plastic will test whether the microclimate modification effects of polytunnel use (e.g. increased temperatures and humidity) have an impact on rhubarb production in the absence of any significant spectral modification. The opaque plastic test the use of field forcing to provide a comparison of rhubarb produced under spectral modification compared with that produced in complete darkness. The opaque plastic is double sided (white and black) and so can be used in two confirmations – white out and black out – while still blocking light transmission. This may impact the temperature/humidity under the tunnel due to differences in reflectance/absorbance between the white and black outward surface. The plastic selection was confirmed through a presentation of the literature review results to the project steering group.

2.6 Trial Approach

It was considered that a small-scale commercial trial to develop an evidence base for the use of photoselective plastics in field rhubarb production was the most efficient approach. It is possible to test the impact of modified spectral mixes using laboratory-scale trials using LED arrays, although this approach was considered unlikely to yield meaningful data in this instance. As a perennial crop, rhubarb is harvested from an established crown drawing on reserves laid down during the past season. Lifting crowns to test in laboratory settings will significantly impact sink:source relationships in the crown through root damage during lifting, making it is difficult to obtain meaningful results from crowns examined *ex situ*. More significantly, rhubarb production in the early season is normally at temperatures of 10°C or below, and these are unlikely to be achievable in laboratory facilities equipped with LED arrays. Therefore, moving directly to small-scale commercial trials was considered most likely to generate commercially relevant information on meaningful timescale.

Therefore, a small-scale commercial trial of the plastics identified above was developed. The trial was created to address the objectives given above. A polytunnel system suitable for field production will be established and used for trialling the plastic treatments above. The use of these plastics will be used to test whether light manipulation of field-grown rhubarb can increase the productivity of field production. Productivity will be examined in a variety of contexts: i) gross and marketable yield per crown ii) timing of yield outputs (to test whether plastic use can bring forward rhubarb harvests) and iii) the market quality of rhubarb when compared against commercial specifications (e.g. colour, size and texture). By evaluating the use of plastics against a range of criteria it will be possible to develop a holistic evidence base to demonstrate to growers what (if any) use plastics may offer for increasing the productivity of field grown rhubarb.

Initially, a trial was attempted at E Oldroyd & Sons, Rothwell in spring 2019, but heavy storm damage prevented meaningful results from being obtained. A trial was then successfully carried out at Grove Field, Broadlands, in 2020.

2.7 Materials & Methods

2.7.1 Site Selection & Trial Development

A five-year old crop of Timperley Early was selected for use in the trial. The trial area was examined in the autumn of 2019 to verify that it was representative of the wider plantation, and with an adequate number of active crowns. A pre-emergence herbicide spay of Shark, Kerb and Stomp Aqua was used to limit early season weed development. Pre-emergence fertiliser was also applied in keeping with the commercial management of the plantation – 150kg N/Ha as calcium ammonium nitrate (3rd January), followed by a further 50kg N/Ha before trial establishment (19th February).

Tunnels were constructed in late February 2020 and were skinned on the 2nd March in low wood-bunded polytunnels. Previous constructs based on unsupported steel hoops were insufficient and were lost during early storm damage, although this was most likely as a result of the small-scale experimental nature of the tunnels as this designed is used effectively for large-scale field forcing. Each tunnel had a footprint of 1m x 4.8m, with a peak height of 1m. Tunnels were skinned entirely, with closed openings at each end, although these were loosely tied to provide access for harvesting. This corresponded to between 5 – 10 active crowns per tunnel – on average 8.7 crowns per tunnel were active during the trial, although tunnels were sited on as representative rows as possible. Each tunnel represented a single plot, and each plastic treatment was applied to four replicate plots arranged in a randomised block design (**Figure 7**, **Figure 8**).

Block		Tunnel Set 1	Tunnel Set 2	Tunnel Set 3	Tunnel Set 4	Tunnel Set 5	Tunnel Set 6
4	Plot	401	402	403	404	405	406
	Trt.	2	5	3	4	1	6
3	Plot	301	302	303	304	305	306
	Trt.	1	4	2	3	6	5
2	Plot	201	202	203	204	205	206
	Trt.	3	1	6	5	2	4
1	Plot	101	102	103	104	105	106
	Trt.	6	2	4	1	5	3

1	No Plastic - Untreated Control
2	Clear Polythene
3	Opaque Polythene - White
4	Opaque Polythene - Black
5	Blue Polythene
6	Green Polythene

Figure 7. Trial Outline Plan

Figure 8. Photograph of trial area.

The crop was flailed before construction of the tunnels to ensure that allow growth was produced under the treatment conditions and were of a comparable age between plots. After tunnel construction, the plots were left for two weeks before the first harvest which was carried out on the 18th March. The first harvest was selective – taking only petioles of marketable size, while the second (26th March) and third harvests (6th April) were entire as an alignment with common commercial practice.

2.7.2 Pre-harvest Assessments

Before each harvest a series of measurements were made to appraise the general crop vigour. For the first assessment, the selective harvest was based on length along. Petioles which were of marketable length but unmarketable due to other criteria (e.g. twisting) were harvested and distinguished as marketable/unmarketable after harvest. For the second and third harvests all petioles were removed. For each plot the following assessments were made:

- Number of crowns with emergent petioles
- Number of petioles - Total
- Number of petioles - Harvested
- Number of petioles left to mature – First harvest only
- Total Fresh Weight of Harvestable Petioles
- Total Fresh Weight of Marketable/Unmarketable Petioles

2.7.3 Postharvest Assessments

Following each harvest, material was subject to a range of assessments to appraise achieved quality. For measurements that are routinely assessed as part of commercial supply (e.g. length, dimensions) assessments were based on commercial specifications as far as possible.

From the marketable fraction six petioles were selected at random from each plot and subject to the following measurements:

Dimensions
Petiole width and depth was recorded 5cm from the snapped end, alongside total length from snapped end to leaf blade base.

Texture
Petiole firmness was measured using a Bareiss HPE II digital shore meter. Measurements were taken 5cm from the snapped end on the inside face of each petiole.

Colour
Petiole colour is a key criteria for the marketability of rhubarb. Red pigmentation in the petiole fades as chlorophyll concentration increases, particularly near the top of the petiole in green pull rhubarb. Measurement of colour based on visual assessment (e.g. categorical assessments) can be subjective. To avoid this, petioles were subject to assessment by colorimeter to determine petiole colour against the L*, a* and b* axes (white-black, green-red and blue-yellow respectively). These parameters were used to calculate the color index value using the equation $2000 \times a^*/L^* \times (a^{*2} + b^{*2})^{0.5}$. This approach was described previously by López Camelo *et al*. (2004) to numerically quantify the green-to-red shift in tomato ripening

and given that a similar transition is seen in rhubarb this approach was considered justified. A more positive colour index indicates a stronger red, while a smaller (or negative value) indicates increasing depth of green. L* a* b* values were taken using a Konica Minolta CR-400 Chroma Meter. Measurements were taken at three equidistant points along each petiole, with the first 5cm from the snapped end to represent the top, middle and bottom measurement from the inside face of the petiole.

Biomass

Total petiole and leaf biomass – both fresh and dry weight – were record for each plot. To evaluate the development of the leaf blade, the proportion of dry matter allocation to the leaf blade in relation to the whole leaf unit (petiole + leaf blade) was measured on a whole-plot basis to give a leaf blade DW percentage. Material was dried at 80°C for 72 hours.

Leaf Blade Chlorophyll

Development of the leaf blade was further quantified through spectrophotometric measurement using a SPAD meter (SPAD-502 meter, Konica Minolta). Measurements were taken from the centre of the leaf blade in a region free of major veins.

2.7.4 Spectrophotometry Assessments

The spectral transmission of each plastic used was assessed before and after use to quantify the achieved wavelengths and to test for any loss-of-function during a season's growth. Achieved spectra were assessed in full sunlight using the WaveGo sensor (Wave Illumination).

2.7.5 *Ad hoc* Assessments

Besides specified assessments, the crop was monitored for any incidental changes such as increased pest/disease pressure that may be seen as a result of plastic use.

2.7.6 Impact of Outside Influences

The trial activities were subject to the impact of two significant outside influences. Initial tunnel construction in early January was planned to encapsulate the early season by providing additional harvests, but these were subject to heavy storm damage delaying the onset of the trails. The outbreak of the covid-19 epidemic also limited how late into the season measurements could be taken due to limits on staff movement and the halting of non-essential work. Despite these challenges three complete harvests were achieved and it is considered that these are sufficient to give meaningful results to address the objectives of this project.

2.8 Results

2.8.1 General Comments

Several practical issues arose over the course of the trial. Initially, several different tunnel confirmations had to be trialled to find structures of sufficient strength to withstand seasonal storms. The tunnels that were used for the trial were rigged structures with the plastic secured to wooden bunds on the side of each tunnel, meaning that access to the crop was achieved from each end (**Figure 9**). The tunnels also required significant time and labour inputs to construct, so this approach may be limited on a larger scale. However, larger tunnels, constructed on a field scale rather than isolated treatment plots are likely to be more self-sustaining and require less robust materials to be constructed.

Figure 9. An example of the tunnel construction used in the trial.

This method of tunnel construction made it difficult to ensure a complete fit (particularly between the wood bund and the soil surface), creating cracks where light could penetrate the tunnel. This is not likely to have been a concern in the transmitting plastics, but it may have reduced the efficacy of the opaque plastics in replicating field forcing conditions. In addition, phototropic responses of the crop lead to bending of the petioles towards the light cracks. While this is likely to have had a minimal effect on overall production, it may potentially have increased the proportion of bending/twisting petioles (**Figure 10**). However, larger tunnels used on a commercial basis are normally prepared with the plastic dug down on each side which would avoid this. However, evaluation of the proportion of marketable produce indicates that the opaque tunnels showed a comparable level of marketable produce to the other tunnel treatments (see **Table 4** below) so this effective is not considered to have had a significant effect. No significant incidence of pest, disease or weed problems were identified across the trial.

Figure 10. Phototrophic responses of emergent rhubarb under the opaque plastic towards light cracks underneath the wood bund, potentially increasing the risk of significant petiole bending.

2.8.2 Yield Outputs

Yield outputs showed significant variation within and between treatments when examined from different perspectives. Petioles per crown varied significantly between harvests ($p = 0.01$), and there was a significant interaction between harvest and treatment for total petiole number ($p = 0.023$) as greater petiole numbers were seen in early harvests for the clear and white/black opaque plastics, while increased numbers were seen later harvests in the blue and green plastics, and untreated control (**Table 1**). Petiole number is predominately related to the number of leaf buds present on the crown that would have been laid down in the previous season. The rate of maturity of these may be linked to environmental factors (e.g. temperature) but are unlikely to respond to light as these will be buried at the start of elongation, so these results are more likely to reflect innate variation in the trial area as opposed to treatment effects. While few petioles were seen in the black/white opaque plastics overall, there were no significant differences between treatments in total petiole number produced over the course of the trial ($p = 0.09$) as illustrated in **Figure 11.** The relative consistency of petioles per crown can be taken as indicative that the crowns used in this trial were comparative and that any further observed differences are due to treatment effects as opposed to external influences such as crown condition.

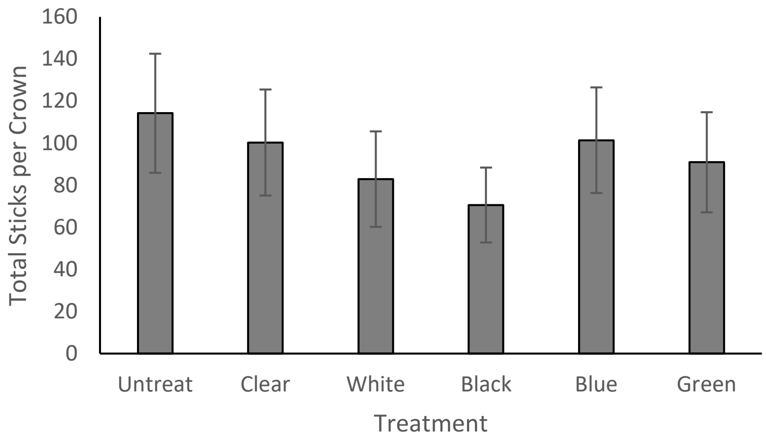

Figure 11. Total petioles per crown produced over the course of the trial. While the few petioles per crown were produced in the black plastic treatment, this was not significantly different from other treatments or control.

Table 1. Average number of petioles per crown at harvests 1, 2 and 3, and in total.

	Average Number of Petioles per Crown			
Treatment	Harvest 1	Harvest 2	Harvest 3	Total
Control	37.7 (±4.4)	33.6 (±3.9)	42.9 (±5.1)	114.2 (±28.3)
Clear	46.9 (±5.5)	35.3 (±4.1)	36.3 (±3)	100.3 (±25.2)
White	34.5 (±4.1)	28.1 (±3.4)	27.1 (±3.2)	82.9 (±22.7)
Black	35.1 (±4.1)	24.6 (±2.8)	21.8 (±1.8)	70.6 (±17.8)
Blue	32.4 (±3.8)	30.8 (±3.6)	38.3 (±4.5)	101.4 (±25.1)
Green	30.9 (±3.7)	28.7 (±3.3)	41.8 (±4.3)	90.9 (±23.8)

Total gross yield outputs were relatively comparable (**Figure 12**), and there was no significant difference in total gross yield between treatments and the control (p = 0.70). Despite the lack of significance, there were minor differences in total gross yield – the control and clear treatments recovered a slightly reduced gross yield (934.7 and 1135.0 g/crown respectively) compared with the black, white and blue plastics gave higher but relatively comparable yields (1475.1, 1471.2 and 1579.0g/crown respectively). Despite the lack of significant difference in cumulative gross yield between treatments, there was a significant interaction between treatment and gross yield between the separate harvests (p = 0.015). In all plastic treatments the first harvest far exceeded that seen in the second and third harvests. Conversely, the untreated control saw the greatest yield output at the last harvest (**Figure 12**). Summary figures for yield output are given **Table 2** in below.

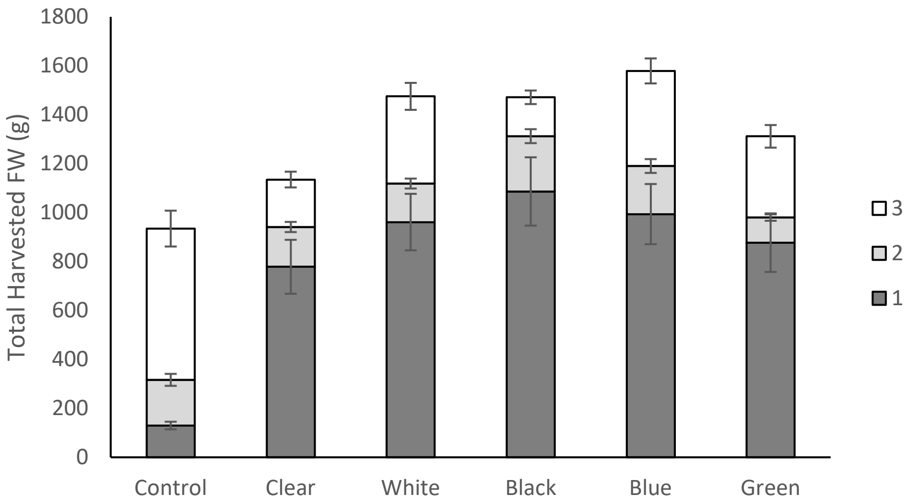

Figure 12. Gross fresh weight harvested per crown over the course of the trial, separated by harvests 1, 2 and 3. Total FW in the clear plastic and control plots was reduced compared with the other plastic treatments. The first harvest recovered the greatest FW in the plastic treatments while harvest 3 gave the greatest FW yield in the control plots.

Table 2. Summary figures for gross yield as g/crown as averaged across the trial area for the first, second and third harvests, and a cumulative gross yield for the trial period.

	Average Total Fresh Weight per Crown (g)			
Treatment	Harvest 1	Harvest 2	Harvest 3	Total
Control	129.9 (±15.5)	186.6 (±24.5)	618.2 (±73.3)	934.7 (±121.9)
Clear	778.6 (±110.2)	162.6 (±20.8)	193.9 (±32.2)	1135.1 (±293.6)
White	961.2 (±115.5)	157.5 (±20.2)	356.3 (±55.1)	1475.1 (±304.1)
Black	1086.4 (±139.6)	226 (±28.5)	158.8 (±27.7)	1471.2 (±405.6)
Blue	993.9 (±122.9)	196.5 (±28.2)	388.6 (±51)	1579 (±319.3)
Green	877.2 (±119.6)	102.5 (±13.1)	331.9 (±46.2)	1311.6 (±366.4)

Marketable yield showed similar variation between treatments and harvests. At the first harvest, there was a significant difference between the control plots and the plastic treatments – only 116.2 g/crown of marketable yield was harvested from the control, compared with 927.7 g/crown in the black plastic. Within the plastic treatments, the clear plastic returned the smallest marketable yield (699.2 g/crown). Marketable yield in the second and third picks were less than 200 g/crown across the trial but showed no significant difference between the treatments and the control plants. The control crop was relatively consistent in its marketable yields between the three harvests (116.2, 157.9 and 149.7 g/crown respectively) unlike the plastic treatments which showed significant reductions in yield in the later harvests (**Figure 13**). The proportion of marketable yield compared with gross yield was also significantly lower across the three harvests in the control crop compared with the plastic treatments (p = 0.034): while the proportion of marketable yield in the plastic treatments ranged from 68 – 79%, only 44% of the gross yield of the control gross harvest was marketable (**Table 4**). There was a significant harvest/treatment interaction on marketability (p = 0.001) which reflected the significant decline in the proportion of marketable produce across all treatments in the second harvest, but this is most likely an artefact of the selective harvesting process used in the first instance as opposed to a treatment or harvest effect.

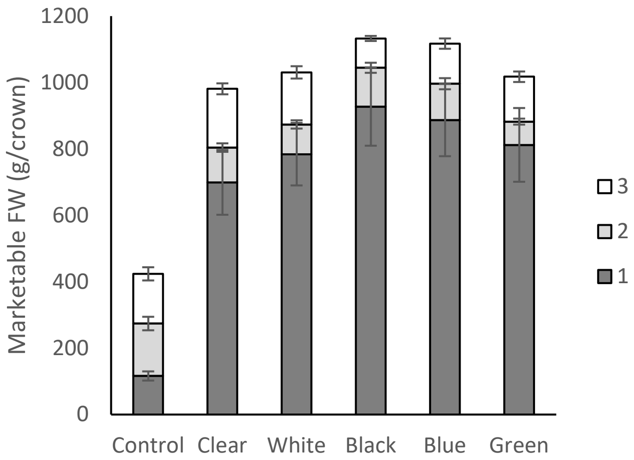

Figure 13. Marketable yield outputs for the first, second and third harvests, averaged per crown. Marketable yield from the control plots were significantly lower than those achieved in the plastic treatments, although there was no significant difference within the plastic treatments.

Table 3. Marketable and Unmarketable Yields, and proportion of marketable produce, for the first, second and third harvests and total yields over the trial period.

	Marketable Fresh Weight per Crown (g)			
Treatment	Harvest 1	Harvest 2	Harvest 3	Total
Control	116.2 (±13.8)	157.9 (±20.3)	149.7 (±19.8)	423.7 (±86.4)
Clear	699.2 (±97.6)	104.8 (±12.8)	177 (±16.5)	892.5 (±251.4)
White	784.2 (±94.2)	89.5 (±12.5)	156.8 (±18.6)	991.3 (±187.7)
Black	927.7 (±118)	116.7 (±15.2)	88.3 (±7.6)	1088.5 (±291)
Blue	886.8 (±108.7)	109.6 (±16.8)	120.8 (±15.6)	1117.2 (±215.3)
Green	812.1 (±111)	70.1 (±9)	135.1 (±15.8)	983.5 (±322.2)

	Unmarketable Fresh Weight per Crown (g)			
Treatment	Harvest 1	Harvest 2	Harvest 3	Total
Control	13.7 (±1.7)	28.7 (±5.9)	468.5 (±59.8)	510.9 (±49.5)
Clear	79.3 (±13)	57.8 (±18.4)	210.9 (±31.7)	242.6 (±65.1)
White	177 (±21.6)	68 (±29.4)	318.3 (±61.1)	483.8 (±117.2)
Black	158.7 (±21.8)	109.3 (±34)	229.3 (±50.2)	382.7 (±73.7)
Blue	107.1 (±14.7)	86.9 (±23.9)	267.8 (±57.6)	461.9 (±86.3)
Green	65.1 (±8.9)	32.5 (±12.7)	307.4 (±40.8)	328.1 (±82.1)

	Percentage of Marketable Yield (%)			
Treatment	Harvest 1	Harvest 2	Harvest 3	Total
Control	89.8 (±10.4)	14.4 (±1.8)	77.2 (±9)	44.2 (±11.1)
Clear	91.2 (±10.5)	30.6 (±3.8)	56.1 (±4.9)	79.5 (±19.8)
White	81.6 (±9.4)	49.7 (±6.1)	67.5 (±6.8)	68.2 (±16.8)
Black	86.4 (±10)	49.9 (±6)	71.7 (±5.9)	74.6 (±18.4)
Blue	90.4 (±10.4)	50.5 (±6.1)	68.4 (±7.9)	71 (±17.5)
Green	92.4 (±10.7)	32.4 (±3.8)	71.4 (±7.3)	71.3 (±18.1)

Yield outputs showed strong variation within and between treatments. The black plastic treatment showed the smallest number of petioles per crown, but there were no significant differences between in crown per head (**Figure 11**). Despite this, significant differences where seen in total fresh weight harvested between treatments (**Figure 12**). Greatest FW was harvested from the blue plastic (1579 g/crown) which exceeded that seen in both opaque treatments (1471 and 1475 g/crown from black and white respectively). The smallest total FW harvested was recovered from the clear plastic and control (1135 and 935g/crown respectively). The proportion of FW harvested differed between harvests, and there was a significant interaction between harvest and marketable fresh weight (p = 0.024). For the plastic treatments the greatest proportion of FW was seen in the first harvest, while the largest proportion of the untreated control was sampled in the last harvest (**Figure 14**). The marketable proportion of petioles harvested varied within treatments and between harvests. However, the proportion of marketable petioles in the control plots (44.2% of total by FW) was significantly less (68.2 – 79.5%) in the plastic treatments (p = 0.03). Summary harvest data is given in **Table 4**.

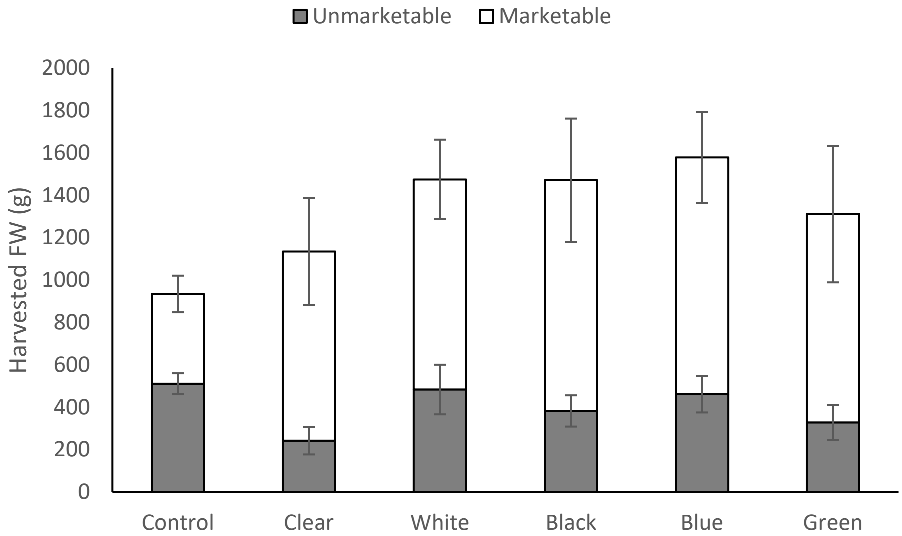

Figure 14. Proportions of marketable and unmarketable FW from combined harvests across the trial. In addition to reduced gross yield in control plots, the proportion of marketable yield was significantly reduced in the control plots relative to the plastic treatments.

Table 4. Summary harvest data. Average values for petioles per crown, marketable, unmarketable, and total FW, and percentage marketable for harvests 1, 2 and 3, and total.

	Harvest	1	2	3	Total
Petioles per Crown	Control	37.7 (±4.4)	33.6 (±3.9)	42.9 (±5.1)	114.2 (±28.3)
	Clear	46.9 (±5.5)	35.3 (±4.1)	36.3 (±3)	100.3 (±25.2)
	White	34.5 (±4.1)	28.1 (±3.4)	27.1 (±3.2)	82.9 (±22.7)
	Black	35.1 (±4.1)	24.6 (±2.8)	21.8 (±1.8)	70.6 (±17.8)
	Blue	32.4 (±3.8)	30.8 (±3.6)	38.3 (±4.5)	101.4 (±25.1)
	Green	30.9 (±3.7)	28.7 (±3.3)	41.8 (±4.3)	90.9 (±23.8)

	Harvest	1	2	3	Total
Marketable Fresh Weight per Crown (g)	Control	116.2 (±13.8)	157.9 (±20.3)	149.7 (±19.8)	423.7 (±86.4)
	Clear	699.2 (±97.6)	104.8 (±12.8)	177 (±16.5)	892.5 (±251.4)
	White	784.2 (±94.2)	89.5 (±12.5)	156.8 (±18.6)	991.3 (±187.7)
	Black	927.7 (±118)	116.7 (±15.2)	88.3 (±7.6)	1088.5 (±291)
	Blue	886.8 (±108.7)	109.6 (±16.8)	120.8 (±15.6)	1117.2 (±215.3)
	Green	812.1 (±111)	70.1 (±9)	135.1 (±15.8)	983.5 (±322.2)

	Harvest	1	2	3	Total
Unmarketable Fresh Weight per Crown (g)	Control	13.7 (±1.7)	28.7 (±5.9)	468.5 (±59.8)	510.9 (±49.5)
	Clear	79.3 (±13)	57.8 (±18.4)	210.9 (±31.7)	242.6 (±65.1)
	White	177 (±21.6)	68 (±29.4)	318.3 (±61.1)	483.8 (±117.2)
	Black	158.7 (±21.8)	109.3 (±34)	229.3 (±50.2)	382.7 (±73.7)
	Blue	107.1 (±14.7)	86.9 (±23.9)	267.8 (±57.6)	461.9 (±86.3)
	Green	65.1 (±8.9)	32.5 (±12.7)	307.4 (±40.8)	328.1 (±82.1)

	Harvest	1	2	3	Total
Total Fresh Weight per Crown (g)	Control	129.9 (±15.5)	186.6 (±24.5)	618.2 (±73.3)	934.7 (±121.9)
	Clear	778.6 (±110.2)	162.6 (±20.8)	193.9 (±32.2)	1135.1 (±293.6)
	White	961.2 (±115.5)	157.5 (±20.2)	356.3 (±55.1)	1475.1 (±304.1)
	Black	1086.4 (±139.6)	226 (±28.5)	158.8 (±27.7)	1471.2 (±405.6)
	Blue	993.9 (±122.9)	196.5 (±28.2)	388.6 (±51)	1579 (±319.3)
	Green	877.2 (±119.6)	102.5 (±13.1)	331.9 (±46.2)	1311.6 (±366.4)

	Harvest	1	2	3	Total
Percentage of Marketable Produce (%)	Control	89.8 (±10.4)	14.4 (±1.8)	77.2 (±9)	44.2 (±11.1)
	Clear	91.2 (±10.5)	30.6 (±3.8)	56.1 (±4.9)	79.5 (±19.8)
	White	81.6 (±9.4)	49.7 (±6.1)	67.5 (±6.8)	68.2 (±16.8)
	Black	86.4 (±10)	49.9 (±6)	71.7 (±5.9)	74.6 (±18.4)
	Blue	90.4 (±10.4)	50.5 (±6.1)	68.4 (±7.9)	71 (±17.5)
	Green	92.4 (±10.7)	32.4 (±3.8)	71.4 (±7.3)	71.3 (±18.1)

2.8.3 Quality Measurements

Besides yield outputs, quality parameters were also explored to identify the impact of the treatments on harvested produce. Treatment had a significant impact on petiole length, width, and depth (*p* = <0.001, 0.029, 0.003 respectively). Harvest number did have a significant effect, although there was no significant interaction between harvest and treatment, so the observed differences are liable to be due to the selective nature of the harvest. Therefore, all samples were combined in a single analysis of size dimensions. Petioles recovered from the clear and control plastics were significantly shorter when compared with the other plastic treatments 286mm and 292mm compared with an average petiole length of 335mm in the other plastic treatments (**Table 5**; **Figure 15**). Within the plastic treatments there were no significant differences between the blue/green plastics (324mm and 321mm respectively, *p* = 0.334) and the white/black opaque plastics (352 and 343mm respectively, *p* = 0.661), although there was a significant difference between petiole lengths between these two group (*p* < 0.001). For the petiole cross section, there were significant differences between treatments for both the petiole width and depth (*p* = 0.029 and 0.003 respectively). In both instances the control petioles were wider and thicker than petioles harvested from the plastic treatments – control petiole dimensions were 21.8 x 15.8 mm compared with 19.6 x 14.3mm averaged across the plastic treatments (**Table 5**; **Figure 15**). Within the plastic treatments there was no significant difference between treatment effects on width, although differences were seen in petiole depth (*p* = 0.002) – petioles grown under the blue plastic were marginally thicker than those measured from other plastics, with the thinnest petioles harvested from the black opaque plastic. A general inverse relationship is seen between petiole length and width/depth: thinner, longer petioles were produced in the plastic treatments compared with the unprotected control – opaque plastic grown petioles were over 20% greater in length than the open-grown control.

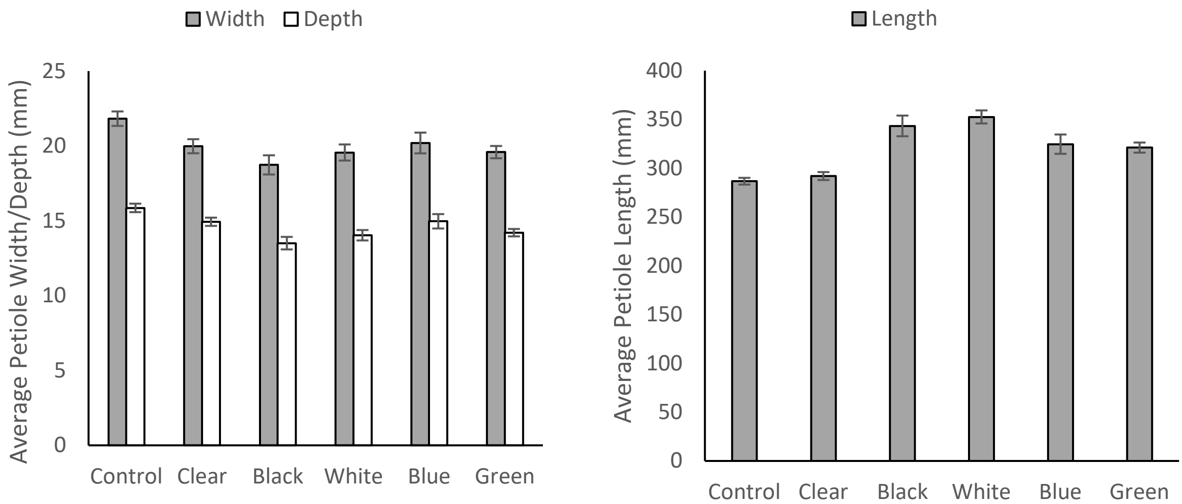

Figure 15. Average petiole length, width and depth as recorded across the trial.

Table 5. Summary figures for petiole and leaf dimensions from samples collected across the trial.

	Petiole			Leaf	
Treatment	Length (mm)	Width (mm)	Depth (mm)	Length (mm)	Width (mm)
Control	286.7 (±3.4)	21.8 (±0.5)	15.9 (±0.3)	258.1 (±8.1)	290.7 (±9.5)
Clear	292.0 (±4.1)	20.0 (±0.5)	14.9 (±0.3)	300.2 (±9.8)	321.1 (±10.8)
Black	343.4 (±10.6)	18.7 (±0.6)	13.5 (±0.4)	205.0 (±6.0)	186.2 (±7.2)
White	352.6 (±6.7)	19.6 (±0.5)	14 (±0.3)	194.1 (±6.0)	178.3 (±6.0)
Blue	324.7 (±9.9)	20.2 (±0.7)	15 (±0.5)	277.7 (±9.2)	323.3 (±27.8)
Green	321.2 (±5.2)	19.6 (±0.4)	14.2 (±0.2)	284.5 (±8.2)	294.7 (±9.0)

In addition to petiole dimensions, leaf length and width were examined. Leaf length and width was significantly different between treatments (p <0.001) predominately as a result of the low level of leaf expansion seen in the black and white plastic treatments (**Table 5**). An analysis of those treatments where some light was available to the crop (the control, clear, blue and green plastics) showed no significant difference between leaf width, although a significant difference between leaf length within this group (p = 0.010). The reduced leaf dimensions of the opaque plastics compared this the other treatments are indicative of the reduced leaf blade development seen in these conditions.

2.8.4 Leaf Blade Development

Development of the leaf blade was explored through two additional routes. The quantification of chlorophyll through a spectrographic technique (SPAD) provides an indication of the leaf blade greening up (**Figure 16**). There was a significant difference in SPAD value between treatments (p <0.001) as the average SPAD values for black and white opaque plastics (24.7 and 24.9 respectively) was lower than that seen in the other plastic treatments and the control (37.7 on average). There was no significant difference in SPAD values between the other plastic treatments and the control indicating that leaf greening was comparable in these treatments.

In addition to the SPAD value, leaf blade development was quantified as a proportion of dry matter accumulated in the leaf blade relative to the entire leaf section (leaf blade and petiole). A comparable relationship between treatments was seen as leaf chlorophyll development (**Figure 16**). The black and white opaque plastics achieved 44.1% and 45.6% dry matter accumulation in the leaf blade partition, compared with 50 – 60% in the other treatments (p = 0.012) , although there was no significant difference between the other plastics and the control.

Therefore, based on these parameters only the opaque plastic had an impact on leaf blade development, with reduced chlorophyll development and dry matter investment in the leaf.

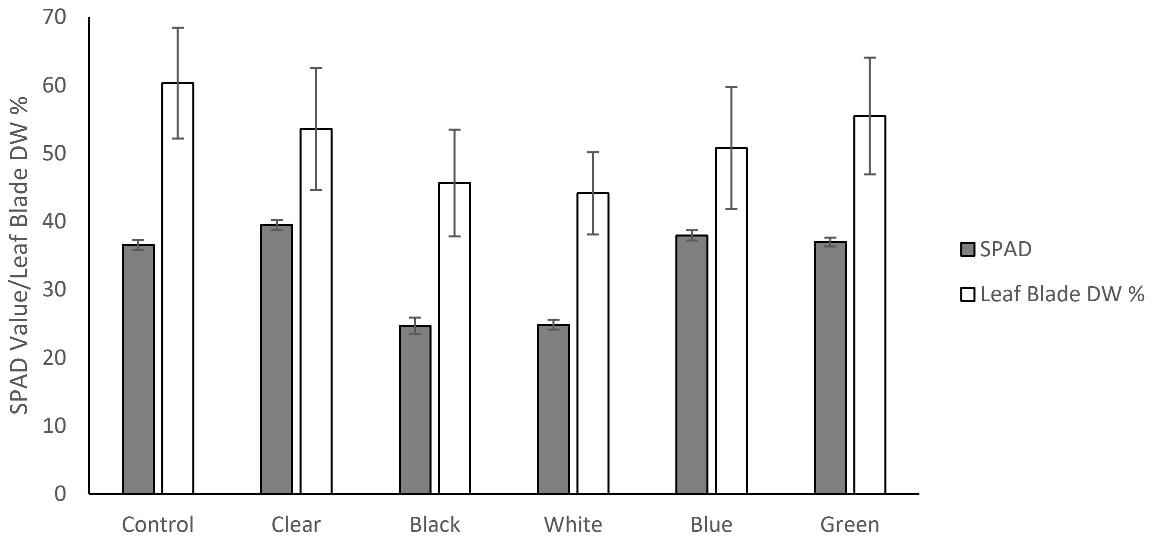

Figure 16. Leaf blade development in response to treatments as expressed by average chlorophyll content (SPAD value) and dry matter allocation to the leaf blade (Leaf Blade DW %).

2.8.5 Petiole Quality

Petiole quality was examined through two routes: colour and texture. Petiole colour demonstrated significant differences between treatments (**Figure 17**) at the top, middle and bottom positions (p <0.001 in each instance). The change in colour along the petiole was least pronounced in the black/white opaque plastics, which maintained red pigmentation at all three positions. The control and clear plastic treatment showed comparable red intensities, with green pigmentation developing only at the top of the petiole. The green and blue plastics showed a similar pattern of pigmentation to the clear plastic/control plots with a decrease in red colouring from the base to the top of the petiole, with significant greening in the top potion. While the pattern was comparable, the extent of green colouring in the blue and green plastics was significantly more advanced when compared with the clear and control treatments. The depth of red pigmentation at the mid-section of the blue and green plastics was significantly reduced compared with the other treatments, while the depth of green colour in the top section was far advanced compared with the other treatments, exceeding that of even the clear and control plastics. Based on these data it is evident that only the opaque plastic treatments could suppress any green development in the petioles, matching the reduced development of the leaf blade itself. Colour intensity of the blue and green plastic treatments was weaker compared with that of the control petioles. Normal commercial specifications require a minimum of 50% red on the petiole, and no petioles harvested in this trial were outside of these criteria. Representative photographs of harvested petioles are given in **Figure 19** below.

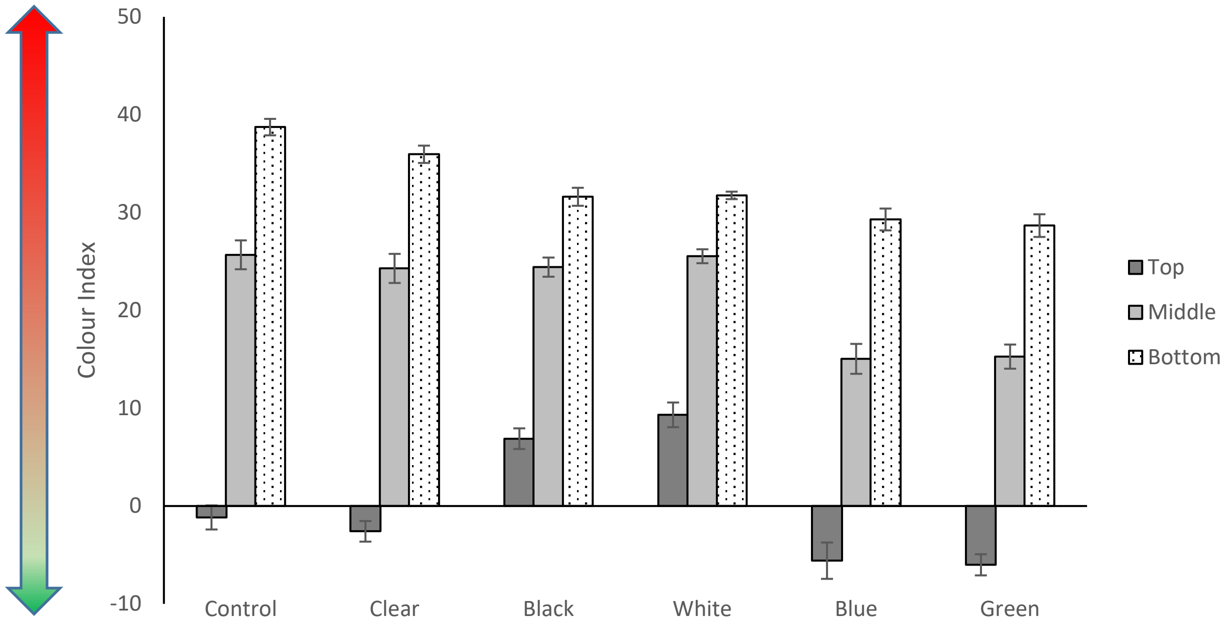

Figure 17. Petiole colour index measured at the top, middle and bottom petiole position. A more positive colour index indicates increasing red, lower (or negative) colour index value indicates a stronger green colour.

In addition to colour, petiole texture is also of market relevance, with soft petioles being desirable. Average shore value of the untreated control crop was significantly greater than that seen in the plastic-treated crops (p = 0.002) although there was no significant difference between the plastic treatments. (**Figure 18**). This indicates that the texture of the petioles harvested under plastic are significantly softer than that seen in the field grown crops.

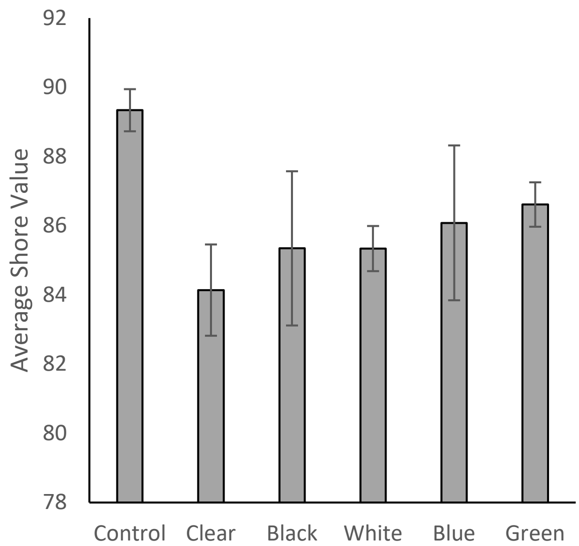

Figure 18. Average petiole texture of marketable petioles harvested over the trial. An increased Shore value indicates a firmer texture. Average petiole texture in the control crop was firmer than that seen in those grown under plastic, although there were no significant differences between petioles from plastic treatments.

Untreated Control

Clear Plastic

Black Opaque

Blue Plastic

Green Plastic

White Opaque

Figure 19. Photographs of representative sticks harvested from each treatment.

2.8.6 Microclimate Modification

Use of plastic covers is liable to have had a significant impact on the microclimate that the crop was exposed to. Data loggers were placed in a representative plot of each treatment type, together with a background logger to monitor temperature and relative humidity (RH) every 30 minutes across the trial. Average daily temperatures were highest in the clear plastic (9.5°C) and blue plastic treatments (9.1°C) compared with the open field control (8.7°C). The opaque plastic treatments showed the coolest temperatures (8.1 – 8.4°C) which were comparable if not below that of the open field (**Figure 20**). Night temperatures were relatively comparable between the treatments, but the increased day temperatures of the plastic resulted in the largest day/night variation between the plots. The opaque plastics were likely to be cooler due to direct absorption of light by the plastic rather than transmission into the interior during the day limiting warming. Conversely, the high light transmission of the clear plastic allowed it to achieve proportionately greater temperatures and this may have accelerated growth within.

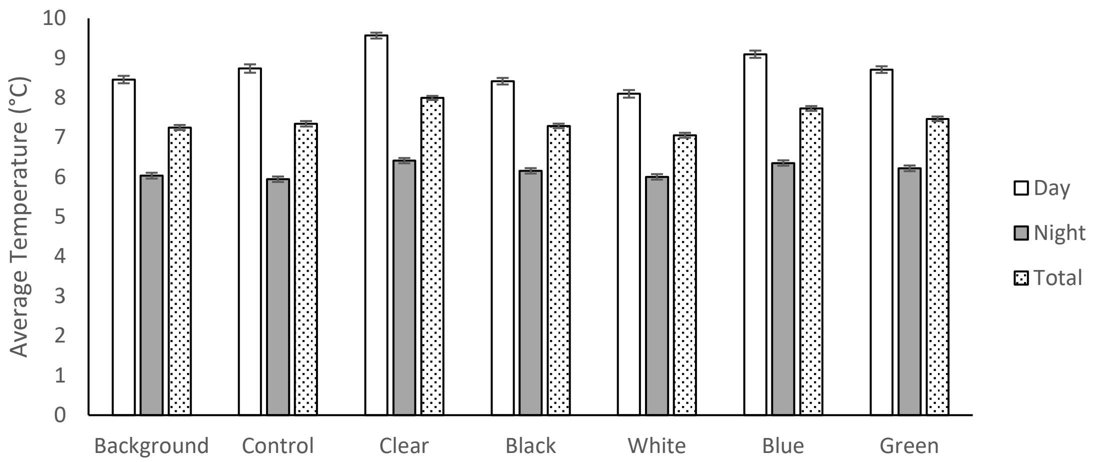

Figure 20. Average day, night and whole day temperatures recorded in a representative tunnel of each treatment of the course of the trial.

Temperatures were marginally warmer under plastic with the plastic treatments averaging 406 °C Days between the 17th February and 7th April compared with only 386 °C Days in the open field. However, the black and white opaque plastics were cooler (389 and 363 °C Days respectively) while the clear, blue, and green plastics were considerably warmer achieving 449, 423 and 405 °C Days respectively. RH was relatively comparable between the plastic treatments, although the RH of the opaque plastics was considerably higher than that achieved in the other plastics (**Figure 21**), and may be reflective of the cooler temperatures seen in these plastics. This may increase the risk of disease development in the crop, although no significant increases were seen in this project. However, the increase in RH is relatively minor and given that no significant disease issues were reported in the trial this is considered to not have had an impact on the yield outputs, at least over the duration of the trial.

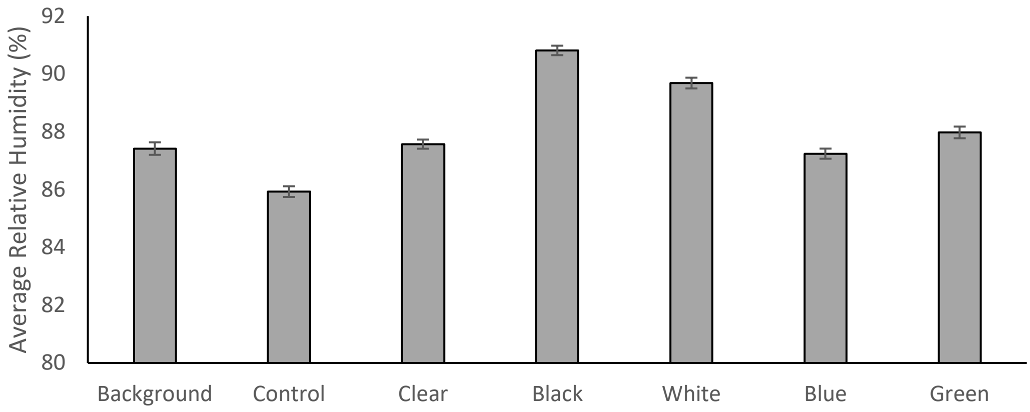

Figure 21. Average daily relative humidity values recorded over the course of the trial.

2.8.7 Light Quality and Plastic Lifespan

An additional aspect of this project was to examine the likely longevity of the plastic products as part of a viability of their use in long-term production. To address this, the achieved spectrum achieved by the plastics used in this trial the light spectrum achieved by each was measured on the 4th May at 9am in full sunlight. The achieved light quality of each plastic was determined by measuring the absolute irradiance of direct sunlight with and without a plastic sample placed over the aperture of a WaveGo spectrophotometer. Both new unused plastic and plastic taken from a sample after the completion of the trial. Observed spectra are given in **Figure 22**. The clear plastic treatment showed near-perfect transmission, with no significant differences between direct sunlight and that measured under clear plastic. The blue and green plastics achieved the proposed adjustments in spectra showing an uplift in in the blue and green regions of the spectrum respectively. The UV section of the spectrum <400nm was also comparatively enriched compared with that achieved in the clear and green plastics. The blue plastic achieves c. 80% transmission between 400 – 500nm, reducing to 20-30% outside of this peak, while the green plastic achieved c. 85% transmission between 450 – 600nm, reducing to 40 – 50% outside these ranges in the manufacture's results. These ranges correspond to the observed spectra achieved in this trial.

While it is not possible to fully quantify transmission of these plastics due to uncertainty in incoming light intensity (in order to achieve the full spectrum of sunlight as opposed to more restricted spectra of constant artificial light sources), minor inferences of transmission may be suggested by these results. The clear plastic showed a high level of transmission, corresponding to the manufacture's reporting of >90% transmission across all spectra, while the suggested reduction in transmission seen in the blue and green plastics correspond with the manufacturer's measurements. The black/white opaque plastic was examined but showed no identifiable light transmission using this method of measurement, indicating a high level of light quenching.

There were no significant age-related effects evident between the achieved spectrum of each plastic, with new and old plastic showing comparable spectra in each case. These data may suggest that the clear and blue plastics suffered a minor reduction in overall transmission with age, most likely as a result of dust, dirt or scratches impacting the surface of the plastic although the extent and significance of these cannot be fully explored at this stage. However, based on these data it is considered likely that the plastic could be used for subsequent seasons without suffering any significant reduction in observed effects.

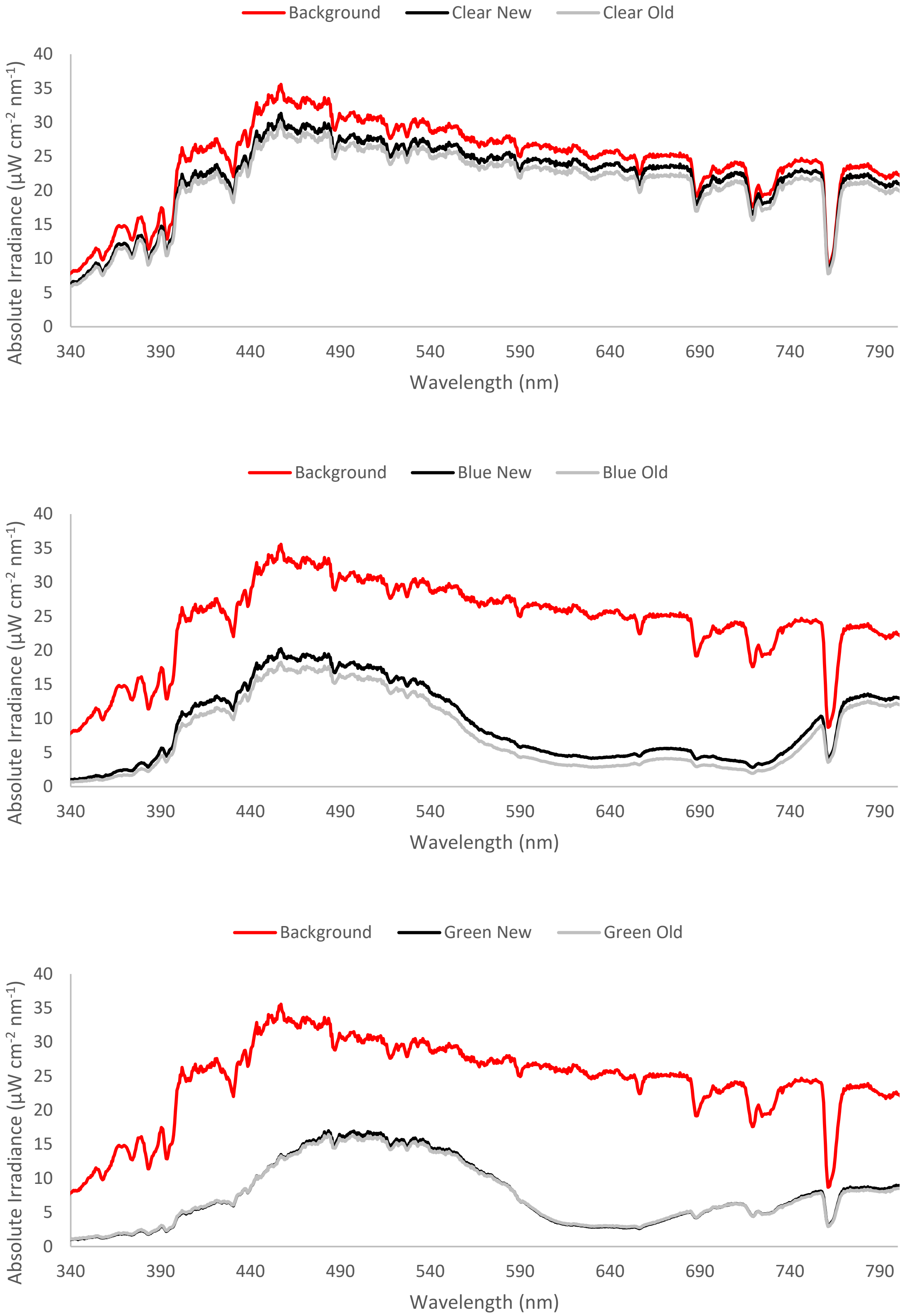

Figure 22. Observed spectra of plastic treatments. The absolute irradiance of direct sunlight achieved after transmission of both new and old plastics are plotted alongside the spectra of unfiltered sunlight. Data collected in full sunlight on the 4th May and 9.30 am, ADAS Boxworth, Cambridgeshire.

2.9 Discussion

This project sought to examine the potential for plastic protection to improve the profitability of field grown rhubarb by two key routes. Firstly, it sought to quantify the impact of field-forcing under opaque plastic following a current (if uncommon) commercial practice. Secondly, the impact of light-modifying photoselective plastics were tested as a way of improving outputs without resorting to near-complete darkness required for field forcing. Both methods we compared against open-field and clear-plastic grown rhubarb to separate the impact of the changes in microclimate liable to be seen with the plastic treatments.

Opaque Plastic

Opaque plastic was included in this trial in two conformations – white out and black out – because of potential changes in microclimate as a result of these two confirmations. The black-out plastic did show marginally warmer temperatures than the white-out plastic (0.3°C day, 0.1°C night) but this temperature range was relatively comparable with background levels although both the white and opaque plastics were marginally cooler during the day than the other plastics. The lack of significant microclimate difference between these two treatments is reflected in the lack of significant difference between measured responses between the two treatments, implying that either confirmation could be used with equal effect.

As shown in **Figure 10** and **Figure 19** petioles recovered from the opaque plastic treatments had a markedly different habit to conventional forced rhubarb, showing petiole and leaf greening with limited leaf development – this is reflected in the insignificant differences in leaf dry weight in the opaque plastics compared with the other treatments (**Figure 16**). However, it is possible that petioles are initiated with a high proportion of dry matter already present in the juvenile leaf prior to expansion so the comparable leaf content may not be truly indicative of a slowing of leaf development. The significantly lower SPAD measure for the opaque plastics (**Figure 16**) would indicate the leaf development has been reduced to some extent when compared with the lit treatments.

It is likely that the more advanced development of field forced rhubarb compared with shed forced is due to the inability to completely exclude light from the growing environment. It may be difficult to achieve full quenching of outside light from the tunnels, and the crop will be periodically exposed as the covers are removed to access the crowns for harvest. Therefore, incidental light exposure is likely to trigger normal morphogenesis leading to more typical development. This may also introduce the risk of higher proportions of bent/curved petioles if the developing petioles bend towards light cracks in the plastic coating, although this could be mitigated by digging in the plastic on either side of the tunnel as is more commonly practiced in field forcing as opposed to the above-ground tunnel structures used in this experiment.

In terms of yield output, the black opaque plastic gave the second greatest marketable yield output of the treatments, and both the black and white plastics gave marketable yields more than double that of the untreated control. The greatest proportion of the yield was achieved in the first harvest, rather than the last harvest three weeks later seen in the open control plots (**Figure 13**). Data is not available as to the whole season yield as it is likely that subsequent harvests over the next six to eight weeks could be made. Stockbridge House variety trials suggest yields of around 44.2 tonnes/ha for Timperley Early – based on these data only 6.3 tonnes/ha (open control) of 14.8 / 16.3 tonnes/ha (white/black respective, assuming 15k crowns/ha) were harvested in this trial. This means that while total yields are likely to be greater across the whole season, we were able to significantly bring forward the timing of the harvest through the use of opaque plastics.

As discussed above there were some instances of twisting in the opaque plastics most likely because of light bleeding in. There was also a minor but noticeable increase in leaf rots, most likely because of the high humidity seen in the tunnels. However, these aspects did not have a significant impact on the proportion of the marketable produce in the opaque plastics which recovered a marketable percentage comparable with the other plastic treatments (and significantly exceeding that seen in the open field control). In terms of marketable quality petioles from the opaque plastics showed a generally high level of market quality. Petiole length was significantly greater in the opaque plastics compared with the other treatments and open field control, and the petioles were narrower and thinner than the open field control, and slightly narrower than the other plastic treatments (**Figure 15**). The colour the opaque treatments showed a much stronger pigmentation across the length of the petiole than the other treatments, with a positive colour index (indicating a red colour) at all three petiole positions unlike the other treatments (**Figure 7**). The opaque plastics also showed significantly tenderer petioles compared with the untreated control (**Figure 18**).

Taken holistically, using opaque plastics to produce field-forced rhubarb offers a variety of benefits over conventional field-forced rhubarb. Greater yield volumes can be achieved earlier in the season, and with produce of a greater quality when compared with open field grown rhubarb. While the petioles are not at the same quality level as forced rhubarb (most likely because of light penetration and variable temperatures) these may represent a half-way position between green pull and forced rhubarb.

Clear Plastic

The clear plastic treatment was included to test whether the impact of plastic use on rhubarb production was due to light-mediated effects or other impacts of tunnel use such as microclimate modification that may impact yield output. Marketable fresh weight was increased in the clear plastic treatment compared with the open-field control (0.89kg/crown vs. 0.42kg/crown), and the timings of peak harvest were earlier than the open-field production, similar to that of the other plastic treatments. The clear plastic treatment also showed a high level of marketability, indicating that similar benefits in yield quality were achieved by the clear plastic compared with the other plastic treatments. However, petiole length in the clear plastic was significantly less than that seen in the other treatments and was comparable to that of the open field control – 29.2cm compared with 32.1 – 34.3cm in the plastic treatments (**Table 5**). Petiole colour was comparable to the open field control, with petioles not seeing as advanced greening seen upper portions of petioles from the blue/green plastics (**Figure 17**). Interestingly, the clear plastic petioles showed the softest texture on average (**Figure 18**). The mixed influence of the clear plastic suggests that the impact of plastic covering for rhubarb may have an impact on a variety of levels. The lack of any specific light-related influence in this treatment (either in intensity or quality) coupled with an increased yield output would suggest that protection increases crop responses through an alternate route. As discussed in **Section 2.8.6** the achieved temperature of the clear plastic was significantly warmer than the open-field plot, and so the increased rate of yield production here may correspond with a simple acceleration of growth as a result of the warmer soil and air temperatures under protection.

Blue Plastic

Of the plastics allowing light transmission, the blue plastic demonstrated the greatest overall impact. The marketable yield of the blue plastic exceeded that of the clear and green plastics (1.11kg/crown vs. 0.92kg and 0.98kg respectively) and was more than double that of the open field control over the same period (**Table 3**). Compared with the opaque plastics, marketable yield was comparable. Similar to the opaque plastics the blue plastic treatments showed a comparatively high level of marketable yield exceeding that of the open field control (**Figure 13**) while giving the greatest proportion of its yield in the first harvest rather than low, flat line yields seen in the open field control (**Figure 12**). Assuming a density of 15k crowns/ha, the blue plastic would have achieved marketable yields of 16.75 tonnes/ha compared with 6.3 tonnes/ha in the open field control.

Petiole length was comparable between the blue and green plastic treatments, and while these were less than the opaque treatments they still exceeded that seen in the clear plastic and open field treatments by 32mm and 38mm respectively, although there was no significant difference in petiole width/depth (**Table 5**). In terms of colour the blue plastic-treated petioles showed a weaker red colouring than the control, clear or opaque plastics – the lower colour index at the base and top of the petiole indicates and overall weaker red when compared with the controls (**Figure 17**). However, at least two thirds of the petiole remained red at harvest, meaning that the marketability of the crop was not impacted by a high level of petiole greening.

Similar to the clear plastic, the blue treatment also recorded an increase in temperatures most likely due to an insulating effect of that plastic warming the air and soil around the crop. These results may be interpreted to show that the blue plastic effects were purely due to temperature alone based on this similarity. For example, the blue plastic treatment showed no significant difference in leaf blade development (in terms of dry matter accumulation or SPAD value) compared with the clear plastic or control treatments (**Figure 16**). This would suggest that leaf blade development has not been curtailed (as seen in the opaque treatments).

However, the blue plastic treatment was capable of driving elongation of the petioles, giving an additional 3cm of length compared with the control plots as discussed above, as well as giving a greater average marketable yield than the clear plastic alone. This would imply that the treatment was having some impact on the development of the crop, promoting them to elongate to a greater extent seen in the controls. The lack of a comparable elongation in the clear plastic treatment, and greening up of the petioles in the blue plastic treatment suggests this is not due to microclimate changes (e.g. a warmer environment driving growth faster) and is instead due to changes in the crop responding to the changes in received light instead.

Green Plastic

Performance of the green plastic was relatively comparable to that of the blue plastic treatment, although the average marketable fresh weight per crown was marginally lower at 0.98kg/crown compared with 1.11kg/crown for the blue plastic, although this difference was not statistically significant. Yield outputs also showed comparable timings with the most significant proportion in the first harvest, and comparably high proportion of marketable yield with the plastic treatments. In terms of quality the green plastic treatment was also similar to the blue plastic treatment – petioles were longer than the clear plastic and open-field controls, but did not show the same elongation as that seen in the opaque plastics, and similar levels of petiole greening were seen green and blue treatments. Given the achieved spectra presented in **Figure 22** the green plastic achieved relatively comparable transmission as the blue plastic except with reduced transmission in the 400 – 425nm range. These data confirm the manufacturer's spectra given in **Figure 5**/**Figure 6** – although it should be noted the measurement range of the data presented in **Figure 22** does not extend below 340nm so the increased transmission around 250 – 300nm of the green plastic compared with the blue given in cannot be fully explored. While these plastics differ in transmission at the shorter end of the spectrum, transmission in the main visible section is largely comparable. As discussed above the shorter end of the spectrum was linked with pigment development, while the red region was linked with morphological development through distortion of the red:far red ratio. Given that both the blue and green plastics seen an increase in petiole length (32.4/32.1cm respectively compared with 28.6cm in the open field control) it is considered that the adjustments to the red portion of the spectrum that are common to both treatments may be triggering the observed petiole elongation.

2.9.1 Economic Aspects of Plastic Use

In terms of marketable yield output, the use of plastic protection for field rhubarb production allowed yields to be 2.1 – 2.6x that of open field production over the period of the trial between February and March. This may not correspond to an increase in overall yield, this marks a significant increase in productivity early in the season. Based on the data presented in **Figure 1** there is around a 30% decrease in green pull rhubarb value between March and April, so brining forward the crop outputs by a month may allow growers to achieve a significantly greater value for their crops. For growers without forcing facilities this may offer the ability to bring forward the season offering produce to customers from earlier in the season. This may also bring forward later harvests, potentially allowing a second pull to be made in April rather than mid-May in open field-grown Timperley Early – there a further decline in market value between April and May of around 20% (**Figure 1**) so promoting earlier crop would continue to be of benefit in helping growers better match customer demands. An earlier second pull may allow the crop to regenerate further in the late reason, reducing the risk that the crop will need to be idled in the following season as it will have been able to recover its strength more than a later-pulled crop before the onset of winter dormancy.

The use of tunnels may also have impacts on other aspects of production. For example, cultivation under plastic may help to reduce weed pressure (especially in opaque plastics) as weed establishment may be distributed. Crop access for plant protection product application, or for top dressing of nutrients after the first pull, maybe hindered if the tunnels are in place for a significant period of time. While no significant disease pressures were observed in this trial, warmer temperatures are likely to exacerbate any disease development with prolonged tunnel use so this may need to be taken into consideration.

Between the blue and opaque plastics relatively comparable results were obtained in terms of yield output and produce quality. Blue plastic is around 20% more expensive than comparable lengths of opaque plastic, so based on these results there may not be the financial case for the use of photoselective plastics over opaque plastics in the short term. However, it is likely that the use of blue plastic is less draining on the crown compared with near-complete darkness in opaque film. For the data given in **Figure 21** the blue plastic was achieving photosynthetically active radiation (PAR) levels around 170 µmol m^{-2} s^{-1} compared with 380 μmol m^{-2} s^{-1} in the unfiltered background at the time of measurement (for reference full midday sun will produce PAR levels approaching 1500 μmol m^{-2} s^{-1} although photosynthesis is typically saturated around the 1000 - 1200 μmol m^{-2} s^{-1} level). While measurements errors and distortions of the spectral composition preclude direct comparison of these values this indicates that an appreciable level of PAR was being transmitted through the plastic, allowing the developing leaves to carry out some level of photosynthesis – this is reflected in the appreciable accumulation of chlorophyll as measured by the SPAD value (**Figure 15**). This is contrast to the opaque plastic treatments where PAR values were approaching 0. Therefore, it is likely that the blue plastic-treated crowns were able to supplement crown sugar stores with newly synthesised sugars as the leaves expanded as would normally be seen in a green-pull crop allowing marketable yield to be achieved without placing as significant a drain on the crown as would be seen in opaque treatment. Therefore, it is possible that the use of blue plastic may offer a route to unlocking the benefits of plastic use (e.g. increased petiole elongation, earlier harvests) without having as draining an effect on the crown as opaque plastic, potentially increasing yields either within a season by providing additional sources of sugars, or by supporting so the crown so that an appreciable harvest may be produced in the following season and this may be sufficient to justify the additional expenditure on the blue plastic treatment as opposed to the opaque plastic. Due to the limited length of this trial (particularly because of the reduced window of activities due to the covid-19 epidemic) it has not been possible to examine this area fully but is worth considering for further exploration.

2.10 Conclusions

The project sought to explore the impact of photoselective plastics on rhubarb production. The evidence obtained has demonstrated that the use of plastics can have a positive impact on rhubarb productivity by bringing forward the season, enabling greater yields to be accessed when inherent market value is likely to be greater due to consumers seeking to access as earlier a UK supplier as possible. While it has not been possible to fully demonstrate the impact of this approach on early season rhubarb production as effects may continue from one season into the next due to the perennial nature of the crop, this project has demonstrated that plastic use in rhubarb production may have the potential to aid growers in adjusting their periods of peak productivity to better align harvests with market demand, increasing the profitability of their production. The use of photoselective plastics has been shown to have comparable effects on produce quality as field-forcing with opaque plastic, while potentially providing sufficient light for an appreciable amount of productivity to occur in the developing leaves, unlike field-forced crops. This may improve yields within a season or reduce crown fatigue allowing productivity in the following season to be enhanced. While it has not be possible to fully address this aspect in the current project, plastic use in field-forced rhubarb may have significant benefit to growers seeking to improve the profitability of field-forced rhubarb. While we have been able to demonstrate that plastic use can improve the profitability of early season rhubarb production, it is considered unlikely that there will be large-scale application of this approach, particularly when the cost of materials and installation are considered (although these would be spread a typical plastic lifespan of five years) they may provide a way for growers to bring forward a portion of their production, better meeting the needs of their customers by improving the continuity of supply.

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2.12 References

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