Final Report 2020-21

Efficacy of sprout suppressants used alone, or in combination, to control sprouting of stored potato

A. Briddon & G.P. Stroud

Sutton Bridge Crop Storage Research

Project Ref: 11140043

Contents

Efficacy of sprout suppressants either alone or in combination to control sprouting of stored potato

1. Introduction

Effective sprout control is critical to the year-round supply of ware potatoes and the industry has been largely reliant on chlorpropham (CIPC) for this. In official figures from 2016[1], CIPC accounted for 82% of treatments to stored potatoes, while ethylene and spearmint oil accounted for 15% and 3% respectively. The potato processing industry especially is dependent on the availability of effective growth regulators because storage at lower temperature (c. 3-6°C) cannot be used because of its effect on quality[2]. Minimisation of the potential for acrylamide formation has become an important consideration during storage of potatoes[3].

The EFSA routine review of CIPC, which should have completed in 2017, identified a number of data gaps and the European Commission recommended that the compound no longer be approved. The decision to not renew approvals was published on 18 June 2019 and all EU member states were required to withdraw approvals for formulations containing CIPC by 8 January, 2020. In the UK, the final use by date, determined by the Chemical Regulation Division of the Health and Safety Executive, was 8 October 2020. The 2020/21 potato storage season became the first when CIPC products were not generally available. Although it was possible for an early application to be made in October 2020, this was discouraged by the Potato Industry CIPC Stewardship Group because of uncertainty around when a new, lower

[1] Hinchcliffe, A., I. Barker, D. G. Garthwaite & G. Parrish (2016). Pesticide Usage Survey Team FERA, Pesticide Usage Survey Report 275, Potato stores in the United Kingdom. Sand Hutton, York YO41 1LZ, UK.
[2] Blenkinsop, R.W., Leslie J. Copp, Rickey Y. Yada, and Alejandro G. Marangoni (2002). Changes in compositional parameters of tubers of potato during low-temperature storage and their relationship to chip processing quality. Journal of Agricultural and Food Chemistry 50 (16),4545-4553.
[3] https://www.fooddrinkeurope.eu/wp-content/uploads/2021/05/FoodDrinkEurope_Acrylamide_Toolbox_2019.pdf

(temporary) MRL may come into force[4]. After 8 October 2020, it became illegal to store or use pesticide products containing chlorpropham.

The aim of this project was to investigate whether treatments using alternative sprout suppressants, or the combined use of alternatives, provided effective sprout control. After the loss of CIPC, products containing one of three active substances remain registered for control of sprouting in stored potatoes in the UK. The active substances are ethylene, maleic hydrazide and spearmint oil. They are generally considered less effective than CIPC, may have adverse effects on other qualities of the stored crop and, in all cases, are more costly[5].

In addition to the UK registered alternative sprout suppressants, applications of 1,4-dimethylnaphthalene (DMN, marketed as 1,4-SIGHT®[6]) and 3-decen-2-one (marketed as *SmartBlock®*[7]) were assessed.

DMN is available in many EU member states, and elsewhere, but it did not received registration in the UK prior to Brexit. The approval of DMN in the UK is ongoing. A limited emergency approval for DMN was granted in the UK, for specified processing varieties after long term storage in the 2020-21 storage season.

Hot fog applications of 3-decen-2-one were also assessed during storage. Marketed as *SmartBlock®* by the approval holder Amvac in the USA and elsewhere, registration is underway in the UK and the EU.

There is little data on the use of alternative (non-CIPC) sprout suppressants in the processing sector, and it is not clear current products, or combinations of products, can provide effective control in all potato storage scenarios where CIPC has been in use. This study was aimed at

[4] PICSG press release at http://www.cipccompliant.co.uk/uploads/fileman/Stewardship-q-a.pdf
[5] Kalt, W. , Prange, R. K., Daniels-Lake, B. J., Walsh, J. , Dean, P. and Coffin, R. (1999). Alternative compounds for the maintenance of processing quality of stored potatoes (Solanum tuberosum). Journal of Food Processing and Preservation, 23: 71-81.
[6] DormFresh Ltd, Algo Business Centre, Glenearn Road, Perth PH2 0NJ, Great Britain
[7] AMVAC Netherlands BV, Kosterijland 72, 3981 AJ Bunnik, the Netherlands

the assessment of potatoes stored for processing, a similar study for potatoes stored for the fresh-pack market is reported separately (AHDB Project Ref: 11140057).

2. Materials and methods

Crops, treatments and experimental design

Stocks of five processing cultivars, Innovator, Maris Piper, Performer, Royal and VR808, were each sourced from independent sites treated in the field with maleic hydrazide (MH) at 3 kg active substance per hectare. At each site four separate MH untreated plots were shielded from spraying using polythene sheeting pegged to the ground on all sides (Fig. 1). After spraying, the sheeting was left until dry and then carefully removed. The untreated strips and the follow-on MH treated rows were harvested by hand.

Fig. 1. Shielding ‘untreated’ plots from in-field application of maleic hydrazide.

During storage, the ten stocks (five varieties + and – MH) were subjected to further sprout suppressant regimes in separate six tonne capacity controlled environment rooms (CERs). The storage treatments were: 1,4-dimethylnaphthalene (DMN), 3-decen-2-one (*SmartBlock*®), ethylene (*Restrain*), spearmint oil (*Biox-M*), and untreated. Management software was set to ventilate stores to maintain a target maximum carbon dioxide concentration of 0.3%. Following applications, DMN and spearmint oil stores were sealed for 48 hours and *SmartBlock*® for 24 hours. An additional store, with DMN applied, was also sealed for 48 hours post-application, but with software control of carbon dioxide concentration to a maximum level of 1% (10 000 ppm).

All treatments were held at a target holding temperature of 9.0 °C. Four replicate sample nets for each of three sampling occasions were buried approximately three tubers down in fully randomised positions among six pallet boxes of MH treated Russet Burbank bulk material.

Store set up and control

All CERs were configured for positive ventilation (Fig. 2). Boxes were stacked tightly in three columns of two, against a plenum chamber with foam-lined battens screwed to vertical joins to ensure a good seal. Pressurised air discharged from the plenum was blocked at ground level and forced through the middle slot. At the opposite end of the stack, the aperture between boxes was blocked to promote air-flow through the crop. Temperature probes were buried in boxes to monitor crop temperature. Store air was recirculated through a conditioning duct for automatic refrigeration or heating as necessary. Store air was automatically sampled every hour and extracted from floor level where necessary to prevent a build-up of carbon dioxide beyond set-point. All stores were fitted with overlapping polythene curtains inside the main door to minimise product loss during essential store inspection and maintenance operations.

Fig. 2. Boxes stacked two high, three deep against a plenum, at the back of the store, for positive ‘letterbox’ ventilation.

Pull down and applications

Stores were loaded on 9 October 2020 and steadily pulled down from an average temperature of approximately 13°C to 9°C, at a rate of 0.3°C per day.

DMN [supplied by *DormFresh Ltd*] was applied using a *Cedax Electrofog EWH-3000* [*Xeda International SA*], at a target product temperature of 250 °C, directly into the plenum chamber (Fig. 3). The stores were switched off but a slow fan recirculated store air during, and for 30 minutes after, application. The stores then remained off and still for a period of 48 hours before unsealing and returning to automatic control. Starting on 22 October 2020, DMN was applied at a decreasing dose rate with one occasion at 20 ml tonne^{-1}, one occasions at 15 ml tonne^{-1} and four at 10 ml tonne^{-1}, all at c. 6 week intervals. DMN totalling 75 ml tonne^{-1} was applied.

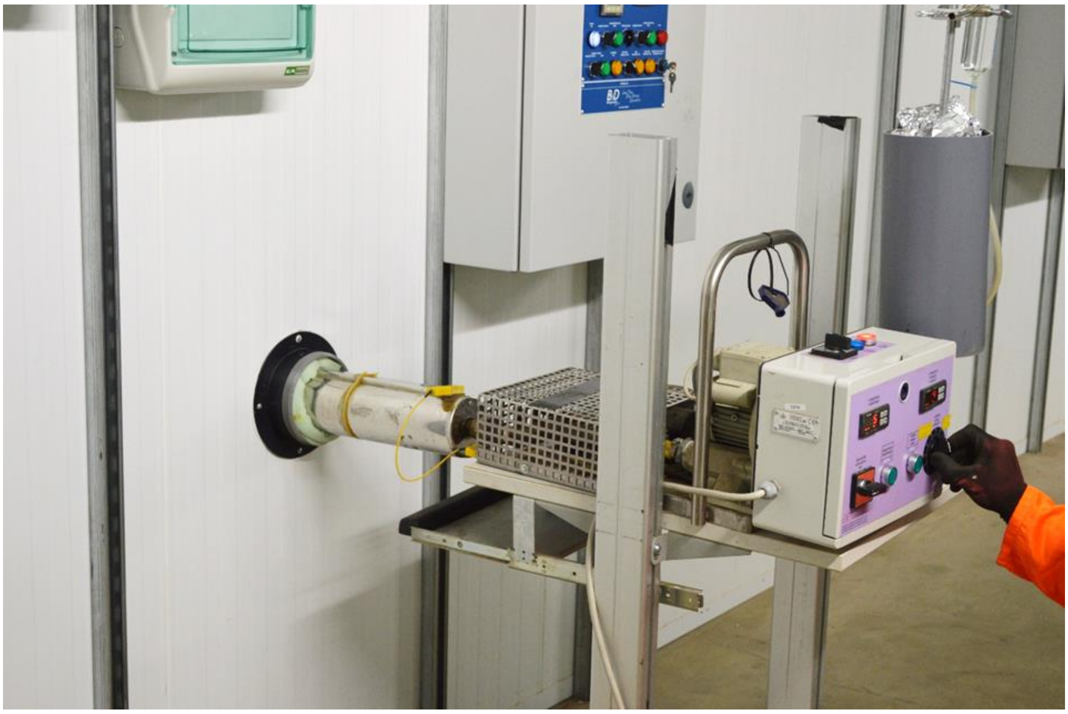

Fig. 3. CEDAX Electrofog EWH-3000 for application of spearmint oil, DMN and *SmartBlock®*.

Ethylene control was initiated on 11 November 2020, using a *Restrain* generator [Restrain Company Ltd, Breda, Netherlands] with ethylene measured and recorded by sensor units. The pre-programmed 'soft start' was utilised to preserve processing quality by reducing physiological stress. After completion of the 'soft start' ethylene was maintained continuously at a concentration of 10ppm. As the generator was designed for large scale storage, ethylene fuel was diluted to 20 % by adding deionised water.

SmartBlock®, 3-decen-2-one [supplied by Amvac® Chemical Corporation, Los Angeles, CA 90023, USA] was applied using the *Electrofog* at a target product temperature of 175 °C, directly into the plenum chamber. Applications were made at 70 ml tonne^{-1}, starting at the onset of sprouting in the second variety to sprout, and then every 60 days. The treated store was sealed for 24 hours after application with positive, slow fan recirculation. *SmartBlock®* was applied on four occasions to a total dose of 280 ml tonne^{-1} .

Spearmint oil [*Biox-M®*, MAPP 16021, Juno PP, Maidstone, UK] was also applied using the *Electrofog* directly into the plenum chamber at a target product temperature of 185 -190 °C. The store was switched off but a slow fan recirculated store air continuously during application. When application was complete, fan speed was increased to 100% for the subsequent sealing period of 48 hours; the store was then unsealed and returned to automatic control. *Biox-M* was applied at a standard dose of 60 ml tonne^{-1}, but 80 ml tonne^{-1}

was applied on one occasion where increased sprouting was evident. The maximum total dose of 360 ml tonne^{-1} was applied.

The experimental stores have a relatively large fridge coil for the store capacity; this was physically isolated to prevent condensation of product when any treatments were fogged into stores. Dates and rates of all applications are shown in the Appendix.

Sampling and assessment

Samples were taken at intake and after 3, 6, and 9 months of storage (6 January, 6 April and 21 June, 2021 respectively for sampling occasions [SO] 1, 2 and 3). For each sample, the longest sprout length was measured on all tubers of a 25 potato sub-sample. Fry colour was measured for potatoes processed as chips (French fries) for Innovator, Maris Piper, Performer and Royal and as crisps for VR808.

For crisping, 300 g of slices between 1.22 and 1.47 mm thick were taken from 30 mechanically-peeled tubers and washed in water for 45 seconds. Each sample was then fried for 3 minutes in oil heated up to 177 °C at the start of frying. After frying, the sample was weighed and then crisps with defects (any dark discolouration larger than a 5 mm diameter circle) removed and weighed. The remaining, fry defect-free sample was then assessed three times using a *HunterLab D25NC* colour quality meter [Stotto, Mountsorrel, Leics., UK]. Hunter L values were recorded.

Chips were processed as single $^{3}/_{8}$th inch (9.5 mm) square, longitudinal sections from each of 20 sound tubers and fried for 90 seconds in oil heated to 190 °C at the start of frying. The fry colour of individual strips was assessed subjectively by comparison with a USDA standard colour chart [Munsell Color, Baltimore, Maryland, USA] under standard artificial white light. The USDA assessment scale used for assessing chips (light to dark - 000, 00, 0, 1, 2, 3 & 4) was linearized 1 to 7 (SBCSR scale) and reported as a mean. Scores of 1 to 3 are good; scores of 4 and 5 acceptable and higher scores rejected.

In addition, MH untreated tubers were sampled in the field for each of the five varieties for dormancy measurement. Samples of 50 tubers from each MH untreated plot were placed in paper sacks and held at 15°C. Samples were assessed regularly for sprout length and any showing 3 mm or more counted and discarded. Apparent dormancy[8] was represented by the number of days taken, from harvest, for half of the sample tubers to cross the 3 mm sprout threshold.

Residues of MH in the treated plots were measured at lifting and during storage. Four samples of 12 tubers were taken in the field from each replicate field plot. The stored samples were buried in the untreated treatment store and retrieved on the three sampling occasions. One sample was taken from each MH untreated plot, to confirm shielding success, at intake only.

Approximately 100 tuber samples were selected from each stock/treatment combination both with and without MH field treatment and these were all cut into quarters longitudinally and internal sprouting recorded.

The statistical significance of differences was calculated using students t-tests or ANOVA [*Microsoft Excel* Analysis ToolPak add-in] as appropriate.

3. Results

Dormancy & maleic hydrazide residue levels

The period of apparent dormancy of MH untreated samples of each cultivar is shown in Table 1. The duration of dormancy for cvs Innovator, Maris Piper and Royal was rather similar, in the range 74 to 89 days. Dormancy was shortest in cv. VR808, at 59 days, and longest in cv. Performer, at 149 days.

[8] Dormancy proper is the period between tuber initiation and the onset of sprout growth.

Table 1. Apparent dormancy (days) of varieties in trial

cultivar	dormancy period	standard deviation
Innovator	89	2.2
Maris Piper	74	3.9
Performer	149	9.7
Royal	88	4.5
VR808	59	7.3

In MH treated crops, four replicate samples of 12 tubers were taken at intake and at each sampling occasion from the untreated store and analysed for maleic hydrazide residue concentration. The mean residue concentration of samples is shown in Table 2. Cultivars Innovator, Maris Piper and VR808 had similar concentrations, in the range 21-24 mg kg^{-1} (ppm). The concentration was significantly lower in cv. Royal (p= 0.0001) and significantly higher in cv. Performer (p=0.0001) with values of 7.3 mg kg^{-1} and 36.2 mg kg^{-1} respectively. Maleic hydrazide residue concentration varied little during storage (Table B1 in Appendix B).

Table 2. Mean maleic hydrazide residue concentration (mg kg^{-1})

cultivar	MH residue	standard deviation
Innovator	23.4	2.13
Maris Piper	21.9	1.98
Performer	36.2	5.34
Royal	7.3	0.87
VR808	22.9	3.28

Sprouting

Sprouting was assessed at intake, and after storage for approximately 3, 6 and 9 months (12, 25 and 37 weeks respectively). There was no sprouting in any variety at store loading. Results for the final sampling occasion are shown in Figures 4-8 for cvs. Innovator, Maris Piper, Performer, Royal and VR808 respectively.

Sprouting of MH-free samples in the untreated store was similar for cvs. Innovator, Maris Piper, Performer and Royal; all were in the range 44-52 mm after storage for 37 weeks. Sprouting of cv. VR808 at this time point was less, with a mean maximum sprout length of 27mm.

Sprout control of MH treated samples of cv. Innovator (Fig. 4) was generally very effective, with all post-harvest treatments resulting in low sprouting levels (<5 mm). Without post-harvest treatment, MH alone resulted in a mean maximum sprout length close to 10 mm.

Only DMN treatment resulted in effective sprout control (<5 mm) with MH untreated samples of cv. Innovator. The other treatments (i.e. ethylene, Biox-M® and *SmartBlock®*) resulted in similar levels (one way ANOVA p=0.197) with sprout lengths in the range 18-24 mm.

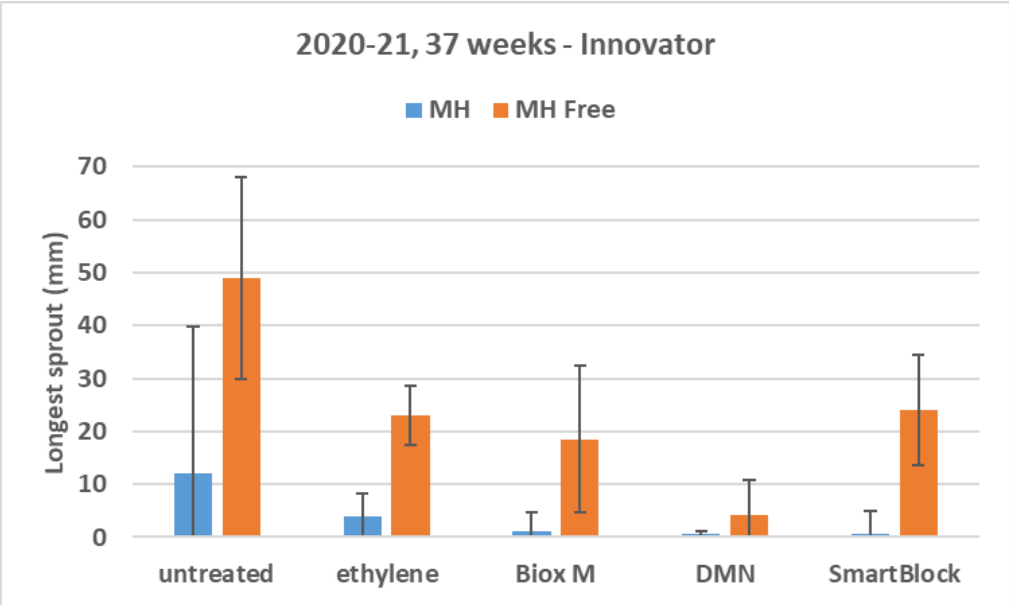

Fig. 4. Mean maximum sprout length (+/- standard deviation) of cv. Innovator.

Sprouting of MH treated cv. Maris Piper was effectively controlled by in-store treatments (Fig. 5). Samples treated with ethylene and those receiving no post-harvest treatment had similar, low sprouting levels between 4 and 5mm. Sprout control was virtually complete in MH treated Maris Piper subsequently treated in-store with Biox-M, DMN or *SmartBlock®*.

Sprout control in MH free cv. M. Piper was relatively poor using ethylene and Biox-M, both with a mean length of 18mm. Sprouting was maintained at a low level (<5 mm) by DMN and *SmartBlock®* but sprout length was significantly shorter (p=0.0005) after use of DMN.

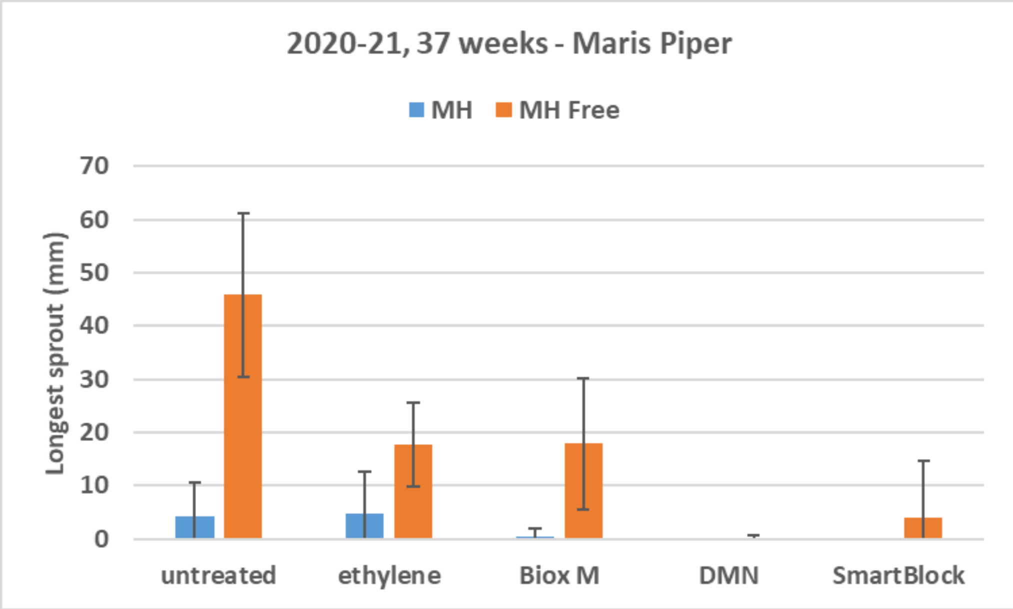

Fig 5. Mean maximum sprout length (+/- standard deviation) of cv. Maris Piper.

Sprouting of MH treated cv. Performer (Fig. 6) was very well controlled in-store. All post-harvest treatments resulted in sprout length of less than 2 mm after 37 weeks' storage. In MH-free samples, similar levels of sprouting occurred following Biox-M and *SmartBlock®* treatments (length 9.0 and 8.1 mm respectively). Sprout control was more effective with DMN (sprout length <1 mm) and less effective using ethylene (sprout length >25 mm).

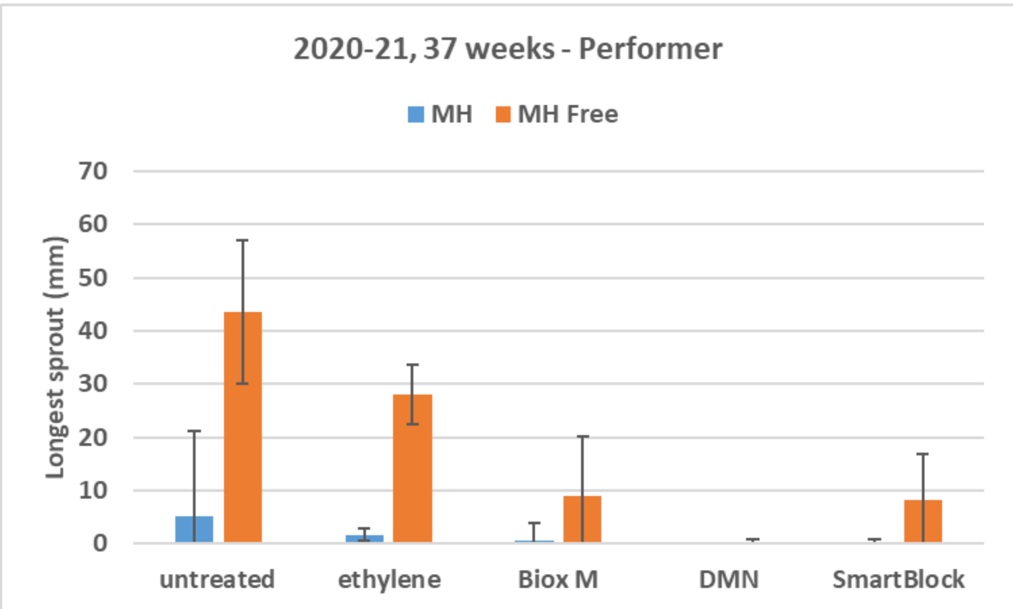

Fig 6. Mean maximum sprout length (+/- standard deviation) of cv. Performer.

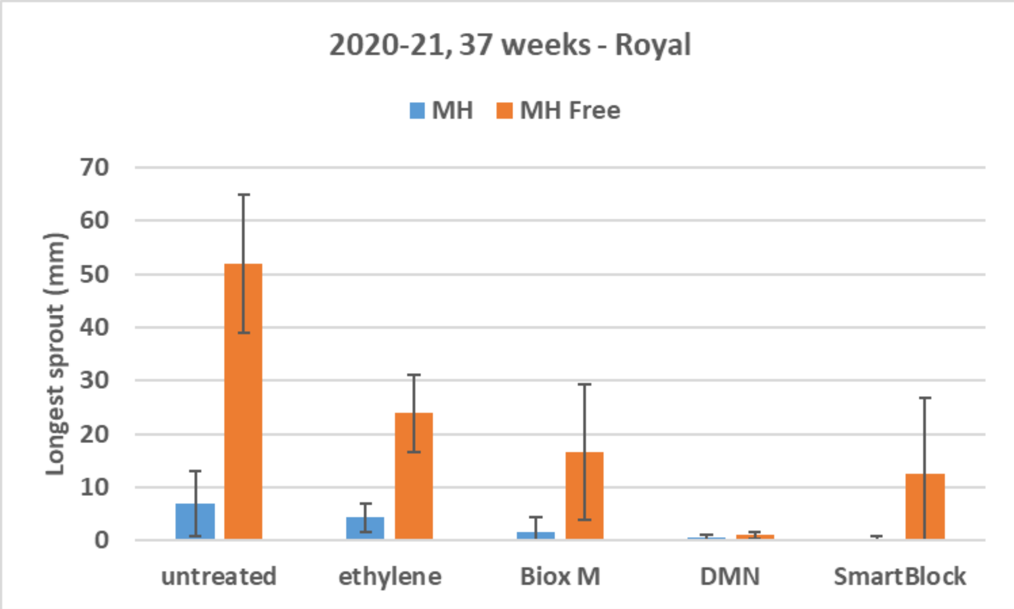

Fig. 7. Mean maximum sprout length (+/- standard deviation) of cv. Royal.

All MH treated samples of cv. Royal had sprout lengths of less than 10 mm following storage for 37 weeks, irrespective of in store treatment. Of the post-harvest treatments, DMN and *SmartBlock®* resulted in similar, very low sprouting levels (<1 mm). There was slightly more sprouting where ethylene and Biox-M were used; the difference between these treatments was significant (p=0.0001). In MH-free samples of cv. Royal only DMN maintained sprouting at a low level (1.1 mm). Biox-M and *SmartBlock®* treatments resulted in similar sprout lengths (p=0.153). The difference in sprout length between ethylene and Biox-M treatments was significant (p=0.025).

In MH treated samples of cv. VR808, sprouting was only evident in samples treated in-store with ethylene and samples without any post-harvest treatment; sprout length in these samples was well controlled (<2 mm). MH treated samples of VR808 treated in-store with Biox-M, DMN or *SmartBlock®* were largely sprout free.

Sprouting of MH untreated samples of cv. VR808 was also very well controlled by DMN and *SmartBlock®* (sprout length <1 mm). Sprout control was less effective with both Biox-M and ethylene treatments with sprout lengths closer to 10mm.

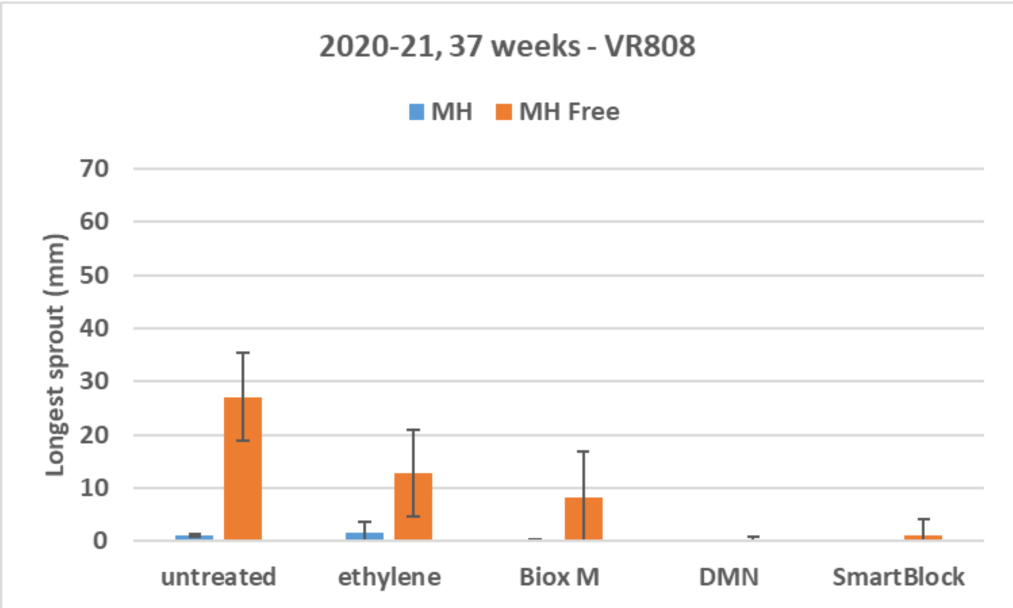

Fig. 8. Mean maximum sprout length (+/- standard deviation) of cv. VR808.

Processing quality

The cultivars Innovator, Maris Piper, Performer and Royal were processed as chips (French fries) and VR808 as crisps.

Chips (French fries)

Fry colour of cv. Innovator was relatively poor compared with the other cultivars. Average colour, for all treatments, was between scores 4 and 5, equivalent to USDA 1 and 2.

There were no significant differences in fry colour, as a result of post-harvest treatments, in MH treated (one-way ANOVA, p= 0.236) and MH untreated (one-way ANOVA, p=0.168) samples of cv. Innovator.

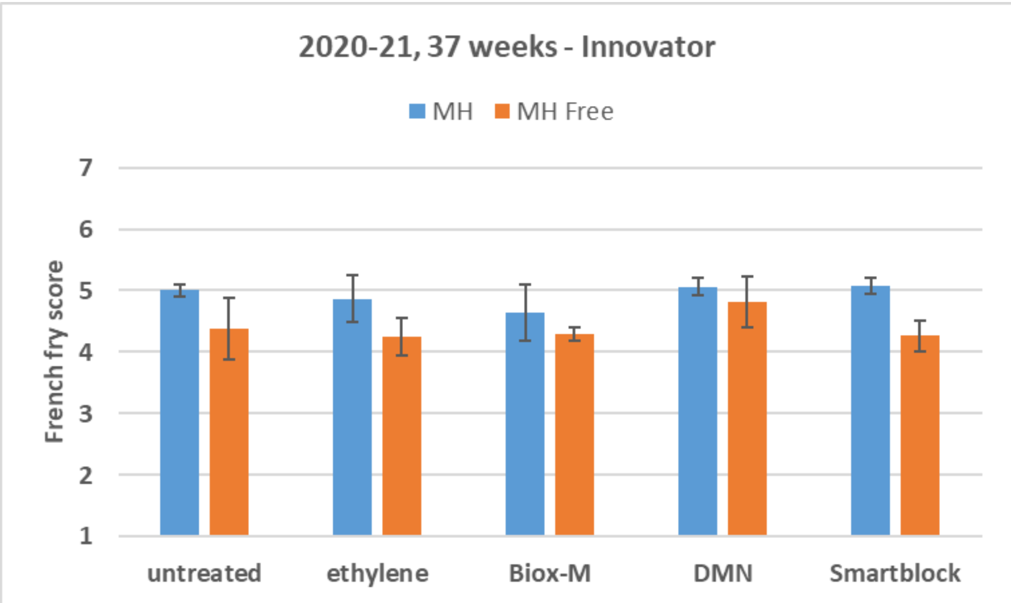

Fig. 9. Fry colour (mean score, +/- standard deviation) of cv. Innovator.

The fry colour of cv. Maris Piper, after storage for 37 weeks, was generally very light (Fig. 10). Mean fry colour was close to a French fry colour score of 3 (USDA 0). Fry colour did not vary significantly as a result of post-harvest treatments in MH treated (one-way ANOVA, p=0.967) or MH untreated (one-way ANOVA, p= 0.594) samples.

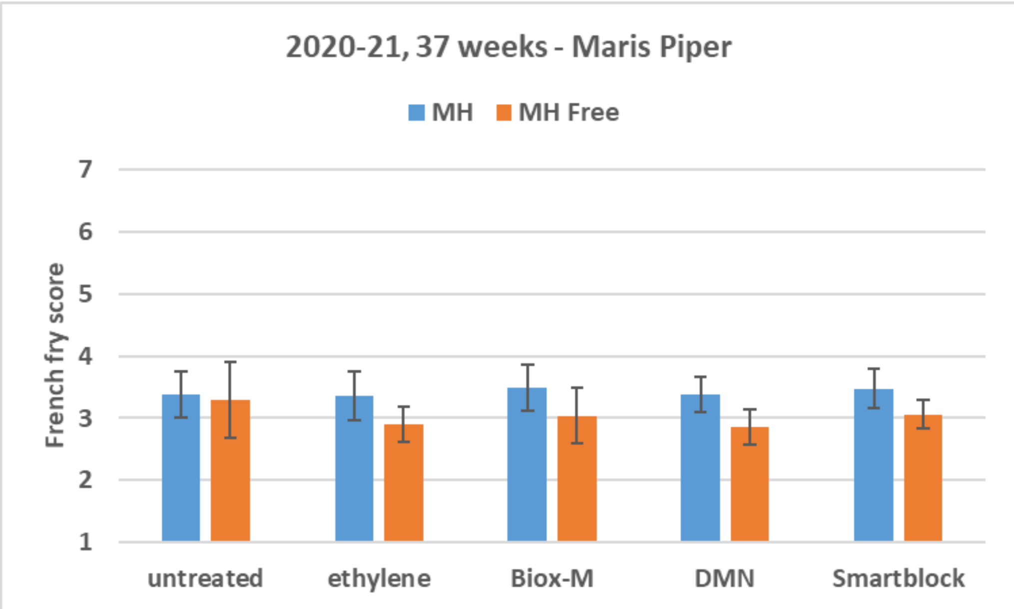

Fig. 10. Fry colour (mean score, +/- standard deviation) of cv. Maris Piper.

After storage for 37 weeks, the mean fry colour of all samples of cv. Performer (Fig.11) was light, with fry colour scores ranging between 3 and 4 units (USDA scores 0 and 1). Storage treatments did not give rise to differences in fry colour of MH treated (one-way ANOVA, p= 0.636) or MH untreated (one-way ANOVA, p= 0.343) samples.

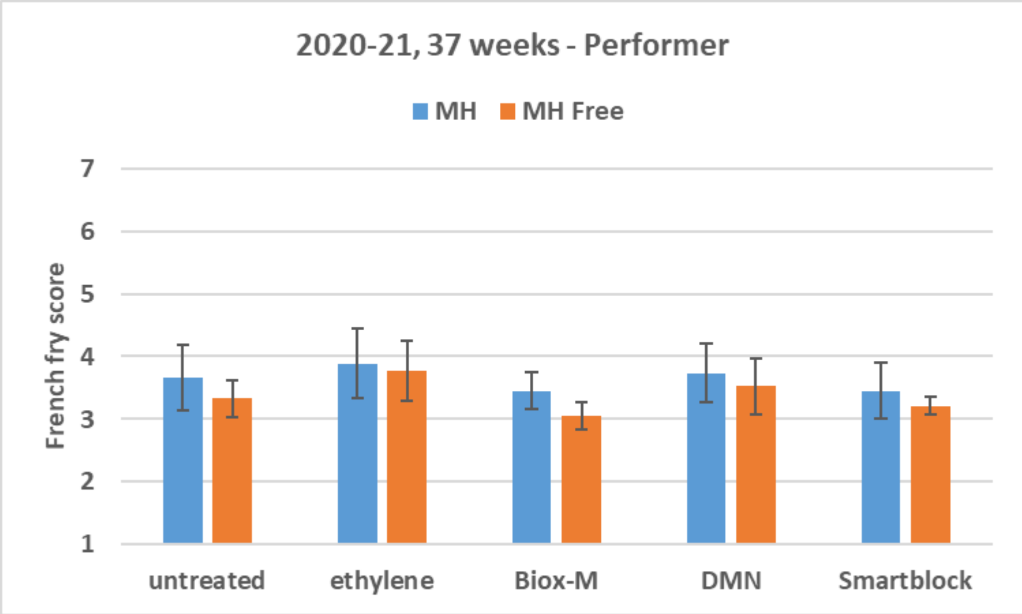

Fig. 11. Fry colour (mean score, +/- standard deviation) of cv. Performer.

Fry colour of cv. Royal was generally light with mean scores between 2.9 and 4.3 (approximately USDA 0 and 1). Differences in fry colour were not significant for MH treated (one-way ANOVA, p= 0.252) and MH untreated (one-way ANOVA, p= 0.060) samples.

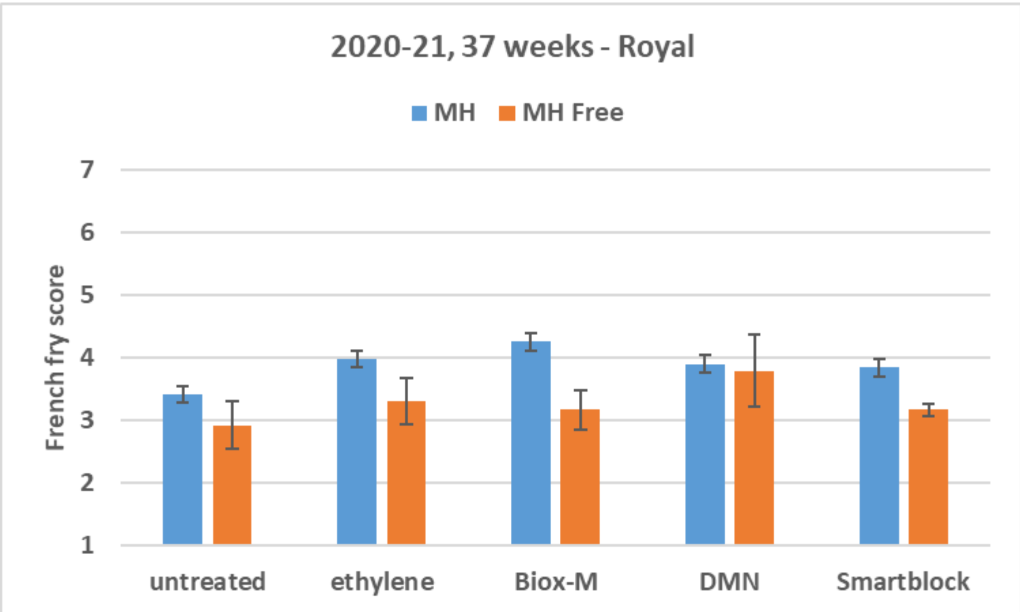

Fig. 12. Fry colour (mean score, +/- standard deviation) of cv. Royal.

Crisps

Fried samples of VR808 after 37 weeks' storage were generally poor with defects levels in all treatments making samples unacceptable (defect range 15-55%). Deterioration was seen across all storage treatments and is considered most likely to be as a result of field conditions. Quality at sampling occasion 2 (after storage for 25 weeks) was generally good, with many treatments resulting in zero fry defects and all treatments having less than mean 5% fry defects (Fig. 13). Fry colour was also very light, in the range 61.3-63.6 Hunter 'L' units. Differences in fry colour were not significant in MH treated (one-way ANOVA, $p = 0.252$) and MH untreated (one-way ANOVA, $p = 0.855$) samples.

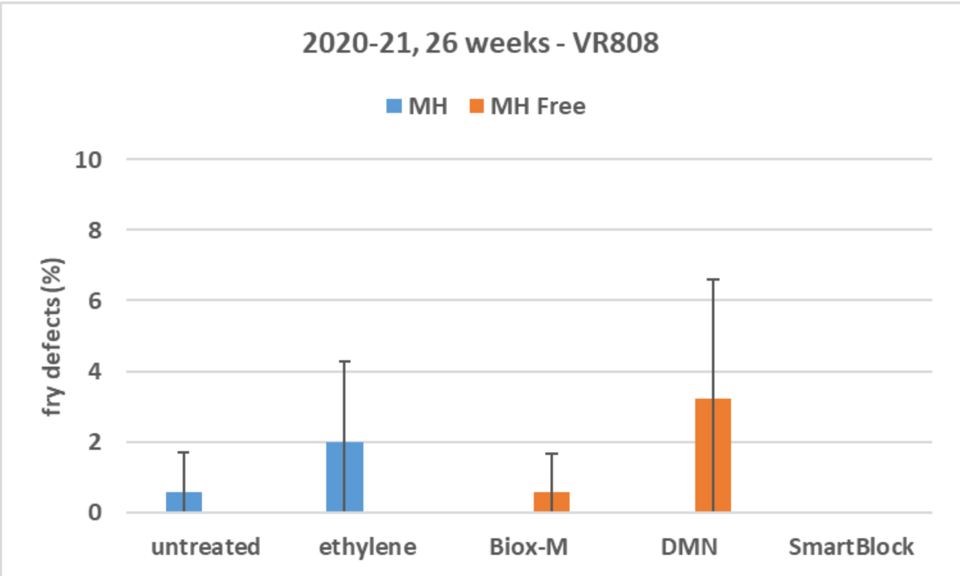

Fig. 13a. Crisp fry defects cv. VR808.

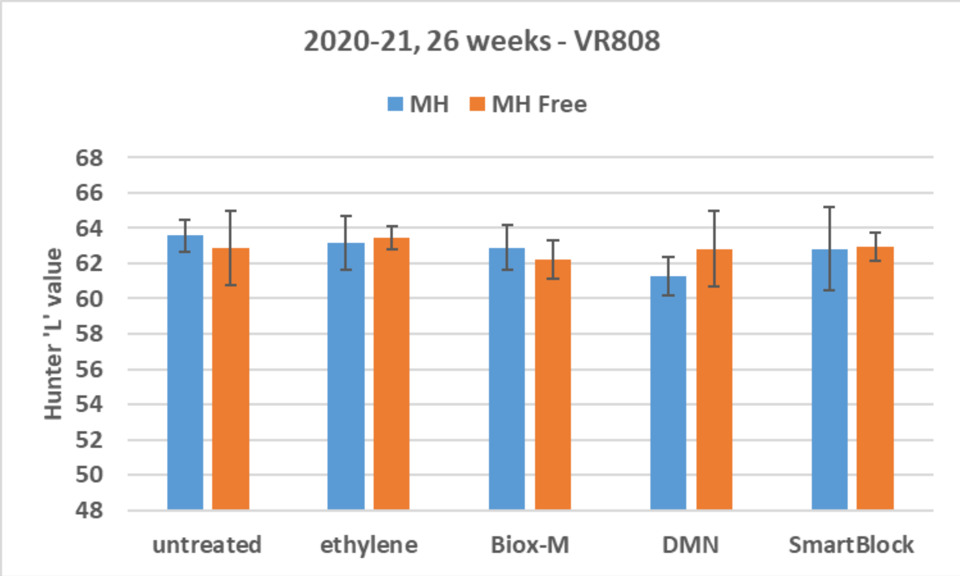

Fig. 13b. Crisp fry colour (Hunter L value) cv. VR808.

Carbon dioxide concentration

In addition to the standard store treated with DMN (where the store was managed not to exceed 0.3% carbon dioxide), a second store was managed to a threshold of 1% carbon dioxide. The DMN application regime and store closure period, following applications, was similar in both stores. The carbon dioxide concentration of the stores is shown in appendix E. The fry colour of the French fry cultivars, under the contrasting carbon dioxide regimes, is shown in Fig. 14 after 37 weeks' storage.

Fry colour of the French fry varieties was not influenced by the contrasting carbon dioxide concentrations. Differences between the control (0.3%) and 1% carbon dioxide treatments were generally not significant (unpaired t-test, Innovator MH p=0.382, Innovator MH free p=0.785, Maris Piper MH p=0.081 , Maris Piper MH free p=0.422, Performer MH p=0.306, Performer MH free p=1.000, Royal MH p=0.796, Royal MH free p=0.361).

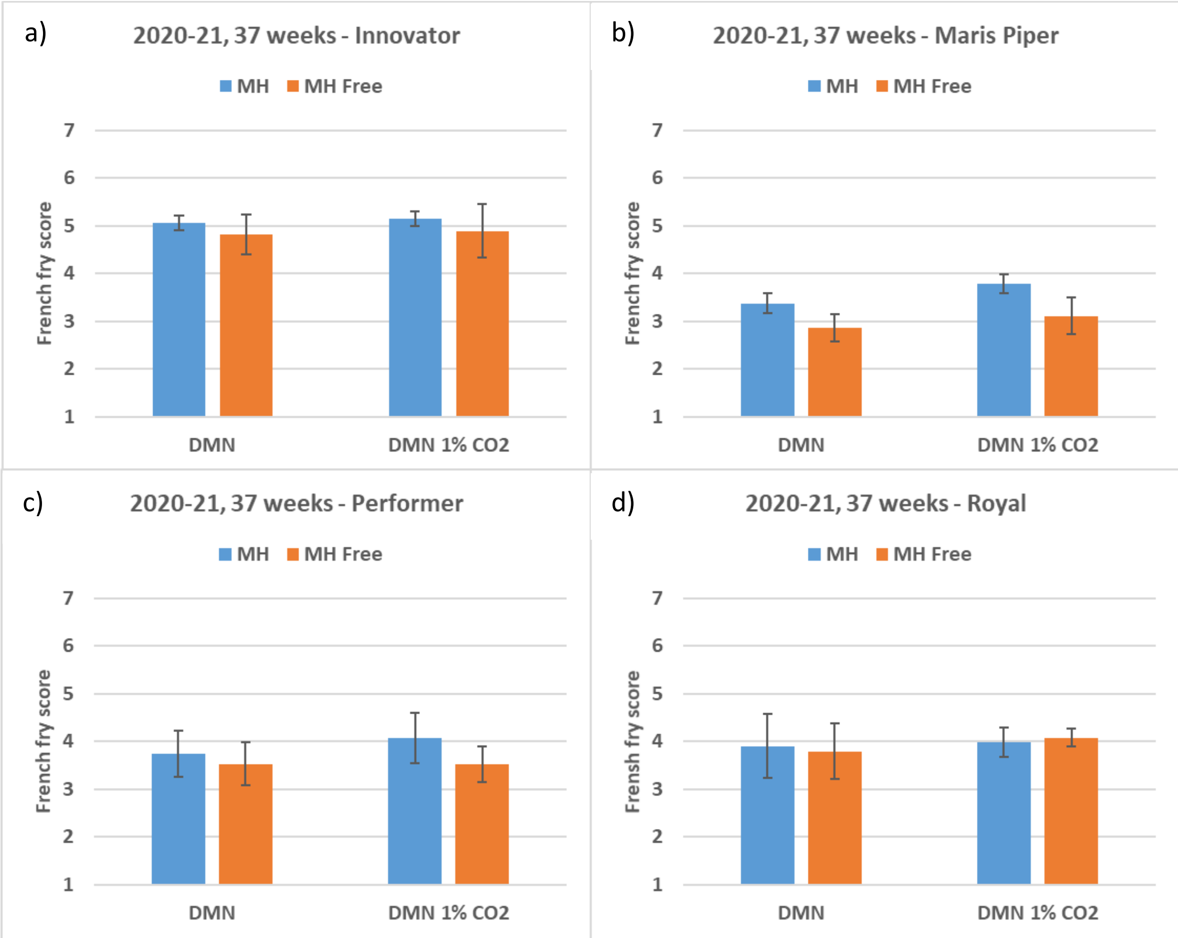

Fig. 14. Fry colour of French fry cultivars Innovator (a), Maris Piper (b), Performer (c) and Royal (d) after storage under contrasting carbon dioxide regimes.

The processing quality of VR808 is shown after 26 weeks' storage (SO2, Fig. 15) as quality was generally unacceptable at the final sampling occasion (SO3). After storage for 26 weeks, processing quality of VR808 was excellent irrespective of store carbon dioxide concentration with few or no fry defects and light fry colour. Differences in fry colour, as a result of carbon dioxide concentration, were not significant (unpaired t-test, MH p=0.484, MH free p=0.878)

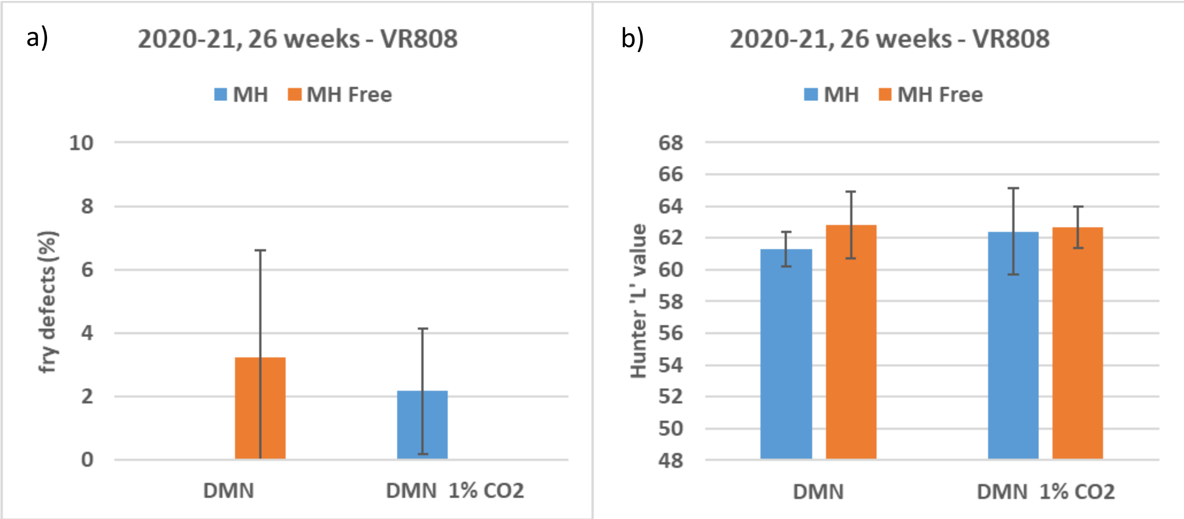

Fig. 15. Fry defects (a) and fry colour (b) of cv VR808 after storage under contrasting carbon dioxide regimes

Internal sprouting

The incidence of internal sprouting after 37 weeks' storage is shown in Table 3. At the end of storage, internal sprouting was found in *all* cultivars. The incidence was generally low, except in cv. Innovator where, in untreated samples, almost 25% of tubers were affected. Maleic hydrazide was very effective at controlling internal sprouting. The defect was not found in three cultivars, and only found at very low levels in cvs Innovator and Royal when MH was used.

Table 3. Incidence (%) of internal sprouting after storage for 37 weeks.

treatment	Innovator		Maris Piper		Performer		Royal		VR808		**mean**	
	MH+	MH-	MH+	MH-	MH+	MH-	MH+	MH-	MH+	MH-	**MH+**	**MH-**
untreated	3	25	0	2	0	1	1	4	0	2	**0.8**	**6.8**
ethylene	1	14	0	0	0	1	0	1	0	0	**0.2**	**3.2**
Biox M	0	39	0	6	0	6	1	6	0	8	**0.2**	**13.0**
DMN	0	9	0	0	0	0	0	1	0	0	**0.0**	**1.9**
DMN 1% CO_2	0	11	0	0	0	0	0	0	0	0	**0.0**	**2.2**
SmartBlock	1	37	0	6	0	2	0	7	0	0	**0.2**	**10.3**
mean	**0.9**	**22.4**	**0.0**	**2.4**	**0.0**	**1.6**	**0.3**	**3.1**	**0.0**	**1.6**	**0.2**	**6.2**

4. Discussion

Sprout control

As in the previous seasons of this study, maleic hydrazide had an important and lasting effect on sprout control. Maleic hydrazide residue concentrations of samples in the 2020-21 storage season were approximately twice those of samples in 2019-20 (average of all cultivars *c.* 23ppm in 2020-21, compared with *c.* 11ppm in 2019-20; see Table B2 in appendix B). The efficacy of MH, when applied alone, or in combination with post-harvest treatments was evident. For some varieties, where MH application had been particularly successful and high residue levels ensued, additional post-harvest treatment did little to improve sprout control. With cv. VR808 for example, with an average MH residue concentration close to 25 ppm, all post-harvest treatments resulted in a mean maximum sprout length of less than 2 mm. Although sprout growth of MH untreated samples of VR808 was least vigorous of all the cultivars, the effect was apparent in other cultivars.

While maleic hydrazide can be very effective, it remains a difficult product to use because, for optimal applications, it requires appropriate weather and agronomic conditions to coincide. The relatively high MH residue concentrations seen in this study in 2020-21 appear to be a reflection of field conditions, which were similar across much of the country. If correct, it is unclear if this was just due to better conditions for applications prevailing during the summer of 2020 or whether a conscious attempt was made by growers to improve application technique, because CIPC was no longer commercially available.

Difficulty with predicting the success of MH application is problematic because it is a critical factor affecting the success of other post-harvest treatments. While residue testing may be useful for predicting storability of crops, it can only indicate the residue level achieved; it cannot be altered. Developments in technology that would allow applications to succeed under a wider range of climatic conditions, such that application success and MH residue could be better predicted, would be very useful.

With MH proving to be increasingly important for storage now CIPC has gone, more research on variety interactions is needed. Data suggest that for MH residue levels, there may be a variety interaction (see Table B2 in appendix B). In cv. Royal, an indeterminate cultivar, residue levels were consistently lower than in cv. Innovator, a determinate cultivar. While a relationship with determinacy may seem intuitive – i.e. that canopy size influences application efficiency of a product applied to the canopy - it could also be as a result of a dilution effect from the distribution of a similar amount of MH across the larger yield characteristic of indeterminate varieties. Although in this season the lower MH residue of cv. Royal (c. 7ppm) was not associated with poor efficacy, in other years lower residue levels may have negative effects on sprout control. Further information on this would be useful for growers as it would allow greater optimisation of applications to varieties predisposed to low residue levels. Best practice also suggests that slightly earlier application and/or application in a larger volume of water will increase application efficiency.

Of the post-harvest treatments, control using DMN was generally most effective and low sprouting levels were not dependent on pre-treatment with maleic hydrazide or variety. Without MH, only DMN treatment resulted in generally low sprouting levels after 37 weeks; cv. Innovator was greatest at 4.1 mm, other varieties had 1 mm or less.

Application of *SmartBlock®* gave complete sprout control in MH treated crops but was not completely effective in MH untreated samples. Control was least effective in cv. Innovator (sprout length c. 24mm). For this 2020-21 season, the *SmartBlock®* application rate was reduced to 70 ml tonne^{-1} from the 100 ml tonne^{-1} rate used in 2019-20. Four applications were made in both seasons. Data suggest, under the conditions tested, that reductions in dose rate would only be acceptable for less vigorously growing crops (e.g. VR808) and those treated with MH.

Biox-M and ethylene treatments, without MH, resulted in mean sprouting levels of c. 9-19mm and c. 13-28mm respectively. With both products, sprouting was least in cv. VR808. Under the conditions tested, very low sprouting levels were only consistently achieved with these products following MH treatment.

Processing quality

After 37 weeks' storage, processing quality of cvs Maris Piper, Performer and Royal was good, cv. Innovator was modest and cv. VR808 was poor. Quality of cvs. Innovator and VR808 was generally good or very good at the earlier sampling, after 6 months' storage. The deterioration in processing quality of Innovator and VR808 between 6 and 9 months was general across post-harvest treatment and so may be a symptom of senescent sweetening and, therefore, related to field rather than storage conditions. None of the post-harvest treatments had a deleterious effect on processing quality.

Ethylene has been associated with a deterioration in fry colour in the literature[9]. However, careful store management, introducing ethylene at a very low concentration initially (the "ramp") and control of store carbon dioxide level, was used to limit its impact on crops. Data from several seasons indicate that ethylene, especially in combination with maleic hydrazide, could be more widely used, without a detrimental effect on fry colour. In trials at Sutton Bridge, the treatment combination has been associated with effective sprout control and good processing quality.

Store closure and carbon dioxide levels

Post-harvest applications are normally followed by a period of store closure when ambient air exchange is restricted to ensure maximum absorption of the product applied. Closure periods of 48 hours are routine for Biox-M and DMN treatments and high carbon dioxide concentrations are therefore likely at these times.

In this work, allowing store carbon dioxide to achieve 1% before flushing and allowing carbon dioxide to exceed 1.5% during the store closure period did not adversely affect processing quality; there was no difference in quality between 1% carbon dioxide treatment and the conventionally managed store. In this work all exogenous sources of ethylene (e.g. petrol/gas powered foggers) were excluded. The results confirm the observation[10] that carbon dioxide

---

[9] Prange, R.K., B.J. Daniels-Lake, J.-C. Jeong, M. Binns (2005). Effects of ethylene and 1-methylcyclopropene on potato tuber sprout control and fry color. Am. J. Potato Res., 82 (2005), pp. 123-128

[10] Daniels-Lake, B. J., & Prange, R. K. (2009). The Interaction Effect of Carbon Dioxide and Ethylene in the Storage Atmosphere on Potato Fry Color Is Dose-related, HortScience horts, 44(6), 1641-1644.

alone does not have an important effect on potato quality. Applications of post-harvest products that require long store closure periods should be made using equipment that does not generate ethylene (i.e. through use of electric or heat-exchange foggers).

Store carbon dioxide management should be maintained whenever ethylene is used. Growers and store managers should also be aware of the effects of carbon dioxide on human health and that safety exposure limits exist for it.

5. Conclusions

- **In samples treated with MH, residue levels were higher in 2020-21 than in 2019-20**
- **In MH treated samples good sprout control (<5mm) was achieved by all post-harvest treatments after long-term storage at 9C.**
- **Sprout control was virtually complete following use of DMN and *SmartBlock®* in MH treated samples.**
- **In MH untreated samples good sprout control (<5mm) was only achieved using DMN.**
- **DMN resulted in good sprout control irrespective of cultivar and MH pre-treatment.**
- **None of the sprout suppressants affected fry colour.**
- **Processing quality following treatment with ethylene was the same as other post-harvest treatments.**
- **Allowing store carbon dioxide concentration to achieve 1%, compared with a conventionally managed store where concentration was managed to not exceed 0.3%, did not give rise to differences in processing quality.**

6. Appendices

A. Study diary

Table A. Diary of study events 2020-21

Date	Activity
16/09/2020	Performer lifted
17/09/2020	Maris Piper lifted
22/09/2020	VR808 lifted
24/09/2020	Innovator lifted
29/09/2020	Royal lifted
09/10/2020	All stores loaded
22/10/2020	DMN 1st applications (20 ml/t)
11/11/2020	All ethylene ramps initiated (subsequent target concentration 10 ppm)
18/11/2020	*Biox-M* 1st application (60 ml/t)
26/11/2020	*SmartBlock* 1st application (70 ml/t)
02/12/2020	DMN 2nd application (15 ml/t)
06/01/2021	Sampling occasion 1
06/01/2021	*Biox-M* 2nd application (60 ml/t)
13/01/2021	DMN 3rd applications (10 ml/t)
25/01/2021	*SmartBlock* 2nd application (70 ml/t)
10/02/2021	*Biox-M* 3rd application (60 ml/t)
24/02/2021	DMN 4th applications (10 ml/t)
24/03/2021	*Biox-M* 4th application (60 ml/t)
25/03/2021	*SmartBlock* 3rd application (70 ml/t)
06/04/2021	Sampling occasion 2
07/04/2021	DMN 5th applications (10 ml/t)
05/05/2021	*Biox-M* 5th application (80 ml/t)
19/05/2021	DMN 6th application (10 ml/t)
26/05/2021	*SmartBlock* 4th application (70 ml/t)
17/06/2021	*Biox-M* 6th application (40 ml/t)
21/06/2021	Sampling occasion 3

B. Maleic hydrazide residue concentration

Table B1. Mean maleic hydrazide residue concentration (mg kg^{-1}) of samples in 2020-21.

cultivar	**intake**	SD	**3 months**	SD	**6 months**	SD	**9 months**	SD	**mean**	SD
Innovator	**22.0**	7.44	**21.3**	2.63	**25.0**	2.45	**25.5**	6.61	**23.4**	2.13
Maris Piper	**23.3**	7.14	**21.0**	7.30	**19.5**	3.51	**23.8**	9.64	**21.9**	1.98
Performer	**42.8**	18.73	**37.8**	6.55	**30.3**	10.24	**34.0**	7.26	**36.2**	5.34
Royal	**8.0**	0.83	**8.1**	1.35	**7.0**	0.78	**6.3**	0.48	**7.3**	0.87
VR808	**24.5**	4.04	**24.0**	5.60	**25.0**	4.55	**18.0**	3.00	**22.9**	3.28
mean	**24.1**	12.38	**22.4**	10.56	**21.4**	8.87	**21.5**	10.27	**22.3**	10.23

Table B2. Mean maleic hydrazide residue concentration (mg kg^{-1}) of samples from four seasons of study 1043. All samples consisted of 12 tubers but replication varied between seasons.

cultivar	**2017-18**	SD	**2018-19**	SD	**2019-20**	SD	**2020-21**	SD	**mean**	SD
Innovator	**16.7**	3.06	**37.4**	24.61	**22.3**	8.58	**23.4**	2.13	**24.9**	8.82
Maris Piper	**10.2**	1.33	**8.6**	2.21	**6.5**	2.34	**21.9**	1.98	**11.8**	6.90
Performer	**9.9**	3.00	**5.9**	1.81	**13.9**	2.49	**36.2**	5.34	**16.5**	13.53
Royal	**5.1**	3.68	**7.8**	1.97	**5.1**	1.40	**7.3**	0.87	**6.3**	1.42
VR808	**17.0**	3.46	**15.2**	4.88	**8.6**	1.87	**22.9**	3.28	**15.9**	5.86
mean	**11.8**	5.03	**15.0**	13.03	**11.3**	7.01	**22.3**	10.23	**15.1**	5.10

C. Weight loss

Weight loss (%) of samples after storage for 37 weeks.

Innovator	**MH**	SD	**MH Free**	SD	**mean**	SD
untreated	**3.8**	0.33	**6.6**	0.62	**5.2**	1.99
ethylene	**4.6**	0.35	**6.9**	0.92	**5.8**	1.66
Biox M	**4.3**	0.52	**5.7**	0.75	**5.0**	0.99
DMN	**4.0**	0.53	**4.2**	0.52	**4.1**	0.18
DMN 1% CO2	**3.9**	0.74	**4.1**	0.21	**4.0**	0.17
SmartBlock	**4.6**	1.01	**5.8**	0.82	**5.2**	0.89
mean	**4.2**	0.34	**5.6**	1.16	**4.9**	0.68

Maris Piper	**MH**	SD	**MH Free**	SD	**mean**	SD
untreated	**4.7**	0.61	**6.8**	0.51	**5.7**	1.50
ethylene	**5.6**	0.51	**7.3**	0.26	**6.5**	1.20
Biox M	**4.4**	0.23	**6.0**	0.59	**5.2**	1.14
DMN	**4.3**	0.91	**4.6**	0.31	**4.5**	0.21
DMN 1% CO2	**3.8**	0.43	**3.9**	0.68	**3.9**	0.07
SmartBlock	**4.7**	0.32	**4.6**	0.45	**4.7**	0.06
mean	**4.6**	0.59	**5.5**	1.36	**5.1**	0.93

Performer	**MH**	SD	**MH Free**	SD	**mean**	SD
untreated	**2.8**	0.21	**4.6**	0.75	**3.7**	1.31
ethylene	**3.3**	0.14	**5.6**	0.33	**4.4**	1.58
Biox M	**3.0**	0.19	**3.8**	0.29	**3.4**	0.55
DMN	**3.3**	0.53	**3.3**	0.47	**3.3**	0.02
DMN 1% CO2	**3.1**	0.56	**3.1**	0.41	**3.1**	0.01
SmartBlock	**3.0**	0.34	**3.7**	0.40	**3.3**	0.52
mean	**3.1**	0.22	**4.0**	0.91	**3.5**	0.47

Royal	**MH**	SD	**MH Free**	SD	**mean**	SD
untreated	**4.5**	1.07	**7.0**	1.09	**5.7**	1.73
ethylene	**6.1**	0.54	**8.2**	1.58	**7.1**	1.53
Biox M	**5.3**	0.57	**6.2**	1.01	**5.8**	0.59
DMN	**5.3**	0.71	**5.6**	0.60	**5.5**	0.19
DMN 1% CO2	**5.3**	0.35	**5.6**	1.80	**5.4**	0.24
SmartBlock	**5.6**	0.78	**5.6**	0.45	**5.6**	0.00
mean	**5.4**	0.51	**6.4**	1.06	**5.9**	0.65

VR808	**MH**	SD	**MH Free**	SD	**mean**	SD
untreated	**5.0**	0.90	**6.9**	0.24	**5.9**	1.35
ethylene	**6.3**	1.73	**8.0**	0.67	**7.1**	1.21
Biox M	**5.3**	0.68	**6.3**	0.80	**5.8**	0.74
DMN	**5.7**	1.29	**5.8**	1.37	**5.8**	0.10
DMN 1% CO2	**4.9**	1.28	**5.5**	1.02	**5.2**	0.42
SmartBlock	**5.7**	0.37	**5.6**	0.84	**5.7**	0.11
mean	**5.5**	0.52	**6.3**	0.94	**5.9**	0.64

D. Weight of sprouts

Weight of sprouts of samples (%) after storage for 37 weeks.

Innovator	**MH**	SD	**MH Free**	SD	**mean**	SD
untreated	**0.5**	0.23	**7.0**	2.62	**3.8**	4.59
ethylene	**0.2**	0.17	**4.1**	1.46	**2.2**	2.79
Biox M	**<0.1**	0.05	**1.6**	0.61	**0.8**	1.10
DMN	**0.0**	–	**0.2**	0.26	**0.1**	0.11
DMN 1% CO2	**0.0**	–	**0.1**	0.06	**<0.1**	0.04
SmartBlock	**<0.1**	0.03	**2.3**	0.57	**1.2**	1.64
mean	**0.1**	0.20	**2.6**	2.66	**1.3**	1.43

Maris Piper	**MH**	SD	**MH Free**	SD	**mean**	SD
untreated	**0.2**	0.09	**5.8**	1.28	**3.0**	4.02
ethylene	**0.1**	0.04	**1.1**	0.25	**0.6**	0.70
Biox M	**0.0**	0.03	**1.6**	0.51	**0.8**	1.15
DMN	**0.0**	–	**0.0**	–	**0.0**	–
DMN 1% CO2	**0.0**	–	**0.0**	–	**0.0**	–
SmartBlock	**0.0**	–	**0.2**	0.10	**0.1**	0.16
mean	**0.1**	0.08	**1.5**	2.25	**0.8**	1.15

Performer	**MH**	SD	**MH Free**	SD	**mean**	SD
untreated	**0.3**	0.49	**4.5**	0.23	**2.4**	2.99
ethylene	**0.0**	–	**3.2**	0.89	**1.6**	2.23
Biox M	**<0.1**	0.04	**0.6**	0.23	**0.3**	0.39
DMN	**0.0**	–	**0.0**	–	**0.0**	–
DMN 1% CO2	**0.0**	–	**<0.1**	0.07	**0.0**	0.03
SmartBlock	**0.0**	–	**0.4**	0.19	**0.2**	0.32
mean	**0.0**	0.10	**1.5**	1.90	**0.7**	0.99

Royal	**MH**	SD	**MH Free**	SD	**mean**	SD
untreated	**0.2**	0.12	**5.8**	0.65	**3.0**	4.00
ethylene	**0.0**	0.02	**1.9**	0.31	**1.0**	1.32
Biox M	**<0.1**	0.02	**1.5**	0.50	**0.7**	1.03
DMN	**0.0**	–	**0.0**	–	**0.0**	–
DMN 1% CO2	**0.0**	–	**0.0**	–	**0.0**	–
SmartBlock	**0.0**	0.02	**1.1**	0.84	**0.6**	0.77
mean	**0.0**	0.07	**1.7**	2.16	**0.9**	1.12

VR808	**MH**	SD	**MH Free**	SD	**mean**	SD
untreated	**<0.1**	0.03	**5.0**	1.43	**2.5**	3.50
ethylene	**<0.1**	0.02	**1.6**	0.68	**0.8**	1.13
Biox M	**0.0**	–	**0.6**	0.16	**0.3**	0.45
DMN	**0.0**	–	**0.0**	–	**0.0**	–
DMN 1% CO2	**0.0**	–	**0.0**	–	**0.0**	–
SmartBlock	**0.0**	–	**0.0**	–	**<0.1**	0.03
mean	**<0.1**	0.01	**1.2**	1.94	**0.6**	0.97

E. Store carbon dioxide concentration

Store carbon dioxide concentration (hourly) recorded by the store control system.

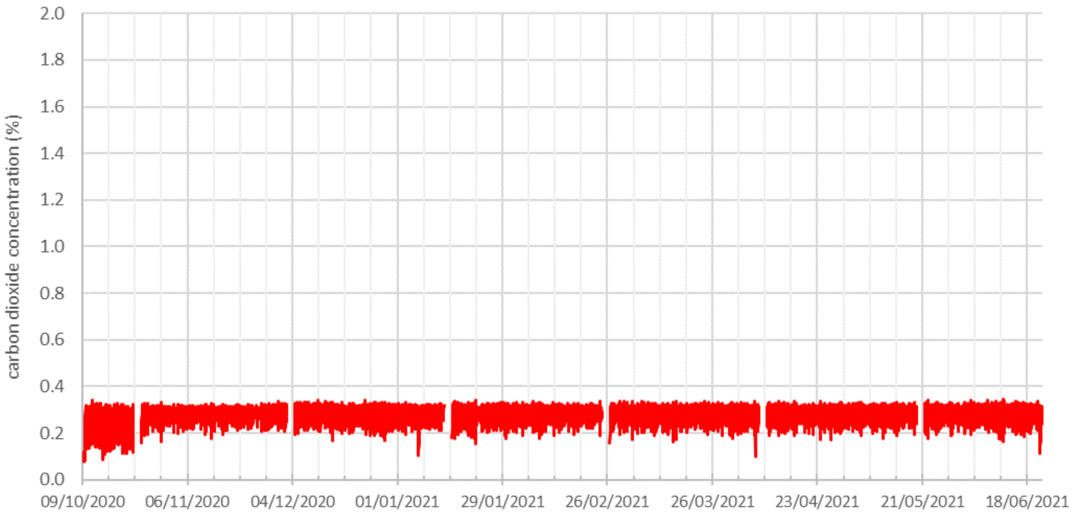

Figure C1: Carbon dioxide concentration in DMN treatment store with ventilation initiated by naturally exceeding a threshold of 0.3% CO_2

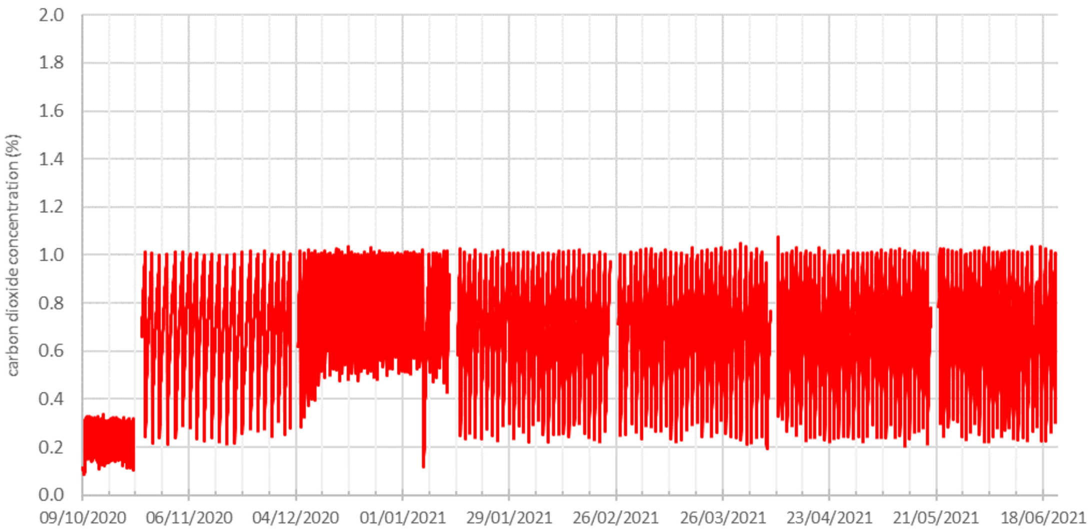

Figure C2: Carbon dioxide concentration in DMN treatment store with ventilation initiated by naturally exceeding a threshold of 1.0% CO_2

Discrete readings of store carbon dioxide concentration prior to re-enabling store control system, following treatments.

Table C. Store carbon dioxide concentration (ppm) following chemical applications and prior to automatic store control resuming.

treatment date	Smartblock 24 hours	Biox-M 48 hours	DMN 48 hours	DMN, 1% CO_2 48 hours
24/10/2020			0.917	0.914
20/11/2020		0.981		
27/11/2020	0.722			
04/12/2020			1.200	1.314
08/01/2021		1.158		
15/01/2021			1.147	1.696
26/01/2021	0.744			
12/02/2021		1.315		
26/02/2021			1.038	1.200
26/03/2021	0.784	1.115		
09/04/2021			1.075	1.243
07/05/2021		1.437		
21/05/2021			1.247	1.378
27/05/2021	0.798			
19/06/2021		1.443		
Mean	0.762	1.242	1.104	1.291