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AHDB Calcium Review – Horticulture (Cucurbits)

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1. Abstract

Blossom end rot (BER) is the development of wet rots in fruit which originate from the flower scar, developing in the fruit and reducing yield volume and quality after harvest. Research in other crops (e.g. tomato) has suggested that the incidence of BER is linked with calcium availability in the fruit prior to harvest. Calcium is required for strong links to form within developing cell walls, and poor calcium availability during development weakens the structure of the fruit, placing it at increased risk from pathogenic breakdown. The incidence of BER is linked to a variety of environmental, geographical and biological conditions, and it can pose a significant risk of postharvest wastage. The development of rots after harvest is particularly problematic in pumpkin, which may be required to retain quality over extended periods of postharvest storage.

This review was undertaken to evaluate how nutritional control is used to reduce BER incidence in cucurbits (including courgette, pumpkin, melon and squash) and other fruit crops (such as apple and tomato), including practices that may be innovative to the UK industry. A wide range of academic and commercial resources were reviewed, alongside targeted consultations with industry stakeholders to fully evaluate the potential for nutritional control to reduce losses to BER.

Calcium availability in the soil can be promoted through suitable management of soil nutrition. A pH of 6.5 should be targeted, and excess nitrogen applications and low nitrate:ammonium ratios avoided to ensure that the availability of soil calcium is maximised. Calcium is transported within the plant through the xylem via the transpiration stream, and is predominately carried into the leaves rather than fruit. Dry conditions, reduced root function or high humidity can reduce the amount of calcium available to the plant, leading to fruit undersupply even if there is sufficient calcium available in the soil. Calcium uptake can be promoted by ensuring consistent soil water levels through trickle tape irrigation or the use of mulches, and promoting root growth through good soil structure.

Further mitigation of BER risk could be achieved through targeted foliar application of calcium directly to the fruit and leaf surface. The application of calcium, potentially in conjunction with boron and magnesium, may promote calcium uptake by the fruit leading to enhanced fruit quality retention after harvest. While a range of calcium products are available, there is limited evidence available to judge their efficacy or to produce robust guidance on application timings or rates. In addition, there are cultural pre- and postharvest approaches that could also be utilised to mitigate the risk of BER development that could be adopted by the UK industry. While further work is recommended in order to address these knowledge gaps to provide growers with more understanding of how to control this condition, nutritional management is likely to be a key method of controlling BER risk in UK-grown courgette and pumpkin.

2. Introduction

2.1. Project objectives

This review was undertaken to assess the potential of crop nutrition to control the incidence of BER in courgette and pumpkin, with specific focus on calcium and boron. The biochemical properties of typical calcium compounds, along with the variety of application methods and interaction with other mineral nutrients and the range of published information was reviewed to develop a comprehensive evidence base to support growers seeking to control BER in pumpkin and courgette.

- To review scientific and industry information on the absorption and motility of calcium and boron on outdoor cucurbits, including the effect of their nutrition on blossom end rot management and pumpkin storability.
- To provide recommendations for the revision of guidance on application of calcium in outdoor cucurbits for future revisions of the fertiliser manual RB209.
- To identify any knowledge gaps for future research.

2.2. Methodology

2.2.1. Discussions with key industry representatives

Selected growers of outdoor courgettes and pumpkins, as well as agronomists, were contacted to provide their 'real-world' experiences of calcium and boron nutrition. Discussion encompassed the various different cultivation methods employed by growers; the timings, quantities and choice of product used; the type of fertiliser (granular or foliar) and the impacts of soil properties on calcium availability and uptake by plants.

Manufacturers of calcium (and boron) containing feeds were also contacted to provide information on their products, including any new products / methodologies currently being developed to enhance calcium absorption and availability to developing fruit.

2.2.2. Review of peer reviewed scientific and relevant 'grey' literature

A focussed literature search of peer reviewed journals was completed using Web of Science, Google Scholar and ResearchGate. Key, relevant search terms were selected based on their appropriateness for this review. Only papers published from 2000 onwards were originally considered, however this was revised to include older work as limited information was available.

Relevant 'grey' literature (including HDC, AHDB Horticulture, Defra and others) on calcium and boron nutrition was also reviewed.

2.3. Postharvest Quality and Yield in Cucurbits

Cucurbit production in the UK is represented by two key crop types, courgette and pumpkin. Home production of courgette achieved a market value of £29m in 2017 (Defra, 2018), and the carving pumpkin market is estimated as £15m. Furthermore, the edible pumpkin market represents an additional £4.5m as this market is developing as consumer demand and popularity of niche cultivars increases. In both courgette and pumpkin a requirement for postharvest storage places produce at risk of the development of postharvest rots, with an estimated loss of 15-20% after harvest (if not greater), although losses are highly variable with growing conditions, location and cultivar. Typically, postharvest rots develop from the blossom end scar as a result of a number of pathogens including *Fusarium*, *Botrytis* and bacterial rots. The development of rots from the flower scar can be enhanced in wet conditions where the flower does not abscise fully from the fruit, remaining attached and providing an early foothold for disease development. As such blossom end rots (BER) can lead to significant crop losses and are one of the main causes of unmarketable fruit in courgette. Methods of reducing the prevalence of BER in courgette and pumpkin have been identified as a key way of reducing waste and improving economic productivity in this sector.

Pathogens responsible for the development of BER are naturally occurring and prevalent in the growing environment, and while there is only limited availability of plant protection products a key mechanism of control is likely to be found through cultivation practice, including nutrient management and postharvest handling. Control of BER in other susceptible crops (e.g. tomato) has been achieved through targeted control of calcium nutrition. AHDB project FV 433 identified a range of effects of calcium deficiency of courgette, and nutrient analysis of symptomatic fruit suggested a decreasing calcium gradient from the stalk to the blossom end of courgettes. Similarly, project FV 439 identified that calcium provision improved storage in pumpkin.

2.4. Calcium Nutrition and BER

There is good evidence that the incidence of BER is strongly linked with crop nutritional status, particularly with the availability of calcium. BER has been described as a physiological disorder resulting from localised calcium deficiencies in tomato, pepper, aubergine and watermelon (Taylor & Locascio, 2004). The risk of BER is often correlated with calcium concentrations in the fruit – for example, Suzuki *et al*. (2003) reported that calcium deficiency in the plasma membrane of cells in tomato fruit lead to increased risk of cell collapse in BER, and a strong negative correlation was found between BER incidence and the calcium content of the bottom half of tomato fruits (Adams & Ho, 1992). Project FV 433 identified a 3-4% decrease in calcium content of a small sample of courgettes expressing BER symptoms. While no threshold calcium value has been identified for BER control in cucurbits, it is believed by many that maximising calcium concentrations in the fruit is liable to enhance the grower's ability to control BER.

2.5. Biological Role of Calcium

The extent of calcium involvement in plant biochemical processed is extensive and not fully understood or appreciated. Calcium is an essential macronutrient for a multitude of biochemical and metabolic processes and is vital for the maintenance and proper development of plant tissues, including the stability and maintenance of cell plasma membranes. Early symptoms of blossom end rot, as a consequence of calcium deficiency, exhibit as water soaked areas due to cellular rupturing or collapse. Calcium ions are required to strengthen and stabilise plant cell walls as calcium allows aggregation of pectin, providing strength within and between cell walls (Jarvis, 1984). Calcium negatively impacts the activity of cell wall degrading enzymes used by bacterial and fungal pathogens (e.g. pectin hydrolases), further reducing cell wall damage by pathogens (Biggs *et al*., 1997). Calcium ions are also utilised for intracellular signalling – when pathogen activity triggers the hypersensitive resistance response, Ca^{2}+ concentrations in the cytoplasm increase as calcium is released from intracellular stores, activating cell death programs (apoptosis) as the plant seeks to rapidly kill infected tissues to prevent further spread of the pathogen (Levine *et al*., 1996). For instance, calcium nutrition is linked with the uptake of other nutrients. Calcium-deficit pumpkin showed depressed nitrate uptake and assimilation (Prasil, 1975), and calcium availability will also impact the uptake of potassium and phosphorus, although calcium uptake can be antagonistic to magnesium absorption in melon (Navarro *et al*., 1999), risking magnesium deficiencies and compromising the plant's ability to synthesise chlorophyll.

2.6. Calcium in the Soil

Calcium can only be absorbed from the soil in the form of the Ca^{2+} ions which are dissolved in the soil solution. Calcium can also be bound to the surface of soil particles, or bound to negative charges in the soil such as calcium oxalate crystals with neither form available for use by plants. The ratio between the bound and free forms of calcium is related to pH: more Ca^{2+} dissolves into the soil solution as pH decreases (e.g. below a pH of 4.5) as chemical weathering and dissolution of calcium oxalate crystals increases Ca^{2+} concentrations (McLaughlin & Wimmer, 1999). Lower soil pH will also reduce root growth (negatively impacting plant and fruit growth) and increase the solubilisation of toxic elements (e.g. aluminium). Therefore, to avoid negative effects on crop development soil pH should be kept between 5.5 – 7.5 for cucurbits, targeting an optimum pH of 6.5. However, at this pH sufficient soil calcium should be available, especially in soils which have been limed. Calcium leaching may also be of concern, particularly in sandy soils or in situations where irrigation has been used extensively. This can result in a reduction in the available calcium content within the soil and lead to BER symptoms developing. In these situations, additional granular / foliar calcium feeds may be required to compensate for this loss.

2.7. Calcium Uptake and Transport

Calcium uptake by the root is relatively unaffected by the level of calcium in the soil as long as it is above a minimum threshold (Kirkby & Pilbeam, 1984). Instead, calcium availability is predominantly limited by the rate at which it can be taken up by the plant. Once calcium is taken up by the plant, it is transported through the xylem via the transpiration stream (**Figure 1**). As water evaporates out of the leaf surface, or is used to enlarge cells in developing fruit, calcium ions are drawn up through the plant (Ho *et al*., 1993). As a result, the rate of calcium uptake is dependent on the rate at which water is taken up by the plant. Under conditions of high rates of transpiration (low humidity, high temperature and high stomatal conductance), calcium will be taken up more rapidly than in conditions where transpiration is slowed by high humidity, low soil water availability or reduced stomatal conductance.

Transport of calcium in the xylem also results in a disproportionate partitioning of calcium between leaf and fruit material. Much greater proportions of water are lost out of the leaf than the fruit, leading to a greater accumulation of calcium in leaf material than in the fruit. Furthermore, developing fruits tend to absorb water from the phloem, leading to lower accumulations of calcium. Gradients of calcium content will also develop in the fruit, with lowest concentrations being encountered at the distal end of the fruit near the flower scar.

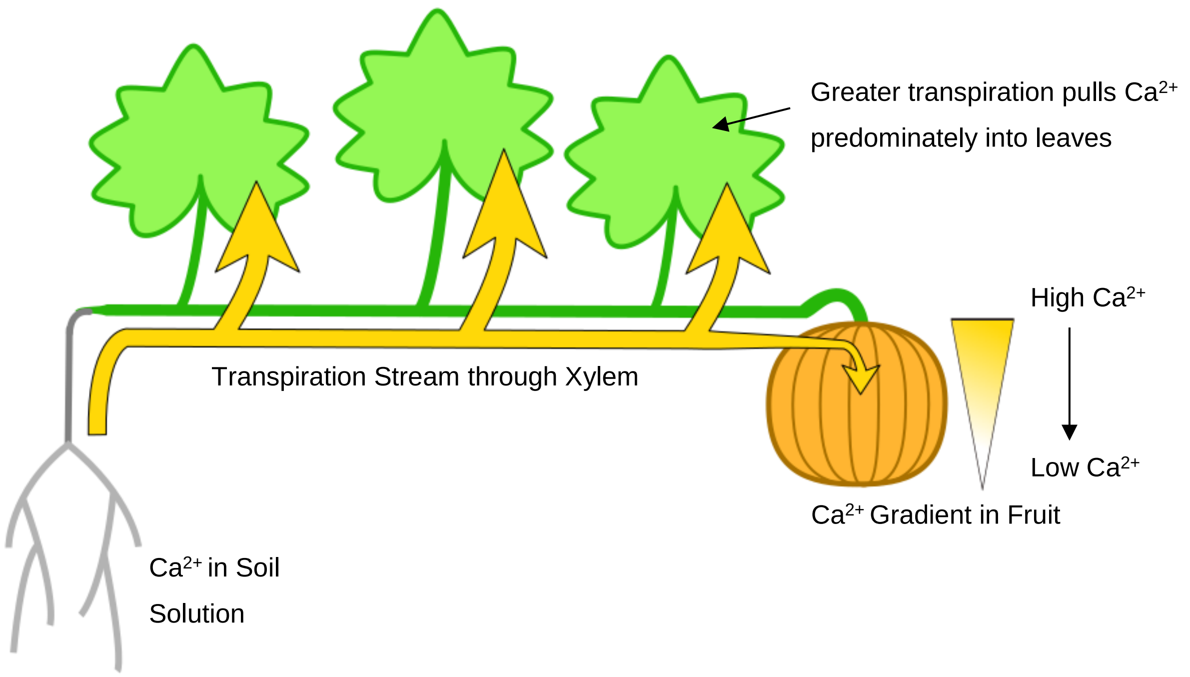

Figure 1. Calcium transportation and partition in plants. Ca^{2+} ions absorbed from the soil solution are transported through the plant using the transpiration stream. High levels of water loss out of the leaves creates the greatest pull of calcium towards the leaves, with only small proportions being partitioned in the fruit. The calcium that accumulated in the fruit is at the greatest concentration near the stalk, with a gradient of declining concentration towards the flower scar end.

This coupling of calcium supply with water movement means that calcium availability is impacted by conditions that also affect the rate of transpiration and water uptake by the plant including low temperatures, high humidities and soil moistures. Apple fruit grown under low relative humidity (and thus high transpiration rates) showed greater calcium concentrations than fruit grown at high relative humidity (Cline & Hanson, 1992) due to a reduction in the number of open stomata. Soil water status will also impact calcium availability, soils with a high water deficit, giving reduced transpiration, will limit calcium availability further. Although reduced water availability will lessen calcium availability to plant tissues, including fruit, dry years such as the 2018 season have generally seen very low levels of BER development. This is likely a consequence of a reduction in the speed of cell elongation of maturing fruit and inclement weather conditions for the invasion and colonisation of the blossom end by opportunistic pathogens. The greatest risk of BER occurs where periods of high and low water availability alternate rapidly, giving uneven periods of growth and cell elongation. Likewise, consistent water availability in irrigated crops also helps to mitigate BER incidence.

2.8. Calcium and Fruit Development

The use of calcium in structural support in cell walls where it is locked away as calcium pectate in vacuoles, reduces the extent to which calcium can be recycled in older tissues for reuse elsewhere (Kleemann, 1999). With calcium involved in so many cellular processes a store of calcium for use when needed likely plays a positive role in plant stress responses (Kinzel, 1989) The role of calcium as a signal for triggering cell death via apoptosis means that plant cells will avoid accumulating high concentrations of free Ca^{2+} ions in the cytosol. This precludes any significant concentration being achieved in living phloem cells, meaning that calcium cannot be easily transported to developing organs in the phloem sap (Ho & White, 2005). This results in a lack of significant calcium recycling within the plant (unlike other nutrients such as nitrogen) so the calcium content of a given organ (e.g. fruit or leaf) is dependent on the availability of calcium during its initial growth and development.

Calcium partitioning within the plant will favour developing leaves over fruits as a result of greater rates of transpiration out of the leaf layer, reducing the availability of calcium for developing fruit (Ho & White, 2005). As fruits develop, reductions in fruit surface area:volume ratios, stomatal density and functionality combined with increased thickening will slow rates of transpiration and calcium uptake through the xylem (Blanke & Lenz, 1989). Furthermore, xylem functionality reduces with fruit development as greater proportions of water are absorbed from the phloem, with tomato fruits obtaining 76-81% of their water content from the phloem in early development, which further increases as the xylem elements loose functionality with development (Ho & White, 2005). This means that fruits accumulate the majority of the final calcium content early in development – the total content will remain constant but concentrations will fall as the fruit continues to enlarge and mature until harvest. For instance, in melon (*Cucumis melo*), 80% of total calcium in the fruit was accumulated within the first 20 days after antithesis, 17 days before harvest (Bemadac *et al*., 1996).

This means that control of BER may be due to precise management of calcium nutrition during the developmental lifetime of the fruit.

2.8.1. Calcium Deficiencies

Deficiencies in calcium manifest as metabolic and physiological symptoms where normal function of the plant is no longer possible. In field-grown cucurbits, advanced calcium deficiency will manifest as patchy yellow chlorosis at the leaf tip and between veins, with leaves cupping to form a claw shape. Adequate soil nutrient management is unlikely to lead to the detection of physical symptoms in growing leaves. However, the lower levels of calcium in the fruit increases the risk of BER incidence, making calcium management during fruit development essential.

Calcium deficiencies may arise as a result of several different environmental factors. It can occur as a result of limited calcium availability in the growing medium and the use of calcium containing fertilisers may remedy this. Many growers choose to grow field based crops under black plastic mulch and the effectiveness of granular calcium containing fertilisers will be restricted by this when applied post planting.

Some growers are now using hydroponic systems to grow pumpkins in artificial growing media e.g. rockwool or coir, and are reliant on liquid fertilisers containing calcium at rates which are sufficient and appropriate for the growth stage and crop grown. Coarse, sandy and / or acidic soils generally contain less calcium than other soil types and crops grown in these will be at the greatest risk. Calcium may also occur as a solid phase insoluble form within the soil and be unavailable to be utilised by the plant. Soils high in phosphorus contain greater levels of insoluble calcium (calcium phosphates) than other soil types which can in part be remedied by reducing the soil pH which can be an expensive process. A low transpiration rate in the plant as a whole, or localised within tissues can lead to calcium deficiency development. Fruits receive greater levels of calcium during the first few weeks of development, but this is considerably reduced over time during the period when fruits are enlarging. Limited water availability reduces the rate of transpiration, and as a consequence, the transportation of water-soluble calcium reaching plant tissues during these times resulting in deficiencies. Where soil properties are not uniform across a field, pockets of calcium deficiency may appear sporadically within crops. High levels of nitrogen in the soil can also inhibit calcium uptake by the roots and the overuse of some fertilisers can cause lead to this, despite there being sufficient calcium availability in the soil. Some growers use the granular fertiliser calcium ammonium nitrate as their fertiliser of choice. The high levels of nitrates within this product leads to rapid plant growth whilst providing calcium to support this growth. However, there is concern that in certain cases ,plant growth may exceed the capacity for adequate calcium to be deposited within the fruit tissue leading to BER developing despite treating with a calcium containing feed.

2.8.2. Calcium deficiency symptoms

Calcium deficiencies can take the form of several different symptoms, depending on the crop in question. BER occurs in cucurbits, tomato and pepper, tipburn in brassicas and black heart in celery. The aim of this review is to examine calcium deficiency in cucurbits and will focus on cucurbits except in situations where information from work on other crops e.g. tomato and cucumber is relevant.

In cucurbits early calcium deficiency symptoms include localised necrosis and stunting of affected tissues. The newest and rapidly growing tissues are those which are first affected. Older leaves suffer slight or no issues due to calcium accumulation in these more mature tissues. Young leaves exhibit tipburn with concave cupping which may become convex in older leaves, leading to a claw-like shape, patchy chlorosis at the leaf tip and between veins develops and where water is a limiting factor and BER may develop in fruit. Where the ends of developing fruit break down dark blemishes appear becoming shrunken, dark and leathery, and can enlarge until the entire fruit is affected. A brief overview of calcium deficiencies in cucurbits (including images) is found in the 2018 AHDB Outdoor Cucurbits Crop Walkers' Guide.

In many crops calcium deficiency results in tissues appearing water-soaked. As calcium plays a role in the stability and maintenance of the plasma membrane, a consequence of increased cellular permeability is fluid entering the intercellular space leading to loss of turgor and cell breakdown. Alternatively, in fruits, water may enter the intercellular spaces within fruit via the phloem and/or water from the atmosphere. This exogenous water may lead to the swelling of the cells and cracking of the fruit. Fruits damaged by BER can cost growers considerable sums of money due to out-of-specification fruit and supermarket rejections. In situations where crops such as pumpkins are stored for long periods of time, fruits suffering from calcium deficiency typically have weaker skins, and have shorter storage shelf lives and are more susceptible to pathogen attack postharvest.

2.8.3. Managing calcium deficiency

Once cucurbit fruit is affected by BER it is unmarketable. Therefore prevention of calcium deficiency development is key to maximise marketable yield. Several control options exist including liming programs, maintaining optimal soil moistures, tilth, variety choice, pH, fertiliser options and cultural control options.

2.9. Boron Nutrition

The use of calcium has been demonstrated to reduce the incidence of BER in cucurbits and other crops. Improved calcium nutrition will enhance fruit quality, increasing marketable yields, but will have no effect on overall fruit yield. In addition to calcium, there is evidence that suitable boron availability is required for achieving target yield volume and quality. While boron is a micronutrient, required at much lower concentrations than other minerals, it is essential for a range of biological roles and there is some evidence that suitable boron nutrition may improve fruit setting, reduce fruit abortion and increase yield quality.

Boron is required for cell wall development and plasma membrane function. It has been proposed that boron is required for crosslinking cell wall polymers and that it has a synergistic effect with calcium in forming pectate crosslinks within the cell wall (Blevins & Lukaszewski, 1998). Yamauchi *et al*. (1986) reported that boron deficiency reduced the proportion of calcium associated with pectin constituents of tomato leaf cell walls, and Sahin *et al*. (2015) reported that supplementary boron provision increased leaf calcium content and gave higher yields in tomato. Similar effects have been reported in pumpkin, where boron deficiency reduced cell wall thickness through reduced pectate linkages (Ishii *et al*., 2001), weakening the resultant tissues and increasing the risk of microbial and mechanical damage. Boron deficiency will also inhibit root growth in squash (*Cucurbita pepo*), potentially due to changes in ascorbate metabolism in root meristems (Lukaszewski & Blevins, 1996), and this is considered to be a particularly significant issue in courgette (Findeklee & Goldbach, 1996) impacting the plants ability to absorb water and nutrients, reducing calcium availability further.

As well as enhanced disease resistance (Khalifa *et al*., 2009), adequate boron provision may also be required to maximise yield outputs. The role of boron in cell wall development is essential in the development of the pollen tube – once a pollen grain lands on the stigma, it germinates and forms the pollen tube which penetrates through the style into the ovary where sperm cells are deposited to fertilise the ova and trigger seed and fruit development. The developing pollen tube absorbs boron from the style, where it is required for growth of the pollen tube wall. In instances where boron is deficient, pollen germination and successful pollination events are reduced, negatively impacting seed set (Blevins *et al*., 1998). Greater pollination gives greater seed number, promoting increased fruit size and growth rate, and reduces the chance of fruit abortion in courgette (Stephenson *et al*., 1988). While this may be of less concern in courgette, fruit size is likely to be of importance in pumpkin where individual fruit are marketed on the basis of weight. A similar effect is likely to be seen in pumpkin, however, with methods of promoting seed number (e.g. pollinator provision) having been identified as a method of promoting pumpkin size in the field (Walters & Taylor, 2006). Therefore, adequate provision of boron may be required to ensure target fruit size and quality can be reached.

Little information is available to guide boron application in cucurbits. Boron is carried in the phloem and so does not face the transport limitations of calcium, although boron concentrations which are sufficient or toxic are highly specific to a given crop type. For instance, hydroponically grown courgette showed visible symptoms of boron toxicity (e.g. necrotic leaf burns and reduced growth) and impaired photosynthesis at concentrations of 10 mg/L of boron, compared with 0.2 mg/L control plants, while cucumber grown at the same concentrations showed no significant adverse effects (Landi *et al*., 2013). Yield reduction was reported in squash grown with irrigation solutions above 1 mg/L through a reduction in fruit number (Francois, 1992).

2.10. Nutrition and Cucurbit Production

There is a strong body of evidence that management of calcium nutrition may reduce the onset of BER in courgette and pumpkin. Correct nutritional management is unlikely to increase gross yields, but by improving the structural quality of fruit during development, postharvest reductions in quality and losses from the development of BER will be reduced. By reducing postharvest losses, net productivity will be increased alongside the sustainability of the cucurbit production through the reduction of waste. Therefore, growers at risk of high incidence of BER can adopt a range of techniques to manage calcium and boron nutrition (see next section). There may be additional benefits of enhanced calcium nutrition – there is anecdotal evidence that improved calcium provision gave straighter courgettes and enhanced the quality of the first crop, improving the proportion of fruit that were within customer specifications. Lastly, improved shelf life potential will allow growers to better match harvests with customer demand.

3. Managing BER in Courgette and Pumpkin

Managing the incidence of BER in courgette and pumpkin is most likely to be a multifaceted approach, with no single “silver bullet” to reduce the incidence of BER. A number of approaches should be included as part of normal crop management.

3.1. Cultivation Practice

As discussed above, the amount of calcium that is available to the developing fruit is dependent on a number of factors, and cultivation practice should be adapted to ensure a consistent and adequate supply of calcium is available to the developing fruit. Growers should frequently sample soil nutrients, and act to ensure ratios are maintained to prevent competition between calcium and other nutrients: calcium uptake can be stimulated by high levels of nitrate, but is negatively impacted by high concentrations of ammonium, potassium, magnesium or aluminium ions in the soil (Kirkby, 1979). Calcium uptake is enhanced when the nitrate:ammonium ratio is high (Chance *et al,* 1999), so the use of nitrate-based fertilisers may increase calcium uptake, although such formations may carry increased costs when compared with ammonium-based fertilisers. High nitrogen content will increase growth rates, increasing the risk that growth rates may exceed the rate of calcium supply, lowering internal calcium concentrations. It should be noted, however, that the availability of calcium in the soil is unlikely to be a causal factor in the development of BER as long as suitable ratios of nutrients, pH and electrical conductivity (EC) are maintained.

Soil sampling for nutrient content should include micronutrient analysis where possible to appraise boron availability. Soil boron content will vary depending on the parent material of the substrate and substrate chemophysical properties, including texture and clay content. pH exerts significant effects on boron availability, with reduced bioavailability at higher pH ranges. Boron interacts with most of the major nutrients (including calcium) and therefore correct maintenance of nutrient ratios will promote the uptake of boron at sufficient levels (Ahmad *et al*., 2012). Boron supplementation can be achieved through the application of a range of chemicals (e.g. borax, boric acid), but is also available in pre-formulated fertilisers. Care must be taken to ensure suitable dosage as the margin between sufficient and toxic concentrations of boron is poorly defined.

Soil conditions which reduce root growth will also impact the crop's ability to absorb calcium. Calcium can only be absorbed by immature root tips prior to suberisation (formation of corky tissue) (Kirkby, 1979) so conditions which reduce root growth, such as low temperature, high pH, poor nutrient status or soil aeration will also restrict calcium availability. Excessive irrigation should be avoided, drainage should be provided where required and methods adopted to prevent soil compaction to promote good root growth and ensure good aeration of the soil. Excessive drainage may also lead to the leaching away of calcium within the soil.

Plant stresses that reduce transpiration or cause unequal growth rates are likely to impact the availability of calcium as crop stress has previously been linked to an increase in BER (Saure, 2014). As calcium is taken up through the transpiration stream, consistent water uptake and normal stomatal function should be encouraged. Irrigation should be provided where available over dry periods to avoid large soil water deficits, and to maintain an EC for suitable for growth. Trickle tape application and mulches will also help prevent large fluctuations in soil water content, providing the crop with a more consistent rate of water and calcium uptake. Irrigation may only be applied during establishment of courgette, and top irrigation may increase the risk of bacterial development after fruit initiation. During hot, dry periods not all growers may irrigate cucurbit crops, although some growers have adopted trickle tape irrigation for courgette – this maintains soil moisture levels while avoiding surface water on the leaves and developing fruit. However, excessive irrigation should be avoided, especially where it is likely to create conditions of high humidity and reduce transpiration rates, and where overhead irrigation is used it should be applied early in the day to promote rapid leaf drying. In lettuce, tip burn (a comparable calcium deficiency symptom) is most often linked with periods of temporary drought following periods of high water availability (Saure, 1998) while Scaife and Clarkson (1978) reported that periods of high soil saturation reduced calcium uptake as a result of reduced aeration impacting root growth. Therefore, irrigation may be best utilised to create a consistent optimal soil moisture level to ensure that calcium supply can be matched with growth rates. The use of mulches may also improve calcium uptake by reducing soil water deficits and warming the root zone, promoting growth and nutrient uptake. Growers may already utilise black mulches to improve weed control.

3.2. Foliar Feeds

The efficacy of soil applications of calcium will still be dependent on the rate of uptake from the soil through the transpiration stream, rather than the availability of calcium in the soil directly. One potential method of uncoupling fruit calcium status from root absorption may be achieved through foliar applications as opposed to soil fertilisation, which may be particularly useful where crops are grown on plastic. As calcium is applied to the leaf/fruit layer, calcium availability will be enhanced through the provision of an above-ground source of calcium which is independent of transpiration rates. Dilute, water-based solutions of required nutrients are spayed over the crop surface as a fine mist, with the nutrients absorbed predominately through the stomata or absorbed directly through the cuticle. While evidence supporting the use of foliar feeding has been around since the 1950's, the practice and effects are generally highly specific to nutrient type and crop. Uptake is generally more efficient than soil application, but at quantities lower than that seen from the rootzone. Therefore, foliar application is generally seen as a targeted, short term correction for micronutrient availability rather than routine bulk application. However, the application of calcium to the fruit surface may provide an efficient way to supplement nutrition during fruit development.

There is strong evidence that foliar application of calcium can enhance the availability of calcium for fruit development. Foliar calcium applications were trialled in field-grown melon (*Cucumis melo*). Applications of calcium nitrate (3 g/L) and calcium ammonium EDTA (5 ml/L, 34% Ca) with weekly applications during fruit development significantly increased calcium concentration in the fruit rind by upwards of 20% (Bouzo & Cortez, 2012). Foliar feeds of calcium nitrate with organic chelating agents (trihydroxyglutarate) at a concentration of 6% calcium were applied at rates of 0.5 – 1.5 L/ha increased fruit calcium content by more than 3.5 times that seen in the control, while drastically reducing postharvest *Myrothecium* rot development in musk melon (Kuti & Boehm, 1994). Foliar application of 0, 1% and 1.5% chelated calcium to squash (*Cucurbita pepo*) at three points after sowing, gave yield uplifts, with peak responses seen at application rates of 1%. Calcium application also altered the observed sex ratio, increasing the proportion of female flowers and was inferred to enhance cold resistance (Mady, 2014). Mohamed *et al*. (2010) reported enhanced growth, fruit quality and yield following foliar application of 14% calcium when applied alongside a nitrogen source in squash.

Combined calcium/boron applications have demonstrated greater benefits than application of calcium alone. In apple, foliar applications of boric acid and calcium chloride were examined for impacts on fruit quality and BER incidence. BER incidence with boric acid application was 4.7-11.1%, 3.6-6.6% with calcium application (either as calcium oxide or calcium chloride) and 0.5-2.9% with combined treatments compared with 32.7-36% in untreated controls. The greatest response was seen with 0.1% boric acid and 0.4% calcium chloride (Khalifa *et al*., 2009). In tomato, foliar application of $CaCl_2$ (0.6%) and borax (0.4%) gave the maximum benefit to increases in crop biomass accumulation, yield and suppression of BER (Abdur & Haq, 2012) with comparable effects being reported in other crops including blueberry (Chen *et al*., 1998) and strawberry (Singh *et al*., 2007) where such treatment enhanced fruit firmness, storage potential and reduced the incidence of rots. Therefore, while specific application ranges are not available for cucurbits, it is considered likely that a combined boron/calcium foliar application is likely to offer additional benefits to control BER incidence.

A range of preformulated calcium foliar feeds are available (summarised in **Table 1**), but it is not possible to specify optimum rates of application as limited information is available for the use of foliar calcium application in either courgette or pumpkin. Where foliar feeds are to be used, application of dilute solutions are required to avoid tip burn, and application should be made in dull, overcast conditions – stomatal opening in light will promote uptake, but will avoid leaf scorch in full sun. Effects can also be increased in cool, moist days where the applied spray will not rapidly dry on the leaf surface before it can be absorbed, and to promote stomatal opening. The greatest benefit of foliar feeds is likely to be attained if an even application can be achieved. Correct spray calibration, with nozzles set above 45° to create a fine mist over the crop will ensure a consistent and even coating.

Typical pre-formulated foliar sprays will include a number of additives including surfactants (to promote even distribution of spray on the leaf), humectants and anti-evaporants to ensure the feed remains liquid for as long as possible to promote uptake. The application of combined calcium/boron feeds can result in precipitation leaving residues on the leaf surface, but it is considered that combined application is of greater efficacy, compensating for the risk of residues. Foliar feeds may also include other elements (e.g. nitrogen, magnesium) which may further promote growth and fruit development, although care must be taken to ensure an adequate N balance is maintained to avoid the risk of enhancing disease incidence by promoting a rush of growth caused by higher N availability. While timing of foliar application is likely to vary between cultivar and growing conditions, application should begin with first flowering, and continue throughout fruit enlargement until maturation begins. In pumpkin, application of foliar feeds is continued from flowering until two weeks before harvest on a weekly basis.

The benefit of foliar applications must be set against the costs of product application, labour provision and the likely incidence of BER in a given crop. The maximum benefit of foliar calcium application may be achieved in conjunction with other management methods. For instance, a consistently high soil water deficit lead to increased laminar thickness and to increased hydrophobic leaf surface chemistry, which may reduce the uptake of foliar feeds by the crop (Oosterhuis, 2009).

Unfortunately, the lack of robust guidelines or an empirical evaluation of the efficacy of different calcium/boron application methods, together with the variability in BER incidence, precludes a vigorous cost/benefit analysis of calcium foliar feeding. However, targeted field trials assessing the impacts of calcium/boron application are supported by the strong evidence highlighting the benefits of supplementation on BER control.

Table 1. Summary of available calcium products

Product	Supplier	Calcium	w/w (%) or mg/kg	w/v (%) or mg/l	Boron	w/w (%) or mg/kg	w/v (%) or mg/l	Notes
Bio18	OMEX	-	-	-	**B**	190	290	An 18-18-18 NPK + 3% Fe concentrated water soluble suspension.
Bio 20	OMEX	-	-	-	B	190	290	Complete fertiliser optimised for foliar application containing nutrients and biostimulants
CalMax Ultra	OMEX	CaO	14.5	21.8	B	490	730	Propriety formulation including AXM to promote calcium uptake in periods of low metabolic activity.
Kelpak	OMEX	CaO	-	800 mg/L	B	0.24	-	Organic biostimulant containing concentrated extract of the kelp species *Ecklonia maxima*.
Kelpomex	OMEX	CaO	-	800 mg/L	B	0.24	-	Organic growth stimulant containing concentrated extract of kelp species *Ecklonia maxima*. Approved as an unrestricted input by the Soil Association.
Micromax	OMEX	-	-	-	B	0.75	1	Water soluble suspension containing a balanced range of micronutrients.
Quad 14	OMEX	CaO	12.5	19.5	-	-	-	Concentrated suspension formulation N, P as phosphite, K and Ca.
YaraLiva TROPICOTE	YARA	CaO	26.3	-	-	-	-	Granular calcium nitrate for field application.
YaraLiva NITRABOR	YARA	CaO	25.9	-	B	0.30	-	Field grade calcium nitrate fertiliser, with added boron.
YaraLiva CALCINIT	YARA	CaO	26.3	-	B	-	-	Water soluble nitrogen and calcium fertiliser (15.5% N + 26.3% CaO) is a fully water soluble nitrogen and calcium fertiliser.
YaraVita STOPIT	YARA	CaO	16	22.5	-	-	-	Liquid micronutrient fertiliser (calcium chloride solution) for foliar application.
Nutrical	Indigrow	CaO	16.5	-	-	-	-	Formulation of calcium for foliar or fertigation application
IndiPlex B	Indigrow	Ca	-	-	B	17	-	A soluble source of boron for foliar application or fertigation.
CaBo	Solufeed	Ca	6.5	7.8	B		-	Calcium and boron liquid foliar fertiliser with 5.2% w/w N
Carnival	Headland	CaO	225 g/L	-	B	750 ppm	-	Soluble calcium formulation with 30 g/L MgO, 149 g/L N and 300 ppm Zn
TECAL	Crop Intellect	CaO	-	7	B	-	0.10	Calcium formulation with patented chemistry to adjust cellular calcium partitioning.
Agroleaf Liquid Calcium+	ICL	$Ca_5H_4N_{12}O_{33}$	40 - 65	-	-	-	-	Calcium formulation including amino acids, plant sugars, lignates and surfactants
Nova Calcium	ICL	CaO	26.5	-	-	-	-	Calcium formulation with nitrogen for fertigation.
Chelan CaP	Nature SA	CaO	14	18	B	0.2	0.26	Liquid Ca/P fertiliser for foliar application. P205, CaO, B and Zn blend.
Chelan B	Nature SA	-	-	-	B	8	10	Liquid Boron fertiliser
Cal-Mag Max	Growth Products	$Ca(NO_3)_2$	4	-	-	-	-	Chelated Ca and Mg blend.
Calcium nitrate (Horticulture Grade)	Van Iperen	$Ca(NO_3)_2$	18.8	-	-	-	-	CaO/NO_3 mix

3.3. Alternative Growing Systems

Grafted Rootstocks

The use of grafted plants has been suggested as a method of enhancing calcium status and reducing BER incidence. The use of grafted plants has become standard in other sectors (e.g. tomato) as a method of allowing desirable rootstock traits (e.g. stress and disease resistance) to be combined with target cultivars. Melon and cucumber scions grafted onto *Curcurbita* rootstocks showed increased resistance to saline conditions (Rouphael *et al*., 2012), and grafts between cultivars of melon improved nutrient and water use efficiency (Rouphael, 2010; Han *et al*., 2009). While grafting would be suitable for those growers which use transplants, grafting plants would represent an additional cost (and time) at the propagator stage and only limited evidence is available to guide rootstock choice in courgette and pumpkin. Furthermore, this would be unsuitable for growers that sow from seed. Therefore, while grafting could be a potential solution, its application is likely to be limited.

Alternative Growing Systems

The use of hydroponic growing systems may also offer increased control over BER incidence. Some growers have trialled growing courgette and pumpkin in hydroponically-fed peat, using either fresh or recycled bags from strawberry production (**Figure 2**), using a similar feed program for strawberry production. Water supply and nutrition can be more precisely controlled through substrate-based hydroponic fertigation systems, while the use of plastic substrate bags improves weed control (**Figure 3**). This will ensure a suitable level of soil moisture and nutrient balance is maintained throughout the lifespan of the crop, and may significantly reduce the incidence of BER. Lastly, growth under plastic may also aid in stabilising the growing environment, promoting even nutrient uptake throughout growth (**Figure 4**). Suitable guidelines for the use of alternative production systems for cucurbits will require further investigation to develop. The increased costs of production (labour and installation costs) may preclude the wider uptake of these approaches, but they may be suitable for growers with an existing infrastructure or for growers producing high value, speciality cultivars of culinary pumpkin.

Figure 2. Pumpkin cultivated in recycled strawberry bags, using line-fed fertigation.

Figure 3. Courgette grown in table top strawberry production systems, allowing precision fertilisation.

Figure 4. Production of courgette under protection in open-ended polytunnels.

3.4. Postharvest Management

Besides cultivation practice, correct storage of produce after harvest may also help to limit yield loss. In pumpkin, storage longevity may be enhanced by curing off fruit, a process used in the USA to allow storage of pumpkin and squash for up to three months. Some growers leave pumpkin crops to cure in windrows within the fields whilst others lift produce from the field which is then cleaned and stored in a well ventilated barn or tunnel for curing. Temperatures of c. 27°C are targeted during the day, and night temperatures are kept above 15°C, with a relative humidity of 80-85%. These conditions promote further ripening of the fruit (enhancing flavour/textural qualities and sugar content), alongside hardening of the rind and healing of wounds further prevent rot development. When produce is to be stored, fruit must be handled with care to avoid damage to the rind, and produce screened for damage/disease incidence before being stored. It may also be advisable to ensure the stem is sufficiently trimmed so as to avoid puncturing other fruit when stored in bins. Curing will also help the healing of the stem scar, although this can be done in the field if the weather is suitable. Chilling is unlikely to be a hazard for UK grown produce grown for the Halloween market, but fruit should not be exposed to temperatures below 10°C to avoid chilling damage and increased risk of rots. Pumpkins can be stored in cool, dry and well ventilated conditions at temperatures around 14°C with a relative humidity of 50 – 70% to limit microbial growth. In courgette, fruit is typically not stored for prolonged periods and therefore storage is of less concern. Courgette can be stored for 1-2 weeks at 5-10°C at 95% humidity. While this practice is likely to be beneficial for longer term storage, the majority of growers are unlikely to have sufficient facilities to cure pumpkins out of the field and the added labour/energy costs may not be justified. This approach is also incompatible with the pick-your-own marketing model which is becoming common in the sector as growers seek to market directly to the public as part of the evolving dominance of the Halloween holiday. However, for higher value culinary pumpkins, appropriate storage assists growers seeking to better meet variation in consumer demand.

3.5. Knowledge Gaps

While there is strong support for the link between calcium nutrition and the incidence of BER, precise guidelines for effective supplementary feeding in cucurbits is missing. A comparison of commercial products, optimum methods and timing of application through targeted field trials will be required in order to produce robust guidance for growers. In addition, the variety of contributing factors and an inconsistence of BER risk means that without further evidence relating to the efficacy of the various calcium management techniques (including foliar feeding) growers will have difficulty evaluating the financial costs of supplementary calcium/boron feeding against potential benefits. Therefore, further work will be required to fully appraise the potential of nutrient management to aid control of BER.

4. Conclusions

The incidence of BER in cucurbits is highly variable, with variable levels of incidence between locality and season. While no clear threshold for fruit calcium concentration has been defined, there is a strong body of evidence that the probability of produce developing BER is linked with the amount of calcium available to the fruit during its development. The complexities of calcium supply to the growing fruit further add to the complexity of the condition. While the availability of soil calcium can be maintained at optimum levels through careful management of soil nutrient status, the impact of the environment on calcium uptake and use means that adequate calcium supply to the fruit cannot be guaranteed.

Growers should seek to control BER through an integrated approach to minimise the risk of disease development in the fruit. Key action points are:

- Careful management of the soil nutrient status, acting to ensure soil pH is maintained around 6.5 and careful control of nitrogen application to prevent high rates of growth and high concentrations of ammonium in the soil to favour calcium mobilisation in the soil.
- Promote consistent crop transpiration. Root growth can be encourage by avoiding compaction, and careful use of irrigation to ensure that periods of drought are avoided.
- The use of trickle tape irrigation and plastic mulches can improve soil water management.
- Foliar application of calcium and boron-containing fertilisers may increase calcium content of developing fruit, enhancing the robustness of fruit tissues to physiological or pathogenic breakdown.
- Alternative growing practices and postharvest management may further reduce the incidence of BER, but these are unlikely to be economical unless used in high value crops.

The evidence included in this review continues to support the implication that effective calcium nutrition can help to mitigate the risk of BER. While broadly supported by findings in similar fruit crops, there is only limited information is available regarding the efficacy of additional calcium applications in courgette and pumpkin. Further work will be required to develop robust guidelines for calcium supplementation in UK cucurbit production and to update best practice (e.g. RB209).

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