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REVIEW

An Integrated Approach to Control and Manage Potato Black Dot Disease: A Review

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Abstract

Potato black dot is a foliar and tuber blemish disease that has become an increasingly economic problem in recent years. Black dot is caused by the fungus *Colletotrichum coccodes* and is characterised by silver/brown lesions on the tuber skin leading to lower aesthetic quality of potatoes destined for the pre-pack market. Given the consumers' growing demand for washed and pre-packed potatoes, skin blemish diseases (such as black dot and silver scurf), once considered of minor importance, are now serious challenges for the fresh potato industry. The management of *C. coccodes* is far from satisfactory at either pre- or postharvest stages: firstly, the disease symptoms have not been consistently described on potato plant foliage; and secondly, black dot disease is often confounded with other tuber blemishes during postharvest storage. Good field managing practices in combination with improved postharvest strategies and an accurate detection support tool can be a useful integrated approach to manage potato black dot disease. This review aims to evaluate and critically discuss different novel approaches for better management and detection of potato black dot disease.

Resumen

El punto negro de la papa es una enfermedad foliar y del tubérculo que se ha convertido en un problema económico en aumento en los últimos años. El punto negro es causado por el hongo *Colletotrichum coccodes* y se caracteriza por lesiones plateadas/café en la piel del tubérculo que conducen a una menor calidad estética de las papas destinadas al mercado de pre-empacado. Dada la creciente demanda de los consumidores de papas lavadas y preenvasadas, las enfermedades con manchas en la piel (como el punto negro y la sarna plateada), que alguna vez se consideraron de menor importancia, ahora son serios desafíos para la industria de la papa fresca. El manejo de *C. coccodes* está lejos de ser satisfactorio en las etapas previas o posteriores a la cosecha: en primer lugar, los síntomas de la enfermedad no se han descrito consistentemente en el follaje de la planta de papa, y en segundo lugar, la enfermedad del punto negro a menudo se confunde con otras imperfecciones de tubérculos durante el almacenamiento poscosecha. Las buenas prácticas de manejo de campo en combinación con estrategias poscosecha mejoradas y una herramienta de apoyo de detección precisa pueden ser un enfoque integrado útil para controlar la enfermedad del punto negro de la papa. Esta revisión tiene como objetivo evaluar y discutir críticamente diferentes enfoques novedosos para un mejor manejo y detección de la enfermedad del punto negro de la papa.

Keywords *Colletotrichum coccodes* · Image analysis · Postharvest management · Machine learning · Tuber blemish disease

Introduction

Potato (*Solanum tuberosum* L.) is an important crop for the processing and fresh markets worldwide. Global potato production has increased by approximately 20% over the last 30 years; with China being the largest producer globally (FAOSTAT 2020). In 2020, around 5.5 million tonnes were produced in the United Kingdom (UK) and these production levels have been maintained over the past 20 years (FAOSTAT 2020).

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The potato crop can be classified depending on final destination (e.g. processed, fresh [e.g. washed and pre-packed] and seed market) or according to the maturity type (*viz*. first early, second early, maincrop, etc.) (Ivins and Bremner 1965). Potato tubers destined for fresh market can be kept up to ten months under optimum postharvest cold storage conditions including temperatures lower than 4 °C, high relative humidity (*ca*., 98% RH) and controlled air ventilation. These conditions not only ensure good wound healing but also control and reduce both pathogen and sprout development during storage (Olsen 2014).

Changes in consumers' preferences have led to a growing demand for pre-packed potato in Great Britain with a 3.4% increase over the last four years in the share of volume (AHDB 2021). Tuber appearance has a significant impact on marketability (Lees and Hilton 2003), which can be hampered by skin blemish diseases such as black dot or silver scurf.

Potato black dot is a blemish and foliar disease caused by the fungus *Colletotrichum coccodes* (Wallr.) S.J. Hughes, which negatively affects tuber appearance leading to economic losses in the potato pre-pack industry due to consumer rejection. In the UK alone, black dot causes up to £3 million ($3.8 million) in losses to ware crops annually. The main symptom of potato black dot disease is the presence of macroscopic black sclerotia, the survival fungal structures, on infected tissues (Johnson et al. 2018). As the disease progresses through the potato periderm, black dots turn into silver/brown patches, also known as a black dot lesion (Fig. 1), with undefined edges during postharvest storage making the aesthetic impact on potato tubers more significant (Jellis and Taylor 1974).

Reducing black dot levels at harvest can minimise disease progression during postharvest (Lees and Hilton 2003). However, current strategies for the control and management of potato black dot are mostly limited to fungicide application, crop rotation, curing conditions, and storage temperature. Moreover, existing black dot disease research has been carried out either from a pre- or postharvest perspective (Brierley et al. 2015; Cummings and Johnson 2008; Lees et al. 2010; Massana-Codina et al. 2021), with limited studies looking at the interaction across the pre- and postharvest continuum (Peters et al. 2016). Consequently, there is currently insufficient guidance available for growers and storage practitioners on how to effectively manage their crops, highlighting the need for further research to address this knowledge gap, particularly the need for defining an integrated approach to disease and control management.

Silver scurf is another potato tuber blemish disease, caused by *Helminthosporium solani* Dur. and Mont. Both *C. coccodes* and *H. solani* affect the potato periderm, and even though they are two different pathogens, the symptoms on the potato skin are quite similar (Fig. 2), making their detection and differentiation difficult throughout storage (Massana-Codina et al. 2021).

As part of the overall strategy to manage potato black dot, implementing an accurate diagnostic tool that uses computer vision coupled with machine learning techniques can be highly powerful to detect the disease at their early stages. While ongoing research is investigating the applicability of machine learning algorithms, such as Visual Geometry Group (VGG), to detect various potato diseases using RGB (red, green, blue) tuber images (Oppenheim et al. 2019), the small size of microsclerotia and the potential confusion with other diseases with similar symptoms make the detection of black dot disease challenging. As such, the objective and automatic detection of potato black dot could play a crucial role in developing predictive models to determine the optimum storage time for different potato consignments based on the initial incidence and severity (percentage of tuber surface affected by the disease) of black dot at storage loading.

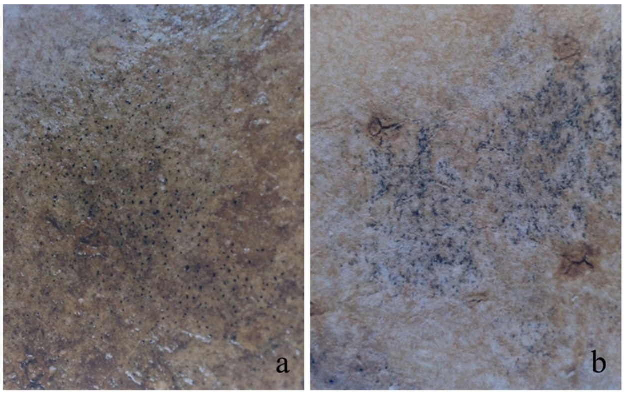

Fig. 2 Close up of (**a**) black dot lesion on tuber showing discrete, black microsclerotia of *C. coccodes*, and (**b**) silver scurf lesion showing *H. solani* conidiophores. Source: Read, P. J (1993). Epidemiology, effects and control of black dot disease of potato caused by the fungus *Colletotrichum coccodes*. PhD thesis, Cranfield University, UK

Fig. 1 **Potato black dot disease development throughout postharvest cold storage**. The development of potato black dot disease was monitored on 'Maris Piper' tubers stored at 3 °C and > 95% relative humidity, for ten months

Therefore, the aim of this review is to critically evaluate pre- and postharvest strategies from the last 20 years, and to identify gaps in knowledge to improve potato black dot disease management. The importance of having an integrated approach to manage potato black dot including novel technologies for controlling and diagnosing potato black dot for efficient disease management is also discussed.

Preharvest Factors Affecting Potato Black Dot Development

C. coccodes not only causes tuber blemish symptoms but also symptoms on the stems and foliage leading to crop losses and yield reduction, even though the effects on yield might not always be consistently observed (Pasche et al. 2010). The disease cycle is complex since both sclerotia and conidia are able to infect potato plants (Ingram 2008). The sclerotia of *C. coccodes* can survive for at least eight years in the field (Dillard and Cobb 1998) but they can also survive on seed tubers, and crop debris. Moreover, fungal colonisation can occur in roots, stolons, stems, and daughter tubers by internal growth of mycelial hyphae (Lees and Hilton 2003).

Previous studies have shown that both planting of clean potato seed in infected soil and infected seed in clean soil (under glasshouse conditions) resulted in a rapid infection of all underground plant parts (Lees and Hilton 2003). Cullen et al. (2002) found that *C. coccodes* was present in fields that had not been planted for 5, 8 and 13 years with potatoes, suggesting that once the soil is infested by the fungus, the soilborne inoculum becomes the predominant source of infection. In contrast, seedborne inoculum plays a less important role in the final disease levels (Lees et al. 2010). Massana-Codina et al. (2021) found that black dot incidence on seed tubers did not correlate with black dot severity in daughter tubers. Lees et al. (2010) also defined different pathogen load categories in the soil based on the fungi inoculum and, therefore, disease risk: soils with < 100 picograms (pg) DNA g^{-1} were considered to confer a low risk of infection; levels between 100 and 1000 pg DNA g^{-1} resulted in soils with medium risk; and soils with > 1000 pg DNA g^{-1} were considered high risk. That said, in a recent potato black dot field study, Massana-Codina et al. (2021) established 50 pg DNA g^{-1} soil as a threshold; and, as a result, fields with less than this inoculum load would reduce the total number of unmarketable tubers from 24 to 16% (considering that tubers with more than 10% of their surface area affected with black dot lesion are unmarketable). That indicates that the selection of a field with low fungal inoculum is important to keep low levels of black dot on daughter tubers and, therefore, the selection of the field is a crucial factor to consider in an integrated approach for a better disease management.

Soil characterisation is another factor to be considered when managing black dot incidence. For instance, Harris et al. (2003) studied the effect of soil structure (modifying soil bulk density) on the spatial exploration of soil by the fungus *Rhizoctonia solani*. They found that fungal mycelia expanded throughout the heterogenous networks of pores to find nutrients and the volume of soil explored by the fungus was higher with increasing bulk density, suggesting that soil structure may influence the final soil inoculum. However, there was no significant effect of soil type (*viz.* sand, clay, and mineral soils) on the amount of DNA from *C. coccodes* quantified by polymerase chain reaction (PCR) (Brierley et al. 2009). This contradiction could be due to the milling procedure (sample preparation under laboratory conditions) where the soil particle structures are broken down and, therefore, the DNA binding capacity of soil particles is reduced (Martin-Laurent et al. 2001).

Under current and forecasted climate change conditions elevated temperatures over summer and an unpredictable pattern of rainfall in the UK are expected (Morison and Matthews 2016). Adesina and Thomas (2020) predicted that in a future scenario (2050–2080) the combined increase of temperatures and spells of droughts can negatively impact the potato production. Moreover, among other biotic factors, pathogens, are also affected by climate change creating future risks for crop production (Verheecke-Vaessen et al. 2019), including the potato crop. Climate conditions, such as temperatures during seed stock growth, have been found to affect the development of potato black dot at harvest. Lees et al. (2010) used controlled environmental conditions to investigate the effect of different growing temperatures (seed tubers grown at 18 °C and 22 °C) and soil moisture content on black dot development in potato tubers, cultivar Maris Piper ('Maris Piper'), one month after harvest. They found that higher temperature (22 °C) and damp conditions stimulated black dot development (*ca.* 40% black dot incidence and *ca.* 8% black dot severity) being four-fold higher than under drier conditions and below 18 °C, supporting the hypothesis that the incidence and severity of fungal diseases will increase because of a changing climate further compromising potato production.

Managing Black Dot Disease in the Field

There are limited disease management measures for black dot disease on potato plants. Current strategies to control black dot disease in the field include crop duration [the time from 50% emergence of the crop until harvest (Cunnington 2008)], crop rotation and fungicide application (Johnson et al. 2018). In 2015, Brierley et al. found that the in-furrow application of fungicide azoxystrobin reduced black dot severity where the soil inoculum was lower, reducing the percentage of unmarketable tubers on 'Maris Piper' from 26.7% to 14.6%, and from 12.9% to 7.1% in 'Sante' at harvest time. However, the effect of fungicide application on black dot development might not be as effective when there are high levels of black dot inoculum in soil (Wicks 2005). In 'Ranger Russet', Cummings and Johnson (2008) showed that a single foliar application of azoxystrobin applied at an early growth period had a greater impact on reducing black dot on stems than in-furrow application at planting. Azoxystrobin was approved for in-furrow soil applications for black dot and *Rhizoctonia* in 2004 (Brierley et al. 2015), but the foliar application of azoxystrobin is not yet approved in the UK for black dot. In addition, due to *C. coccodes* being a highly diverse species, with a degree of genetic and pathogenic differentiation among isolates (Johnson et al. 2018), further research on fungicide resistance is warranted for a better evaluation of the fungicide and a possible incidental reduction in black dot from foliar applications.

Limited studies have investigated the direct fumigation of infected soil and its impact on tuber black dot development. Stevenson et al. (1976) used chlorinated C3 hydrocarbons (DD) and DD-MENCS (DD + methyl isothiocyanate) to fumigate potato pots under glasshouse conditions, yet failed to control *C. coccodes*. Denner et al. (1998) used the currently banned methyl bromide to reduce the incidence of black dot disease in daughter tubers. That said, there are no recent studies that have pursued the approach of direct soil fumigation to control *C. coccodes*.

A more sustainable management of black dot disease, where the use of fungicides is reduced, may result through better understanding the fundamental mechanisms of black dot resistance. However, the genetic, morphologic, physiologic, and metabolic basis of host resistance to black dot are still not well understood (Nitzan et al. 2009; Johnson et al. 2018; Massana-Codina et al. 2020). In 2009, Nitzan et al. identified several potato lines within their breeding program that exhibited certain resistance to black dot. However, the heritability of the resistance to stem colonisation by *C. coccodes* was low, indicating that the development of resistant cultivars to black dot is a challenging process (Johnson et al. 2018). To date, potato cultivars resistant to black dot are not commercially available. Massana-Codina et al. (2020) discovered significant differences in the metabolite composition among five cultivars, uncovering potential biomarkers of black dot resistance. Notably, the glycoalkaloid alpha-chaconine seemed to be associated with black dot resistance. Overall, the results suggested that metabolite composition is the main determinant of potato resistance to black dot, and these compounds could be used within existing breeding programs to contribute to the sustainable production of fresh potatoes.

According to Brierley et al. (2015), delaying harvest by two weeks (longer crop duration) increased disease severity, suggesting that the longer a crop remains in the ground, the greater the risk of black dot development, particularly where there exists a high level of soil inoculum. More recent studies suggested that infection and colonisation take place during initial root growth and that crop duration has a consistent and significant effect on disease severity (Peters et al. 2016). Based on the above, the current consensus to control potato black dot in the field would involve planting in fields with low soil fungal inoculum, applying fungicide (i.e., azoxystrobin at the early stage of potato growth) and limiting the harvest time after the haulm destruction whilst ensuring good skin set. Yet, the impact of the interaction of these risk factors on the progeny tubers during postharvest cold storage is little known and further research would be needed to provide effective management strategies. Following these practices would be the first steps to keep low levels of black dot disease on tubers during postharvest cold storage.

Postharvest Factors Affecting Potato Black Dot Development

Long-term storage is needed to ensure year-round supplies for both fresh and processing potato industries, and tubers intended for fresh market often are stored up to ten months. Common storage practices involve an initial curing period when tubers are subjected to elevated temperatures (10 °C to 14 °C) during the first two weeks after harvest to ensure wound healing (Hide et al. 1994; Ellis et al. 2019; Wang et al. 2020). However, prolonged warm temperatures during the curing process can encourage a faster development of fungal diseases, increase weight loss, and negatively impact quality properties such as frying quality (reducing sugar content) for processing varieties, shelf-life (affecting respiration rate) or dry matter (Ellis et al. 2019). Therefore, reducing the tuber temperature rapidly, straight after loading the storage room, can help in controlling potato black dot disease during postharvest cold storage (Cunnington 2008). For instance, Hide et al. (1994) showed that avoiding the curing process on tubers resulted in the least levels of black dot in the subsequent storage. Supporting that, Peters et al. (2016) found that an extended curing process (i.e., ten days at 12 °C) favoured black dot development compared to an immediate temperature reduction of the crop.

Potato black dot disease does not spread from tuber to tuber during postharvest cold storage, but infections that were latent (showing black dots) at the moment of harvest can turn to silver/brown lesions and expand in size during storage (Johnson et al. 2018). Therefore, storage conditions are crucial in controlling the disease as it can prevent the onset of black dot lesion development. Current practices focus on using a ventilation system to keep optimum temperature and relative humidity conditions. Particularly, for the UK washed and pre-pack potato market, the optimum temperature for long-term storage is *ca*. 2.5 °C to 3.5 °C (Cunnington and Pringle 2012; Peters et al. 2016). Previous studies have tested in vitro black dot development at different temperatures (5 °C, 10 °C, and 15 °C) and showed that *C. coccodes* can produce lesions on potato tubers 'Charlotte' stored for extended periods (*ca.* five months) within 5 °C to 15 °C (Glais-Varlet et al. 2004). Therefore, keeping the temperature low to minimise disease progression can help to avoid lesions on the potato tuber skin, and, as a result, reduce water loss during storage (Lees and Hilton 2003).

Novel Approaches for Detection and Assessment of Potato Tuber Black Dot Disease

Diagnostics is an important part of the overall approach to control and manage potato black dot, together with proper management in the field and during postharvest storage. Quality inspection in packing warehouses is crucial in order to meet consumer demands and to maintain the specifications required for fresh potato market (i.e., consistency in shape and size, and good skin set free of any disease or blemish) (Lees and Hilton 2003). Potato black dot can be examined with a hand lens or microscope to observe the black microsclerotia.

Traditionally, skin tuber inspection has been carried out by operators visually assessing the external appearance. However, this quality control method is subjective and can be affected by different human errors, including a lack of criteria when classifying the product and tiredness (Oppenheim et al. 2019). In addition, manually sorting diseased tubers can be time consuming and more costly. Standard computer vision coupled with machine learning tools has been used for the assessment of external quality attributes of fruits and vegetables resulting in various positive outcomes, including the reduction of postharvest losses (Cubero et al. 2011; Liu and Wang 2021; Munera et al. 2021; Singh et al. 2022).

Recently, machine learning algorithms such as random forest, artificial neural network (ANN), support vector machine (SVM), fuzzy logic, K-means method and convolutional neural network (CNN) are being extensively used in the field of plant disease classification and detection (Ramesh et al. 2018). Deep-learning (DL)-based techniques (a subset of machine learning), particularly CNNs, are one of the most popular feature sets used in machine learning for the classification of plant diseases (Gongal et al. 2015; Hassan et al. 2021). CNN is a network architecture that mimics how the visual cortex of the brain processes and recognises images (Albawi et al. 2017; Kamilaris and Prenafeta-Boldú, 2018). The popularity of CNN can be attributed to its ability to solve complex tasks that ANN can not achieve while being less computationally expensive. Therefore, CNN improves the accuracy of the correct classification on large datasets (Kamilaris and Prenafeta-Boldú, 2018).

Even though CNN requires large amounts of data to train the model, it is possible to work using visible light bandwidth which can be captured by relatively low-cost cameras, hence, a large data set can be readily obtained. Yet, the performance of the model not only depends on the amount of existing data but also on the quality of this dataset (Hassan et al. 2021; Kamilaris and Prenafeta-Boldú, 2018; Oppenheim et al. 2019). Mohanty et al. (2016) concluded that deep learning CNN methods were a powerful agricultural tool for disease identification in plants. They reported an overall accuracy of 99% using a public dataset of 54,306 images with 38 classes of different plants and diseases combination (such as apple scab, tomato late blight, potato early blight, grape black rot, etc.). Recent developments in deep neural network architectures improved the accuracy of disease detection models in plants. A practical and applicable solution in the agricultural field was the robust deep-learning-based detector proposed by Fuentes et al. (2017). The sensor was able to detect and locate 10 different tomato pests and diseases with an accuracy higher than 90% using RGB images captured in-place by camera devices with a different range of resolutions (such as cell phones and digital cameras). More recently, Oppenheim et al. (2019), has used CNN to classify four different potato blemish diseases (*viz.* black dot, silver scurf, black scurf, and common scab) with a classification accuracy from 83 to 96%. They used low-cost RGB sensors under controlled light conditions and the images obtained were classified by the CNN model. Even though just image patches were used for this study, rather than the whole image of the tuber, the outcome of this research is really promising as it can be a low-cost, fast, and reliable monitoring system to classify different diseases simultaneously. Marino et al., (2019) confirmed that CNN can classify and localise blemishes in potatoes (damaged, greening, black dot lesion, common scab, black scurf) resulting in a global evaluation of the tuber, with an average precision of 95% and average recall of 93%, with a reduction of computing time compared to just using other algorithms such as SVM. This suggests that due to the speed and efficiency of the method, it is feasible to implement it into the real industrial setting. Moreover, using deep-learning algorithms gives the possibility to simultaneously detect different diseases on the same plant. Johnson et al. (2021) presented a Mask Region-based convolutional neural network (Mask R-CNN) architecture able to classify and localise blight disease in potato leaves in the field.

Even though there are in-line commercial machine vision systems that are implemented in packing houses to detect and eject potato tubers affected by skin disorders and/or diseases (Tomra ®), to date, there is no automated model available for detecting the early stages of black dot development, e.g. identification of black dot microsclerotia on potato tuber skin. Using Mask R-CNN for detection and also localisation of black dot (microsclerotia and lesion) on potato tubers could be advantageous in the potato industry for grading purposes, since current manual detection requires experts, can be subjective and is tedious. Introducing an objective and automated method of black dot detection and localisation, both for microsclerotia and lesion, will provide a percentage of disease severity that could be used as input in predictive models to determine the outbreak of potato black dot and therefore the tuber storage life.

Novel Approaches for Black Dot Disease Management in Storage

Overall, there is a paucity of research in assessing black dot development during postharvest cold storage and subsequent shelf-life conditions. Therefore, there are limited studies investigating innovative postharvest storage solutions that could be used in combination with low temperature to minimise disease progression. The application of exogenous ethylene and plant volatile organic compounds (VOCs) have been suggested as alternative strategies to control fungal and fungus-like (Oomycete) diseases on potato tubers during postharvest storage (Wood et al. 2013; Yang et al. 2020).

Ethylene treatment is commercially used to suppress potato sprouting. Previous studies showed that continuous ethylene supplementation (10 μL kg^{-1}) applied either at harvest or at first indication of sprouting is beneficial to suppress sprouting and prolong ecodormancy (Foukaraki et al. 2016; Tosetti et al. 2021). Yet, little is known about the effects of exogenous ethylene supplementation on the incidence and severity fungal development in potato tubers, including black dot disease. Transcriptome analysis done by Yang et al. (2020) demonstrated that the application of exogenous ethylene triggers immune and defence response in potato genotypes that exhibit high resistance to late blight (caused by the Oomycete organism *Phytophthora infestans).* Another in vitro study showed that an addition of ethylene reduced the bacterial endophytic colonisation in *Medicago* spp. (Iniguez et al. 2005) suggesting that ethylene signalling pathway has a role on the action of the endophyte involved on the host defence (Kavroulakis et al. 2007). Yet, the effects of high ethylene concentrations (10 μL L^{-1}) on severity of black dot are not known. And for this reason, further research in vivo is required to assess exogenous ethylene application on black dot development.

Essential oils extracted from e.g. spearmint (*Mentha spicata* L.), orange (*Citrus x sinensis* (L.) Osbeck) and caraway (*Carum carvi* L.) have showed antifungal activity (Thoma and Zheljazkov 2022). Carvone, a compound present in high amounts in caraway, dill, and spearmint essential oils, was effective in suppressing sprouts and controlling fungal growth under 10 °C in 'Norland' and 'Snowdon' potato cultivars (Song et al. 2009). More recently, Boivin et al. (2021), demonstrated that black spruce essential oil could also inhibit sprout growth and manage fungal diseases during potato storage. However, to date, there is a lack of research investigating the efficacy of essential oils against potato black dot in storage, suggesting the need for further research in this area.

Another novel strategy to control black dot during storage includes the use of plant VOCs since they are involved in a wide range of adaptive and physiological functions including anti-fungal properties (Zhang et al. 2020). Wood et al. (2013) carried out in vitro studies using acetaldehyde and 2*E*-hexenal for the control of potato blemish diseases; fungal conidial suspensions of *C. coccodes* were pipetted in 5-cm-Petri dishes and placed in sterile 1 L glass jars where the different treatments were applied (liquid volumes of 2.5, 5, 7.5, and 10 μL of either acetaldehyde or 2E-hexenal, were injected into the jars using an airtight syringe). 2*E*-hexenal was effective as a fungicide since it inhibited fungal growth in vitro (5 μL L^{-1} after 96 h at 23 °C). The outcome of these studies suggests that potato black dot could be controlled by natural compounds during postharvest cold storage. That said, large-scale in vivo trials, simulating long-term commercial conditions, e.g. 2.5 °C to 3.5 °C, should be developed to evaluate the efficacy of these natural compounds in disease development. These technologies could be part of a pre- and postharvest integrated approach and may help to reduce the application of fungicides in the field, thus reducing their environmental impact.

Conclusion and Future Prospects

Current practices to control and manage potato tuber black dot disease include pre-harvest strategies such as avoiding planting infected seed potatoes in healthy fields to reduce soil contamination in further harvest seasons, and fields with high levels of fungal inoculum. However, planting records and measurements of soil load inoculum are required, but they are not always available. The application of fungicides is also widely used, yet the current pressure for the reduction of chemical usage is threatening the appropriate management of fungal diseases. Once harvested, optimum curing conditions, as well as cold temperatures and relative humidity can be manipulated to maintain low levels of potato black dot, however, these can be influenced by factors such cultivar, fungal load, and seasonality. In this context, the development of non-destructive, rapid and automated tools for potato black dot assessment can be used as part of an integrated approach for postharvest disease management (Fig. 3). These diagnostic methods, based on machine vision systems in combination with machine learning algorithms, will enable industry practitioners to take objective

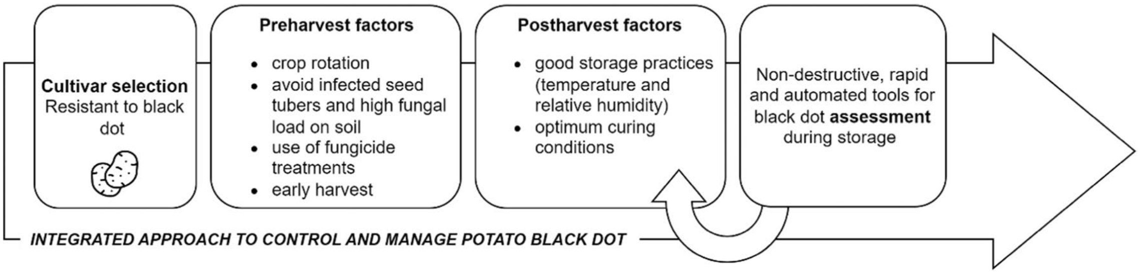

Fig. 3 **Integrated approach to control and manage potato tuber black dot**. Diagram includes the integrated approach to control and manage potato black dot, starting with cultivar selection, current pre- and postharvest strategies and the need of a non-destructive, rapid and automated tool for black dot assessment during postharvest cold storage

and informed decisions about the optimum storage time depending on black dot levels at harvest, which in turn, will prevent diseased tubers from being packed. Overall, an integrated approach for disease control and management is useful not only to provide high quality tubers throughout the year, but also to prevent food loss and waste within the potato supply chain.

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Data Availability Data sharing is not applicable to this article as no new data were created or analysed in this study.

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