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Diseases of dragon fruit (*Hylocereus* species): Etiology and current management options

M.A. Balendres [*], J.C. Bengoa

Institute of Plant Breeding, College of Agriculture and Food Science, University of the Philippines Los Baños, Laguna, 4031, Philippines

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ABSTRACT

More than seven billion people compete for food to survive. Agriculture has increased the production of staple crops, through plant breeding and biotechnology, in arable areas that are now becoming limited due to industrialization. With staple crops becoming a common diet and with people getting the same nutrients from these foods, wild, exotic and underutilized edible plants are being explored as supplements or alternatives. One potential plant is dragon fruit or pitahaya. This vine cactus plant is water-efficient, rich in betalains and antioxidants, has medicinal benefits and is a source of income to growers. However, dragon fruit production faces significant challenges. Among these, losses due to diseases play a significant role in fruit-yield reduction and profitability. This paper provides a comprehensive review of dragon fruit diseases, their associated pathogens, distribution, and their current management options. We conclude that anthracnose, fruit and stem rot, stem canker and the cactus viral disease are among the most frequently reported diseases of dragon fruit and actions are needed to address the growing problems associated with these diseases as effective, sustainable and practical management strategies are yet to be identified.

1. Introduction

Known for its distinctive appearance and delicate texture (Nerd et al., 2002), plants in the Cactaceae family are easily distinguishable from the other families in the plant kingdom (Nobel, 2002). Within this family, the vine (climbing) cacti (*Hylocereus* species) are among the most important members because of their edible fruits (Casas and Barbera, 2002), which have been part of the human diet for over 9000 years (Nobel, 2002). Fruits of *Hylocereus* species or “pitahayas” or “dragon fruit” can range from small (100–250 g) to large (200–800 g) depending on the species (Lichtenzveig et al., 2000; Tel Zur, 2015). The fruit contains high levels of sodium, potassium and Vitamin A, and has total solid contents of up to 16.6% (Martinez et al., 1996; Nerd et al., 1999; Tel Zur, 2015). It is also a source of prebiotics (Wichienchot et al., 2010) and antioxidants (Tenore et al., 2012), of which the latter made dragon fruits known for its medicinal benefits (Le Bellec et al., 2006). For instance, in China, fresh and dried flowers of “Bawanghua” (dragon fruit) are used routinely as a medicinal food (Ma et al., 2014). Though more research is needed, there are some findings that, at higher dose, dragon fruit may reduce blood glucose level (Poolsup et al., 2017). Dragon fruits are rich in betalains (Wybraniec et al., 2001; Stintzing et al., 2002, 2004) that are widely used as colorants in the food industry (Henry, 1996; Ortiz, 1999; Wybraniec et al., 2007) substituting the synthetic colorants (Azeredo, 2009).

Hylocereus species are native to South America, Central America and Mexico (Barthlott and Hunt, 1993; Pimienta-Barrios and Nobel, 1994). It was brought to the Philippines by Spaniards in the 16th century and this introduction was pivotal to dragon fruit cultivation in Southeast Asia (Casas and Barbera, 2002). The French introduced dragon fruit in Vietnam (Mizrahi et al., 1997) and since then Vietnam tremendously increased its dragon fruit production. Vietnam is now the top exporter of dragon fruits (Tel Zur, 2015; Mercado-Silva, 2018). The most commonly cultivated species (Table 1, Fig. 1) are *H. undatus, H. monacanthus* (previously known as *H. polyrhizus*), *H. megalanthus* (previously known as *Selenecereus megalanthus* – also a vine cactus), and *H. costaricensis* (Bauer, 2003; Tel Zur, 2015), but there are 11 more species in the genus *Hylocereus* (Bauer, 2003). Dragon fruit plants are water-efficient – *Hylocereus* species are facultative epiphytes that initially roots in the soil and then later become fully epiphytic (Wallace and Gibson, 2002) – due to the Crassulacean acid metabolism (CAM) and this makes dragon fruit appealing in arid, semiarid and in other regions with limited water or irrigation (Nobel, 1994; Nerd et al., 2002; Nobel, 2002). *Hylocereus*

* Corresponding author.
E-mail address: mobalendres@up.edu.ph (M.A. Balendres).

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Table 1
Cultivated *Hylocereus* species and their distinguished fruit characteristics.

Species	Fruit Characteristics	Cultivation
H. undatus (Hamworth) Britton & Rose	Large oblong, reed peel with large greenish scales and white pulp	Mostly in the Taiwan, Thailand, Cambodia, Philippines, Israel, Mexico and Vietnam. But also, in most dragon fruit-producing countries.
H. monacanthus or *H. polyrhizus* (Weber) Britoon & Rose	Large oblong, dark red peel with scales and violet-red pulp.	Mainly cultivated in Israel but are now grown in many countries.
H. megalanthus or *S. megalanthus*	Medium oblong, yellow peel with tubercles and spines and white pulp	Grown mainly in Colombia, Ecuador and Israel
H. costaricensis (Weber) Britton & Rose	Large globose, dark red peel with large scales and deep red pulp	Mainly cultivated in Nicaragua and Guatemala

Source: Nerd et al., 2002.

undatus, fruits with red peel and white flesh (pulp), is the most cultivated species worldwide (Nerd et al., 2002). Dragon fruits can be propagated by seeds, by micropropagation (Mohamed-Yasseen, 2002) or vegetatively (Ortíz-Hernández, 1999).

Dragon fruit production can offer high returns to growers, particularly in the export market. Colombia was the first country to cultivate dragon fruits for export to Japan (Nerd et al., 2002). Currently, Colombia, Ecuador, and Israel ship *H. megalanthus* to Europe. In the US, dragon fruit has the potential to be a profitable crop (Merten, 2003). Dragon fruits are also produced in Australia, New Zealand, Spain, and the Philippines. There is a high demand from the food industry in the US and Europe because dragon fruit pulp is used as a natural food ingredient and colorant (Ortiz, 1999; Nerd et al., 2002). Taste and yield improvement of dragon fruit are being done in Israel (Nerd et al., 2002; Tel Zur, 2015). Mexico produced dragon fruits from 2000 ha but usually for the local market (Nerd et al., 2002). Area planted for dragon fruit in Vietnam grew enormously from 6000 to 50,000 ha (Tel Zur, 2015), and fruits are common in the local supermarket and are exported to Asian and European markets (Nerd et al., 2002). The same pattern emerged in Israel where dragon fruit production expanded rapidly since the 1970s (Nerd et al., 2002; Tel Zur, 2015). The total world production is about 1 million tons, with the US being the top importing country and Europe as the top importing region (Mercado-Silva, 2018).

However, like many crop ventures, dragon fruit growers are faced with several production issues contributing to yield reduction. Among the issues faced is the short storage life of the fruit and the non-stable fruit supply as flowering and harvesting occurs in waves (Mizrahi and Nerd, 1999; Nerd et al., 2002). Exacerbating the short storage and shelf life is the presence of diseases. Mercado-Silva (2018), Tel Zur (2015), Nobel (2002) Le Bellec et al. (2006), and Ortiz-Hernandez and Carillo Salazar (2012) have reviewed the taxonomy, botany, medicinal properties, geographical distribution and industrial uses of dragon fruits, but no comprehensive review has been made for dragon fruit pathology. In 2013, Valencia-Botin et al. 2013 provided a brief overview of some dragon fruit diseases and their associated pathogens. However, since then, and particularly in the last 5 years, there were significant numerous new and first country reports of dragon fruit diseases and their associated pathogens. This paper reviews the diseases of dragon fruit (*Hylocereus* species), their causal agents and distribution. Finally, strategies that can be used in managing dragon fruit diseases are discussed. Most literature in this paper published after 2003 have adapted *H. polyrhizus* instead of *H. monacanthus*. In the current paper, *H. monacanthus* and *H. megalanthus* were used to refer to *H. polyrhizus* and *S. megalanthus*, respectively, in accordance with the classification of Bauer (2003).

2. A brief overview of cacti diseases

In Mexico, Italy and South Africa, the disease known as *Alternaria* golden spot caused severe damage on cacti (Zimmermann and Granata, 2002). Fungal diseases such as the Armillaria root and stem rot (*A. mellea*), foot rot (*Phytophthora cactorum* and *P. nicotinae*), gray mold (*Botrytis cinerea*), the "Roya" disease (*Aecidium* sp.), Fusarium wilt (*F. oxysporum* f. s. *Opuntiarum*) and necrotic spots (*Cercospora* spp., *Cytospora* spp., *Gleosporium* spp., *Mycosphaerella* spp., *Phoma sorghina, Pleospora herbarum* and *Colletotrichum* spp.) have been also reported (Zimmermann and Granata, 2002). In South America, *Aecidium* spp., *Cercospora* spp. *Phoma sorghina* and *Dothiorella ribis* were also found (Zimmermann and Granata, 2002). Associated with bacterial spot (*Erwinia carotovora*) is the yeast disease cladode soft rot caused by *Candida boidini* (Phaff et al., 1978). In Mexico, crown gall caused by *Agrobacterium tumefaciens* has been reported (Gutiérrez, 1992). There is a scarcity of studies on viral diseases, but few reports existed (Chessin, 1965). These diseases, however, have been reported in cacti in general. Nevertheless, of all these previously reported pathogens, only *Fusarium* spp. *Colletotrichum* spp. *B. cactivora* have been associated with current diseases of dragon fruits occurring worldwide.

3. Current diseases of dragon fruit and their associated pathogens

There are 17 genera and 25 species of plant pathogens currently infecting dragon fruits (Table 2). The majority causes fungal diseases in stem, fruits, and flowers. There are only two bacterial, one viral and a nematode disease. Fruit and stem rot (*B. cactivora*), canker (*Neoscytalidium dimidiatum*), anthracnose (*Colletotrichum* species) and viral disease (*Cactus virus X*) are the most frequently reported diseases. The most recent report was anthracnose caused by *C. siamense* in India (Abirammi et al., 2019) and *C. karstii* in Brazil (Nascimento et al., 2019). Recent and new country records of pathogens associated with dragon fruit were mostly reported in the last 5 years.

3.1. Fungal diseases

There are 21 fungal species that cause various dragon fruit diseases

Fig. 1. Dragon fruits. A) *Hylocereus undatus,* B) *H. monacanthus* and C) *H. megalanthus.*

Table 2
Fungal, bacterial, nematode and viral pathogens and their associated diseases in various *Hylocereus* species.

Genus	Species	Disease	Hylocereus sp. Infected	Country Report	Reference
Alternaria sp.	*A. alternata*	Postharvest rot	*H. undatus* and *H. megalanthus* [a]	–	Vilaplana et al. (2018), Castro et al. (2018), Castro et al. (2017)
	Alternaria sp.	Alternaria blight	*H. undatus*	–	US (Patel and Zhang, 2017)
Aureobasidium sp.	*A. pullulans*	Stem and Fruit Spot	*H. undatus* and *H. monacanthus*	China	Wu et al. (2017)
Bipolaris sp.	*B. cactivora*	Fruit and stem rot, Post-harvest rot disease	*H. undatus*	Israel, China [b], Thailand, Taiwan, US, Korea, Japan	Ben-Ze'ev et al. (2011), He et al. (2012), Oeurn et al. (2015), Wang and Lin (2005), Tarnowski et al. (2010), Choi et al. (2010), Taba et al. (2007)
Botryosphaeria sp.	*B. dothidea*	Stem spot	*H. undatus*	Mexico	Vaencia-Botin et al (2004)
Cactus virus	*CVX*	Viral	*H. undatus* and *H. monacanthus*	US, Taiwan, Korea, China, Malaysia	Gazis et al. (2018), Liou et al. (2001), Kim et al. (2016), Peng et al. (2016), Masanto et al. (2018)
Colletotrichum sp.	*C. aenigma*	Anthracnose	*H. undatus*	Thailand	Meetum et al. (2015)
	C. gloeosporioides	Anthracnose	*H. undatus, H. monacanthus,* and *H. megalanthus*	Brazil, China, US, Thailand, Malaysia, Thailand	Takahashi et al. (2008), Masyahit et al. (2009), Ma et al. (2014), Awang et al. (2010), Palmateer et al. (2007), Meetum et al. (2015), Masyahit et al. (2009)
	C. siamense	Anthracnose	*H. undatus* and *H. monacanthus*	India, Thailand, China	Abirami et al (2019), Meetum et al. (2015), Zhao et al. (2018)
	C. truncatum	Anthracnose	*H. undatus and H. monacanthus*	China, Thailand, Malaysia	Guo et al. (2014), Meetum et al. (2015), Vijaya et al. (2014)
	C. karstii	Anthracnose	*H. undatus*	Brazil	Nascimento et al. (2019)
Curvularia sp.	*C. lunata*	Spots/lesion on stems	*H. monacanthus*	Malaysia	Hawa et al. (2009)
Enterobacter sp.	*E. cloacae*	Bacterial soft rot	*Hylocereus* sp.	Malaysia	Masyahit et al. (2009)
Fusarium sp.	*F. fujikuroi*	Stem rot	*H. monacanthus*	Malaysia	Hawa et al. (2017)
	F. oxysorum	Basal rot, basal stem rot, stem rot, stem blight	*H. undatus, H. monacanthus* and *H. trigonus*	Argentina, South Korea, Malaysia	Wright et al. (2007), Choi et al. (2007), Mohd Hafifi et al. (2019),
	F. proliferatum	Stem rot	*H. monacanthus*	Malaysia	Hawa et al. (2013)
	F. semitectum	Stem rot	*H. monacanthus*	Malaysia	Hawa et al. (2010)
	F. solani	Stem rot	*Hylocereus* sp.	Indonesia	Rita et al. (2016)
Gilbertella sp.	*G. persicaria*	Storage rot	*H. costaricensis*	China	Guo et al. (2012)
Monilinia sp.	*M. fructicola*	Brown rot	*H. monacanthus*		Awang et al. (2013)
Neocosmospora sp.	*N. rubicola*	Stem rot	*H costaricensis*	China	Zheng et al. (2018a)
Neoscytalidium sp.	*N. dimidiatum*	Black rot, stem canker, brown spot, fruit internal browning, fruit canker,	*H. undatus and H. monacanthus*	Israel, Taiwan, Malaysia, China, US	Ezra et al. (2013), Chuang et al. (2012), Hawa et al. (2013), Lu et al. (2015), Lan et al. (2012), Yi et al. (2015), Sanahuja et al. (2016), Xu et al. 2 (018)
Nigrospora sp.	*N. sphaerica*	Reddish-brown spot	*H. undatus*	Chaina	Liu et al. (2016)
Paenibacillus sp.	*P. polymyxa*	Bacterial stem rot	*H. undulatus*	China	Zhang et al. (2017)
Sclerotium sp.	*S. rolfsii*	Souuthern Blight	*H. undatus*	China	Zheng et al. (2018b))
Tylenchorhynchus sp.	*T. agri*	Stunting (Growth inhibition and fruit drop)	*H. monacanthus*	China	Zhang et al. (2018)

[a] Also known as *Selenicereus megalanthus*.
[b] Fruits imported from Vietnam.

(Table 2). Anthracnose is frequently reported and is relatively the most destructive fungal disease of dragon fruit (see disease impact section below). Anthracnose of dragon fruit is caused by four *Colletotrichum* spp., namely; *C. gloeosporioides, C. aenigma, C. siamense, C. karstii* and *C. truncatum* (Takahashi et al., 2008; Masyahit et al., 2009; Ma et al., 2014; Awang et al., 2010; Palmateer et al., 2007; Vijaya et al., 2014; Guo et al., 2014; Meetum et al., 2015; Masyahit et al., 2009, 2009; Zhao et al., 2018; Abirammi et al., 2019; Nascimento et al., 2019). *Colletotrichum gloeosporioides* is the most widely reported (Takahashi et al., 2008; Masyahit et al., 2009; Ma et al., 2014; Awang et al., 2010; Palmateer et al., 2007; Meetum et al., 2015; Masyahit et al., 2009, 2009) and is hosted by all three popular cultivated dragon fruit species (*H. undatus, H. monacanthus* and *H. megalanthus*). *C. siamense* causes anthracnose has been reported only in *H. undatus* and *H. monacanthus* (Abirammi et al., 2019; Meetum et al., 2015., Zhao et al., 2018), while *C. aenigma* (Meetum et al., 2015) and *C. karstii* (Nascimento et al., 2019) has been reported only in *H. undatus.* However, since *Colletotrichum* spp. is a cosmopolitan pathogen (Cannon et al., 2012), it is likely that *C. aenigma* and *C. siamense* may infect the other *Hylocereus* spp. All *Colletotrichum* spp., except *C. karstii,* have been detected in Thailand (Meetum et al., 2015). Anthracnose caused by *C. aenigma* and *C. karstii* has been only reported in Thailand (Meetum et al., 2015) and Brazil (Nascimento et al., 2019), respectively. There are symptom variations also observed among *Hylocereus* spp. For instance, *C. siamense* infection in *H. undatus* starts with reddish-orange spots with severe chlorotic halos (Abirammi et al., 2019) but in *H. monacanthus,* stems showed faint-pink to brown necrotic lesions (Zhao et al., 2018). However, the symptom variation may be attributed to differences in plant varieties, plant age, and *C. siamense* strains.

All *Fusarium* spp. associated with dragon fruit, except for *F. oxysporum* from South Korea (Choi et al., 2007) and Argentina (Wright et al., 2007)*,* cause stem rot (Hawa et al., 2013, 2017; Rita et al., 2016; Wright et al., 2007; Mohd Hafifi et al., 2019) (Table 2). *H. monacanthus* hosts these *Fusarium* spp. However, *F. oxysporum*, the causal agent of basal rot, was only associated with *H. undatus* (Wright et al., 2007) and *H. trigonus* (Choi et al., 2007). All *Fusarium* spp., except *F. solani,* have been reported in Malaysia (Hawa et al., 2010, 2013, 2017; Mohd Hafifi et al., 2019).

The dreaded pathogen *Bipolaris cactivora* has been reported in Israel, China (fruits imported from Vietnam), Thailand, Taiwan, US, Korea, and Japan causing both pre- and post-harvest rot diseases (Ben-Ze'ev et al., 2011; He et al., 2012; Oeurn et al., 2015; Wang and Lin, 2005; Tarnowski et al., 2010; Taba et al., 2007; Choi et al., 2010). Interestingly, the disease has been found only in *H. undatus.* The flowers, stem, and fruits are susceptible to *B. cactivora* infection (Loei et al., 2015). The rapid spread of the pathogen in host tissue is assisted by a large number of destructive spores (Tarnowski et al., 2010).

The other fungal diseases are rot caused by *Monilinia fructicola* (Awang et al., 2013), *Gilbertella persicaria* (Guo et al., 2012), *Alternaria alternata* (Vilaplana et al., 2018) and *Neocosmospora rubicola* (Zheng et al., 2018a), spots caused by *Nigrospora sphaerica* (Liu et al., 2016), *Aureobasidium pullulans* (Wu et al., 2017) and *Botryosphaeria dothidea* (Valencia-Botin et al., 2004), and blight caused by *Alternaria* sp. (Patel and Zhang, 2017) and *Sclerotium rolfsii* (Zheng et al., 2018b). A mycotoxin-producing *A. alternata* has been also reported to cause post-harvest disease in *H. undatus* (Castro et al., 2017, 2018) indicating a potential issue in the context of food safety.

3.2. Bacterial diseases

Soft rot and stem rot caused, respectively, by *Enterobacter cloacae* and *Paenibacillus polymixa* are the two bacterial diseases of dragon fruits (Masyahit et al., 2009; Zhang et al., 2017). The former has been reported in Malaysia (Masyahit et al., 2019) and the latter in China (Zhang et al., 2017). Both diseases start with a water-soaked appearance in the infected tissues. Bacterial soft rot-infected stems show yellowish to brownish soft rot symptoms and the pathogen, *E. cloacae,* can infect all three *Hylocereus* species (Masyahit et al., 2009). Soft rotting develops within 24 h after inoculation (hai) of the bacteria in the stems and within 48 hai in the fruits. Stems infected with *P. polymixa,* gradually turn yellow and brown and all fleshy stems decompose (Zhang et al., 2017). Rotting of dragon fruit develops after 48 h from injecting *P. polymixa* into the stems (Zhang et al., 2017). *Klebsiella mobilis, K. oxytoca, Pantoea dispersa, and Rahnella aquatilis* have been also isolated from soft-rot-infected dragon fruit stem, but these bacteria were not pathogenic to dragon fruit (Masyahit et al., 2009).

3.3. Viral disease

Cactus virus X has been associated with virus disease symptoms in dragon fruits (Table 2). It has been detected in dragon fruit in the US, Taiwan, Korea, Japan China and is widely distributed in Malaysia (Gazis et al., 2018; Liou et al., 2001; Kim et al., 2016; Keiko and Miki, 2001; Peng et al., 2016; Masanto et al., 2018). This virus infects *H. undatus, H. monacanthus,* and *H. megalanthus.* Necrosis (Gazis et al., 2018; Masanto et al., 2018), mottling (Liou et al., 2001), chlorotic spots (Gazis et al., 2018; Peng et al., 2016), red-brown margins, pale yellow-green mosaics and deformed spines (Gazis et al., 2018) are the associated symptoms in *CVX*-infected plants. In Malaysia, secondary infections of fungal pathogens were reported that leads to rotting of the infected tissue (Masanto et al., 2018). CVX from dragon fruit can be sap transmitted to indicator plants *Chenopodium amaranticolor, C. quinoa, Celosia argentea,* and *Gomphrena globosa* (Liou et al., 2001; Kim et al., 2016), of which symptoms can be observed 20 days after inoculation (Kim et al., 2016). *C. quinoa* plants manifest chlorotic lesions when infected with *CVX* (Liou et al., 2001; Kim et al., 2016). Small chlorotic spots, then systemic infection, develop in *CVX*-infected *C. argentea* (Liou et al., 2001), while necrotic lesions were observed in *G. globosa* (Liou et al., 2001; Kim et al., 2016). Both necrotic and chlorotic lesions have been associated with *CVX*-infected *C. amaranticolor* (Liou et al., 2001; Kim et al., 2016). Based on the sequences of the replicase and coat protein, CVX is closely related to the *Bamboo mosaic virus (BMV), Cassava common mosaic virus,* and *Papaya mosaic virus (PMV)* (Liou et al., 2001). However, in immunodiffusion tests, CVX did not react with the antisera to *BMV* and *PMV* (Liou et al., 2001). Liou et al. (2001) presented the complete nucleotide sequence of the strain *CVX*-Hu and found that the putative product of ORF6 showed no significant similarity to other potexviruses.

3.4. Nematode disease

Only one nematode species has so far been associated with a dragon fruit disease (Table 2). Stunted growth of plants and fruit drop were observed in *H. polyrhizus* in China and the stunt nematode, *Tylenchorhynchus agri,* was associated with these symptoms (Zhang et al., 2018). In glasshouse pot trials, plants grown in soil inoculated with 1000 nematodes lost almost 50% of their weight 6 months after the inoculation (Zhang et al., 2018). The stunt nematode has been previously reported in fields planted with corn, barley, avocado, and rice (Handoo, 2000; Ciobanu et al., 2004; Shahabi et al., 2016). This was the first record (Zhang et al., 2018) of a nematode associated with a cacti disease. The role of secondary infection by fungi and bacteria in the dragon fruit rhizosphere, after nematode infection, on the stunting and decline of fresh weight is yet to be examined.

4. Impact of the diseases

The first demonstrated significant impact of a disease in dragon fruit was reported in the 1990's in Colombia when several pathogens, in particular, the fungus *Drechslera cactivora* (*B. cactivora*)*,* reduced the area planted with *H. megalanthus* by 93% (from 4000–250 ha) (Varela et al., 1995; Bibliowicz and Hernandez, 1998; Nerd et al., 2002). The fungus infects the base of pre-mature fruits and induces yellowing (Varela et al., 1995; Bibliowicz and Hernandez, 1998). To date, the fungus *B. cactivora* causes fruit and stem rotting and remains a problem in Israel, China, Thailand, Taiwan, Japan and Taiwan (Ben-Ze'ev et al., 2011; He et al., 2012; Oeurn et al., 2015; Wang and Lin, 2005; Tarnowski et al., 2010; Taba et al., 2007). In China, imported fruits affected with *B. cactivora* showed water-soaked symptoms which later becomes soft rot and thus, affects the quality of fruits.

Anthracnose can also reduce yield. In India, 30% of dragon fruit plants were infected and caused yield reduction (Abirammi et al., 2019). In a 15-ha commercial farm in China, 25% of the plants have been affected by anthracnose (*C. siamense*) and 35% of the severely-infected plants died within 40 days from the initial symptom appearance (Zhao et al., 2018). Infection by *C. gloeosporioides* also resulted in up to 50% in losses (Ma et al., 2014). In Indonesia, none of the surveyed dragon fruit growing areas in Sumatra were disease-free (Nasir and Nurmansyah, 2016). Four commercial dragon fruit farms in the Guangdong Province, China have been affected by stem and fruit spot (*A. pullulans*). This infection rapidly expanded when typhoon Ramasoon hit China and more than half of the plants were infected which led to significant fruit-yield loss (Wu et al., 2017). The abundance of viable spores is a huge challenge with diseases caused by *Colletotrochum* spp. and reducing spore dispersal and production would aid in mitigating disease epidemics.

In Malaysia, stem blight (*F. oxysporum*) and spots (*C. lunata*) affected 41% and 20% of dragon fruit production, respectively (Hawa et al., 2009; Mohd Hafifi et al., 2019). In a farm in Florida, US, *Alternaria* blight was responsible for the 10–20% of yield loss (Patel and Zhang, 2017). Plants showing canker (*N. dimidiatum*) also fails to recover as spots that develop into canker subsequently leads to rotting of the stem (Chuang et al., 2012). In Malaysia, canker was identified in 20 dragon fruit plantations. Infection of *N. dimidiatum* in fruits also results in rotting which makes the fruit pulp quality unacceptable (Ezra et al., 2013).

Bacterial stem rot severely damaged dragon fruit production in China. In 2014, all dragon fruit plants were infected with *P. polymixa.* The severe infection resulted in the decomposition of stems and the infected stems did not produce fruit (Zhang et al., 2017). According to Nerd et al. (2002), cactus plant tissues have a relatively high water content and therefore, disease infection rapidly turn into rotting (Nerd et al., 2002).

5. Current disease management strategies

5.1. Cultural and physical approaches

Temperature management, hot water treatment, and gamma irradiation have been reported to reduce disease incidence and severity of dragon fruit diseases. Storing fruit at 6 °C for 21–26 days can reduce storage rots caused by fungal pathogens e.g., *Alternaria alternata*, *B. cactivora, N. dimidiatum* and *C. gloeosporioides* (Ngoc et al., 2018). Hot water treatment for 2 min at 50 °C, before storage in 12 °C for 21 days, reduced lesion diameter by 63.1% without significant effect on the fruit's sensory qualities (Vilaplana et al., 2017). Irradiating fruits at 800 Gy or less was also effective in inhibiting or reducing fruit decay, although minor changes in fruit quality were observed (Wall and Khan, 2008).

5.2. Chemical approaches

Varying concentrations of calcium chloride were evaluated for their effect on the development of brown rot (*M. fructicola*) in dragon fruit (Awang et al., 2013). The greatest reduction of brown rot severity was achieved at 4.0 g $CaCl_2$/L water (30 min treatment). The same chemical concentrations were also used to control anthracnose (*C. gloeosporioides*). Treatment did not affect anthracnose incidence, but anthracnose lesion size was reduced as $CaCl_2$ level increases without affecting fruit soluble solid concentration and titratable acidity (Awang et al., 2012). Sodium carbonate and potassium sorbate, at varying concentrations (0, 1, 2, 3 and 4%), have been also tested against several fruit-rot-causing fungal pathogens (*C. gloeosporioides, C. capsici,* and *Fusarium* sp.) (Jitareerat et al., 2018). Potassium sorbate completely inhibited the spore germination of all fungal pathogens in culture media. Complete inhibition of *C. gloesporioides* spore germination by sodium carbonate was observed in media amended with 2% of the chemical and at 3% for *C. capsici* and *Fusarium* sp. (Jitareerat et al., 2018). Disease severity was also reduced in potassium sorbate-treated dragon fruits (at 55 °C in cold water). The application of potassium sorbate also had little impact on the plant's respiration rate and ethylene production. Postharvest black rot management has been achieved by using sodium bicarbonate at 298 mM (2.5%) at 21 days at 12 °C (plus 5 days of shelf-life at 20 °C), without negatively affecting the fruits sensory quality (Vilaplana et al., 2018). The quality of fruits treated with sodium bicarbonate also improved.

The use of chitosan in managing post-harvest anthracnose has been also demonstrated. Ali et al. (2013) evaluated chitosan delivered in 600 nm droplet size and conventionally against anthracnose in storage. Both the conventional and submicron chitosan dispersion technique (1.0%) reduced anthracnose development while maintaining the quality of fruits within the 28-day storage period (10 ± 2 °C and 80 ± 5% relative humidity). Similarly, Zahid et al. (2013) used locally prepared and low-molecular-weight chitosan in the form of nanoemulsions to control anthracnose. The low molecular weight chitosan at 1% concentration with 600 nm droplet size inhibited conidial growth and reduced mycelial dry weight of *C. gloeosporioides* (Zahid et al., 2013, 2019) compared to the locally prepared chitosan and control (no-nanoemulsions) treatments (Zahid et al., 2013).

5.3. Biopesticides

Treatment of *Cymbopogon nardus* essential oil in dragon fruits stored in cold room (10 °C, RH 85–90% for 21 days) delayed anthracnose incidence without affecting the quality of the fruits at concentrations below 2% oil (Aifaa et al., 2013). At 2% and above, phytotoxicity effects were observed and is therefore not recommended for postharvest treatment. *Cinnamomum zeylanicum, Cymbopogon flexuosus, Eucalyptus globulus, Eugenia caryophyllus*, and *Rosmarinus officinalis* essential oils have been also assayed against postharvest diseases caused by *A. alternata. C. zeylanicum* and *E. caryophyllus* strongly inhibited mycelial growth at 250 and 500 μg/ml, respectively. On fruits, *E. caryophyllus* reduced mycelial growth of *A. alternata* by 31% compared to the non-treated fruits (Castro et al., 2017). It was found that *E. caryophyllus* and *C. zeylanicum* both contained high amount (90.50% and 80.70%, respectively) of eugenol (Castro et al., 2017), a chemical with known antimicrobial activity. Rain tree (*Samanea saman*) leaf extracts have been also found to inhibit growth of *F. solani* in culture media and at 2.5% inhibited *F. solani* and stem rot development in dragon fruit stem (Rita et al., 2016). Similarly, wild zingiberaceae (*Ellettariopsis slahmong*) CK leaf extracts and its volatile compounds can inhibit the growth of the anthracnose pathogen (*C. gloeosporioides*) *in vitro*.

The use of silicon to reduce the incidence and severity of various fungal diseases in dragon fruit plants has been also reported. Plants treated with silicon (5.0 ml/L) had lower disease incidence and severity compared to the control treatments and lower silicon treatments (1.5 and 2.5 mL/L) (Faziha et al., 2019). Nevertheless, more research would be needed to determine the impact of silicon uptake of plants on fruit development.

5.4. Biological control

Spent mushroom sawdust applied in disease-conducive soil reduced the incidence of basal stem rot to 3–12%, compared to that of the control which is 44–59% (Choi et al., 2007). Accordingly, the bacterial and fungal populations, in the sawdust, was key to the disease-suppressive ability of the spent mushroom sawdust (Choi et al., 2007). Bae et al. (2013) evaluated 943 microbial isolates against *B. cactivora* and identified two bacteria (*Bacillus subtilis* GA1-23 and *B. amyloliquefaciens* GA4-4) with strong antimicrobial activity. The *Bacillus* sp. inhibited mycelial growth and spore germination of *B. cactivora.* The effect was comparable to the chemical control treatment difenoconazole. Mixtures of azoxystrobin (200 g/L) and difenoconazole (124 g/L) has been recommended in controlling diseases of dragon fruit, particularly anthracnose and stem canker (Noegrohati et al. 2019). Meetum et al. (2017) also identified two *Bacillus* sp. from the surface of dragon fruit twigs that were able to inhibit growth and conidial germination of anthracnose pathogens. These biocontrol agents were *B. methylotrophicus* strains PB182, PB255 and PB257, and *B. subtilis* PB223. Accordingly, *B. methylotrophicus* produces volatile compounds that inhibit mycelial growth, which also results in reduced virulence of the pathogen in dragon fruits (Meetum et al., 2017). Anthracnose lesion in dragon fruit twigs was reduced by *B. methylotrophicus* PB182 and PB257 in both protective and curative tests. Aside from bacteria, a fungus has been also identified that has antimicrobial activity against *C. gloeosporioides.* Crude extracts of *Penicillium oxalicum* T3.3 inhibited the growth of *C. gloeosporioides* in disc diffusion test by 33% and the diffused non-volatile metabolite of this fungus inhibited the pathogen's growth by 97% at 7 days post-incubation (Mamat et al., 2018). *Penicillium oxalicum* T3.3 is one of the 7 potential biocontrol agents, out of the 126 endophytes isolated from dragon fruit plants, that can suppress the growth of *C. gloeosporioides* (Mamat et al., 2018).

5.5. Pesticides

Mixtures of azoxystrobin (200 g/L) and difenoconazole (124 g/L) have been used previously to control diseases of dragon fruit, particularly anthracnose and stem canker (Noegrahati et al., 2019). Several pesticides have a fungistatic effect against the stem canker pathogen *N. dimidiatum.* Hexaconazole, tebuconazole, flusiazole, and pyraclostrobin have had a negative effect on *N. dimidiatum* mycelial growth (Xu et al., 2018). Azoxystrobin was also tested but its bioactivity was relatively low compared to the other four chemicals. In the field, 250 g/L pyraclostrobin EC controlled stem and fruit canker of up to 80% and 85%, respectively. Azoxystrobin SC (250 g/L) and tebuconazole (430 g/L) also have had a comparable effect to that of pyraclostrobin EC (Xu et al., 2018). Pre-treatment of imazalil fungicide at 0.4 h/L before storage has been also reported to reduce disease severity by 70.5% (Vilaplana et al., 2017).

6. Conclusion

Dragon fruit used to be a backyard plant grown only for table consumption and medicinal uses. But now, it is more than just fruit from one's backyard. There is a global growth of dragon fruit production of which growers are profiting. The export/import market is booming with Vietnam and Israel producing dragon fruits from production areas that rapidly expanded throughout the years. There is an ever-increasing demand for dragon fruit from the US and European import markets due to dragon fruits medicinal and industrial uses. It might be thought that with the increase of supply and demand, dragon fruit production should be very productive and profitable. Unfortunately, there are challenges associated with dragon fruit production that limits its maximum production potential. Among these problems are diseases caused by 22 species of fungi, two species of bacteria, one species of nematode and a virus particle. Making a significant impact on yield reductions are pathogens causing anthracnose, fruit and stem rot, canker, viral disease, and soft rots. Incidence of these diseases is increasing worldwide and in the last five years, this has been the case. Several control options are available for select dragon fruit diseases and the use of biological control agents has been considered a promising sustainable disease control approach. Breeding efforts are being done (Nobel, 2002; Tel Zur, 2015) and it is likely that within the next decade, breeding for disease resistance will be on the table focusing on major diseases. However, it remains a question whether there are more dragon fruit diseases that needs to be identified. If this is the case, increasing pathogen and disease monitoring would be necessary. As fruits are exported and imported, disease monitoring would be vital to ensure plant biosecurity.

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