1 Diseases of dragon fruit (*Hylocereus* species): etiology and current management options
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9 **Abstract**

10   More than seven billion people compete for food to survive. Agriculture has increased the

11 production of staple crops, through plant breeding and biotechnology, in arable areas that are now

12 becoming limited due to industrialization. With staple crops becoming a common diet and with people

13 getting the same nutrients from these foods, wild, exotic and underutilized edible plants are being

14 explored as supplements or alternatives. One potential plant is dragon fruit or pitahaya. This vine

15 cactus plant is water-efficient, rich in betalains and antioxidants, has medicinal benefits and is a source

16 of income to growers. However, dragon fruit production faces significant challenges. Among these,

17 losses due to diseases play a significant role in fruit-yield reduction and profitability. This paper

18 provides a comprehensive review of dragon fruit diseases, their associated pathogens, distribution, and

19 their current management options. We conclude that anthracnose, fruit and stem rot, stem canker and

20 the cactus viral disease are among the most frequently reported diseases of dragon fruit and actions are

21 needed to address the growing problems associated with these diseases as effective, sustainable and

22 practical management strategies are yet to be identified.

23

24 Keywords: *Hylocereus* species, *Colletotrichum* species, *Fusarium* species, Pitahaya, *Bacillus* spp.

25

1. Introduction

26

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 9,000 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., 2004; Stintzing et al., 2002) that are widely used as colorants in the food industry (Henry, 1996; Ortiz, 1999; Wynbraniec 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

48   dragon fruits (Tel Zur, 2015; Mercado-Silva, 2018). The most commonly cultivated species (Table 1,

49   Figure 1) are *H. undatus, H. monacanthus* (previously known as *H. polyrhizus*), *H. megalanthus*

50   (previously known as *Selenecereus megalanthus* – also a vine cactus), and *H. costaricensis* (Bauer,

51   2003, Tel Zur, 2015), but there are 11 more species in the genus *Hylocereus* (Bauer, 2003). Dragon

52   fruit plants are water-efficient – *Hylocereus* species are facultative epiphytes that initially roots in the

53   soil and then later become fully epiphytic (Wallace and Gibson, 2002) – due to the Crassulacean acid

54   metabolism (CAM) and this makes dragon fruit appealing in arid, semiarid and in other regions with

55   limited water or irrigation (Nobel, 1994; Nerd et al., 2002; Nobel, 2002). *Hylocereus undatus*, fruits

56   with red peel and white flesh (pulp), is the most cultivated species worldwide (Nerd et al., 2002).

57   Dragon fruits can be propagated by seeds, by micropropagation (Mohamed-Yassen, 2002) or

58   vegetatively (Ortiz-Hernandez, 1999).

59   Dragon fruit production can offer high returns to growers, particularly in the export market.

60   Colombia was the first country to cultivate dragon fruits for export to Japan (Nerd et al., 2002).

61   Currently, Colombia, Ecuador, and Israel ship *H. megalanthus* to Europe. In the US, dragon fruit has

62   the potential to be a profitable crop (Merten, 2003). Dragon fruits are also produced in Australia, New

63   Zealand, Spain, and the Philippines. There is a high demand from the food industry in the US and

64   Europe because dragon fruit pulp is used as a natural food ingredient and colorant (Ortiz, 1999; Nerd

65   et al., 2002). Taste and yield improvement of dragon fruit are being done in Israel (Nerd et al., 2002;

66   Tel Zur, 2015). Mexico produced dragon fruits from 2,000 hectares but usually for the local market

67   (Nerd et al., 2002). Area planted for dragon fruit in Vietnam grew enormously from 6,000 to 50,000

68   hectares (Tel Zur, 2015), and fruits are common in the local supermarket and are exported to Asian and

69   European markets (Nerd et al., 2002). The same pattern emerged in Israel where dragon fruit

70   production expanded rapidly since the 1970s (Nerd et al., 2002; Tel Zur, 2015). The total world

71   production is about 1 million tons, with the US being the top importing country and Europe as the top

72   importing region (Mercado-Silva, 2018).

73   However, like many crop ventures, dragon fruit growers are faced with several production issues

74   contributing to yield reduction. Among the issues faced is the short storage life of the fruit and the

75   non-stable fruit supply as flowering and harvesting occurs in waves (Mizrahi and Nerd, 1999; Nerd et

76   al., 2002). Exacerbating the short storage and shelf life is the presence of diseases. Mercado-Silva

77   (2018), Tel Zur (2015), Nobel (2002) Le Bellec et al. (2006), and Ortiz-Hernandez and Carillo Salazar

78   (2012) have reviewed the taxonomy, botany, medicinal properties, geographical distribution and

79   industrial uses of dragon fruits, but no comprehensive review has been made for dragon fruit

80   pathology. In 2013, Valencia-Botin et al. provided a brief overview of some dragon fruit diseases and

81   their associated pathogens. However, since then, and particularly in the last 5 years, there were

82   significant numerous new and first country reports of dragon fruit diseases and their associated

83   pathogens. This paper reviews the diseases of dragon fruit (*Hylocereus* species), their causal agents

84   and distribution. Finally, strategies that can be used in managing dragon fruit diseases are discussed.

85   Most literature in this paper published after 2003 have adapted *H. polyrhizus* instead of *H.*

86   *monacanthus*. In the current paper, *H. monacanthus* and *H. megalanthus* were used to refer to *H.*

87   *polyrhizus* and *S. megalanthus*, respectively, in accordance with the classification of Bauer (2003).

88

89   **2. A brief overview of cacti diseases**

90   In Mexico, Italy and South Africa, the disease known as *Alternaria* golden spot caused severe

91   damage on cacti (Zimmermann and Granata, 2002). Fungal diseases such as the Armillaria root and

92   stem rot (*A. mellea*), foot rot (*Phytophthora cactorum* and *P. nicotinae*), gray mold (*Botrytis cinerea*),

93   the "Roya" disease (*Aecidium sp.*), Fusarium wilt (*F. oxysporum* f.s. *opuntiarum*) and necrotic spots

94   (*Cercospora* spp*., Cytospora spp*., *Gleosporium* spp., *Mycosphaerella* spp., *Phoma sorghina,*

95   *Pleospora herbarum* and *Colletotrichum* spp.) have been also reported (Zimmermann and Granata,

96   2002). In South America, *Aecidium* spp., *Cercospora* spp. *Phoma sorghina* and *Dothiorella ribis* were

97   also found (Zimmermann and Granata, 2002). Associated with bacterial spot (*Erwinia carotovora*) is

98   the yeast disease cladode soft rot caused by *Candida boidini* (Phaff et al., 1978). In Mexico, crown gall

99   caused by *Agrobacterium tumefaciens* has been reported (Gutierrez, 1992). There is a scarcity of

100   studies on viral diseases, but few reports existed (Chessin, 1965). These diseases, however, have been

101   reported in cacti in general. Nevertheless, of all these previously reported pathogens, only *Fusarium*

102   *spp. Colletotrichum spp. B. cactivora* have been associated with current diseases of dragon fruits

103   occurring worldwide.

104

105   **3. Current diseases of dragon fruit and their associated pathogens**

106   There are 17 genera and 25 species of plant pathogens currently infecting dragon fruits (Table 2).

107   The majority causes fungal diseases in stem, fruits, and flowers. There are only two bacterial, one viral

108   and a nematode disease. Fruit and stem rot (*B. cactivora*), canker (*Neoscytalidium dimidiatum*),

109   anthracnose *(Colletotrichum* species) and viral disease (*Cactus virus X*) are the most frequently

110   reported diseases. The most recent report was anthracnose caused by *C. siamense* in India (Abirami et

111   al., 2019) and *C. karstii* in Brazil (Nascimento et al., 2019). Recent and new country records of

112   pathogens associated with dragon fruit were mostly reported in the last 5 years.

113

114   *3.1. Fungal Diseases*

115   There are 21 fungal species that cause various dragon fruit diseases (Table 2). Anthracnose is

116   frequently reported and is relatively the most destructive fungal disease of dragon fruit (see disease

117   impact section below). Anthracnose of dragon fruit is caused by four *Colletotrichum* spp., namely; *C.*

118   *gloeosporioides, C. aenigma, C. siamense, C. karstii* and *C. truncatum* (Takahashi et al., 2008;

119   Masyahit et al., 2009; Ma et al., 2014; Awang et al., 2010; Palmateer et al., 2007; Vijaya et al., 2014;

120   Guo et al., 2014; Meetum et al., 2015; Masyahit et al., 2009; Zhao et al., 2018; Abirami et al., 2019;

121   Nascimento et al., 2019). *Colletotrichum gloeosporioides* is the most widely reported (Takahashi et

122   al., 2008; Masyahit et al., 2009; Ma et al., 2014; Awang et al., 2010; Palmateer et al., 2007; Meetum et

123   al., 2015; Masyahit et al., 2009) and is hosted by all three popular cultivated dragon fruit species (*H.*

124   *undatus, H. monacanthus* and *H. megalanthus*). *C. siamense* causes anthracnose has been reported

125   only in *H. undatus* and *H. monacanthus* (Abirami et al., 2019; Meetum et al 2015., Zhao et al., 2018),

126   while *C. aenigma* (Meetum et al., 2015) and *C. karstii* (Nascimento et al., 2019) has been reported

127   only in *H. undatus.* However, since *Colletotrichum* spp. is a cosmopolitan pathogen (Cannon et al.,

128   2012), it is likely that *C. aenigma* and *C. siamense* may infect the other *Hylocereus* spp. All

129   *Colletotrichum* spp., except *C. karstii,* have been detected in Thailand (Meetum et al., 2015).

130   Anthracnose caused by *C. aenigma* and *C. karstii* has been only reported in Thailand (Meetum et al.,

131   2015) and Brazil (Nascimento et al., 2019), respectively. There are symptom variations also observed

132   among *Hylocereus* spp. For instance, *C. siamense* infection in *H. undatus* starts with reddish-orange

133   spots with severe chlorotic halos (Abirami et al., 2019) but in *H. monacanthus,* stems showed faint-

134   pink to brown necrotic lesions (Zhao et al., 2018). However, the symptom variation may be attributed

135   to differences in plant varieties, plant age, and *C. siamense* strains.

136   All *Fusarium* spp. associated with dragon fruit, except for *F. oxysporum* from South Korea (Choi et

137   al., 2007) and Argentina (Wright et al., 2007)*,* cause stem rot (Hawa et al., 2013; Hawa et al., 2017;

138   Rita et al., 2016; Wright et al., 2007; Mohd Hafifi et al., 2019) (Table 2). *H. monacanthus* hosts these

139   *Fusarium* spp. However, *F. oxysporum*, the causal agent of basal rot, was only associated with *H.*

140 *undatus* (Wright et al., 2007) and *H. trigonus* (Choi et al., 2007). All *Fusarium* spp., except *F. solani,*

141 have been reported in Malaysia (Hawa et al., 2010; Hawa et al., 2013; Hawa et al., 2017; Mohd Hafifi

142 et al., 2019)

143 The dreaded pathogen *Bipolaris cactivora* has been reported in Israel, China (fruits imported from

144 Vietnam), Thailand, Taiwan, US, Korea, and Japan causing both pre- and post-harvest rot diseases

145 (Ben-Ze'ev et al., 2011; He et al., 2012; Oeurn et al., 2015; Wang, 2005; Tarnowski et al., 2010; Taba

146 et al., 2007; Choi et al., 2010). Interestingly, the disease has been found only in *H. undatus*. The

147 flowers, stem, and fruits are susceptible to *B. cactivora* infection (Loei et al., 2015). The rapid spread

148 of the pathogen in host tissue is assisted by a large number of destructive spores (Tarnowski et al.,

149 2010).

150 The other fungal diseases are rot caused by *Monilinia fructicola* (Awang et al., 2013), *Gilbertella*

151 *persicaria* (Guo et al., 2012), *Alternaria alternata* (Vilaplana et al., 2018) and *Neocosmospora*

152 *rubicola* (Zheng et al., 2018a), spots caused by *Nigrospora sphaerica* (Liu et al., 2016),

153 *Aureobasidium pullulans* (Wu et al., 2017) and *Botryosphaeria dothidea* (Valencia-Botin et al., 2004),

154 and blight caused by *Alternaria sp.* (Patel and Zhang, 2017) and *Sclerotium rolfsii* (Zheng et al.,

155 2018b). A mycotoxin-producing *A. alternata* has been also reported to cause postharvest disease in *H.*

156 *undatus* (Castro et al., 2018; Castro et al., 2017) indicating a potential issue in the context of food

157 safety.

158

159 ***3.2. Bacterial Diseases***

160 Soft rot and stem rot caused, respectively, by *Enterobacter cloacae* and *Paenibacillus polymixa* are

161 the two bacterial diseases of dragon fruits (Masyahit et al., 2009; Zhang et al, 2017). The former has

162 been reported in Malaysia (Masyahit et al., 2019) and the latter in China (Zhang et al., 2017). Both

163   diseases start with a water-soaked appearance in the infected tissues. Bacterial soft rot-infected stems

164   show yellowish to brownish soft rot symptoms and the pathogen, *E. cloacae,* can infect all three

165   *Hylocereus* species (Masyahit et al., 2009). Soft rotting develops within 24 hours after inoculation

166   (hai) of the bacteria in the stems and within 48 hai in the fruits. Stems infected with *P. polymixa,*

167   gradually turn yellow and brown and all fleshy stems decompose (Zhang et al., 2017). Rotting of

168   dragon fruit develops after 48 hours from injecting *P. polymixa* into the stems (Zhang et al. 2017).

169   *Klebsiella mobilis, K. oxytoca, Pantoea dispersa, and Rahnella aquatilis* have been also isolated from

170   soft-rot-infected dragon fruit stem, but these bacteria were not pathogenic to dragon fruit (Masyahit et

171   al. 2009).

172

173   ***3.3. Viral Disease***

174   *Cactus virus X* has been associated with virus disease symptoms in dragon fruits (Table 2). It has

175   been detected in dragon fruit in the US, Taiwan, Korea, Japan China and is widely distributed in

176   Malaysia (Gazis et al., 2018; Liou et al., 2001; Kim et al., 2016; Keiko and Miki, 2001; Peng et al.,

177   2016; Masanto et al., 2018). This virus infects *H. undatus, H. monacanthus,* and *H. megalanthus.*

178   Necrosis (Gazis et al., 2018; Masanto et al., 2018), mottling (Liou et al., 2001), chlorotic spots (Gazis

179   et al., 2018; Peng et al., 2016), red-brown margins, pale yellow-green mosaics and deformed spines

180   (Gazis et al., 2018) are the associated symptoms in *CVX*-infected plants. In Malaysia, secondary

181   infections of fungal pathogens were reported that leads to rotting of the infected tissue (Masanto et al.,

182   2018). CVX from dragon fruit can be sap transmitted to indicator plants *Chenopodium amaranticolor,*

183   *C. quinoa, Celosia argentea,* and *Gomphrena globosa* (Liou et al., 2001; Kim et al., 2016), of which

184   symptoms can be observed 20 days after inoculation (Kim et al., 2016). *C. quinoa* plants manifest

185   chlorotic lesions when infected with *CVX* (Liou et al., 2001; Kim et al., 2016). Small chlorotic spots,

186   then systemic infection, develop in *CVX*-infected *C. argentea* (Liou et al., 2001), while necrotic

187   lesions were observed in *G. globosa* (Liou et al., 2001; Kim et al., 2016). Both necrotic and chlorotic

188   lesions have been associated with *CVX*-infected *C. amaranticolor* (Liou et al., 2001; Kim et al., 2016).

189   Based on the sequences of the replicase and coat protein, CVX is closely related to the *Bamboo mosaic*

190   *virus (BMV), Cassava common mosaic virus,* and *Papaya mosaic virus (PMV)* (Liou et al., 2004).

191   However, in immunodiffusion tests, CVX did not react with the antisera to *BMV* and *PMV* (Liou et al.,

192   2001). Liou et al. (2004) presented the complete nucleotide sequence of the strain *CVX*-Hu and found

193   that the putative product of ORF6 showed no significant similarity to other potexviruses.

194

195   *3.4. Nematode Disease*

196   Only one nematode species has so far been associated with a dragon fruit disease (Table 2). Stunted

197   growth of plants and fruit drop were observed in *H. polyrhizus* in China and the stunt nematode,

198   *Tylenchorhynchus agri,* was associated with these symptoms (Zhang et al., 2018). In glasshouse pot

199   trials, plants grown in soil inoculated with 1,000 nematodes lost almost 50% of their weight 6 months

200   after the inoculation (Zhang et al., 2018). The stunt nematode has been previously reported in fields

201   planted with corn, barley, avocado, and rice (Handoo 2000; Ciobanu et al., 2004; Shahabi et al., 2016).

202   This was the first record (Zhang et al., 2018) of a nematode associated with a cacti disease. The role of

203   secondary infection by fungi and bacteria in the dragon fruit rhizosphere, after nematode infection, on

204   the stunting and decline of fresh weight is yet to be examined.

205

206   **4. Impact of the Diseases**

207   The first demonstrated significant impact of a disease in dragon fruit was reported in the 1990's in

208   Colombia when several pathogens, in particular, the fungus *Drechslera   cactivora* (*B. cactivora*),

209   reduced the area planted with *H. megalanthus* by 93% (from 4,000 to 250 hectares) (Varela et al.,

210   1995, Bibliowicz and Hernandez 1998, Nerd et al., 2002). The fungus infects the base of pre-mature

211   fruits and induces yellowing (Varela et al., 1995; Bibliowicz and Hernandez, 1998). To date, the

212   fungus *B. cactivora* causes fruit and stem rotting and remains a problem in Israel, China, Thailand,

213   Taiwan, Japan and Taiwan (Ben-Ze'ev et al., 2011; He et al., 2012; Oeurn et al., 2015; Wang, 2005;

214   Tarnowski et al., 2010; Taba et al., 2007). In China, imported fruits affected with *B. cactivora* showed

215   water-soaked symptoms which later becomes soft rot and thus, affects the quality of fruits.

216   Anthracnose can also reduce yield. In India, 30% of dragon fruit plants were infected and caused

217   yield reduction (Abirami et al., 2019). In a 15-ha commercial farm in China, 25% of the plants have

218   been affected by anthracnose (*C. siamense*) and 35% of the severely-infected plants died within 40

219   days from the initial symptom appearance (Zhao et al., 2018). Infection by *C. gloeosporioides* also

220   resulted in up to 50% in losses (Ma et al., 2014). In Indonesia, none of the surveyed dragon fruit

221   growing areas in Sumatra were disease-free (Nasir and Nurmansyah, 2016). Four commercial dragon

222   fruit farms in the Guangdong Province, China have been affected by stem and fruit spot (*A. pullulans*).

223   This infection rapidly expanded when typhoon Ramasoon hit China and more than half of the plants

224   were infected which led to significant fruit-yield loss (Wu et al., 2017). The abundance of viable

225   spores is a huge challenge with diseases caused by *Colletotrochum* spp. and reducing spore dispersal

226   and production would aid in mitigating disease epidemics.

227   In Malaysia, stem blight (*F. oxysporum*) and spots (*C. lunata*) affected 41% and 20% of dragon

228   fruit production, respectively (Hawa et al., 2009; Mohd Hafifi et al., 2019). In a farm in Florida, US,

229   *Alternaria* blight was responsible for the 10-20% of yield loss (Patel and Zhang, 2017). Plants showing

230   canker (*N. dimidiatum*) also fails to recover as spots that develop into canker subsequently leads to

231   rotting of the stem (Chuang et al 2012). In Malaysia, canker was identified in 20 dragon fruit

232 plantations. Infection of *N. dimidiatum* in fruits also results in rotting which makes the fruit pulp

233 quality unacceptable (Ezra et al., 2013).

234   Bacterial stem rot severely damaged dragon fruit production in China. In 2014, all dragon fruit

235 plants were infected with *P. polymixa.* The severe infection resulted in the decomposition of stems and

236 the infected stems did not produce fruit (Zhang et al., 2017). According to Nerd et al. (2002), cactus

237 plant tissues have a relatively high water content and therefore, disease infection rapidly turn into

238 rotting (Nerd et al., 2002).

239

240 **5. Current Disease Management Strategies**

241

242 *5.1. Cultural and Physical Approaches*

243   Temperature management, hot water treatment, and gamma irradiation have been reported to reduce

244 disease incidence and severity of dragon fruit diseases. Storing fruit at 6 °C for 21-26 days can reduce

245 storage rots caused by fungal pathogens e.g., *Alternaria alternata*, *B. cactivora, N. dimidiatum* and *C.*

246 *gloeosporioides* (Ngoc et al., 2018). Hot water treatment for 2 min at 50 °C, before storage in 12 °C

247 for 21 days, reduced lesion diameter by 63.1% without significant effect on the fruit's sensory qualities

248 (Vilaplana et al 2017). Irradiating fruits at 800 Gy or less was also effective in inhibiting or reducing

249 fruit decay, although minor changes in fruit quality were observed (Wall and Khan, 2008).

250

251 *5.2. Chemical Approaches*

252   Varying concentrations of calcium chloride were evaluated for their effect on the development of

253 brown rot (*M. fructicola*) in dragon fruit (Awang et al., 2013). The greatest reduction of brown rot

254 severity was achieved at 4.0 g $CaCl_2$/L water (30 min treatment). The same chemical concentrations

255   were also used to control anthracnose (*C. gloeosporioides*). Treatment did not affect anthracnose

256   incidence, but anthracnose lesion size was reduced as $CaCl_2$ level increases without affecting fruit

257   soluble solid concentration and titratable acidity (Awang et al., 2012). Sodium carbonate and

258   potassium sorbate, at varying concentrations (0, 1, 2, 3 and 4%), have been also tested against several

259   fruit-rot-causing fungal pathogens (*C. gloeosporioides, C. capsici,* and *Fusarium* sp.) (Jitareerat et al.,

260   2018). Potassium sorbate completely inhibited the spore germination of all fungal pathogens in culture

261   media. Complete inhibition of *C. gloesporioides* spore germination by sodium carbonate was observed

262   in media amended with 2% of the chemical and at 3% for *C. capsici* and *Fusarium* sp. (Jitareerat et al.,

263   2018). Disease severity was also reduced in potassium sorbate-treated dragon fruits (at 55 °C in cold

264   water). The application of potassium sorbate also had little impact on the plant's respiration rate and

265   ethylene production. Postharvest black rot management has been achieved by using sodium

266   bicarbonate at 298 mM (2.5%) at 21 days at 12 °C (plus 5 days of shelf-life at 20 °C), without

267   negatively affecting the fruits sensory quality (Vilaplana et al., 2018). The quality of fruits treated with

268   sodium bicarbonate also improved.

269   The use of chitosan in managing post-harvest anthracnose has been also demonstrated. Ali et al.,

270   (2013) evaluated chitosan delivered in 600 nm droplet size and conventionally against anthracnose in

271   storage. Both the conventional and submicron chitosan dispersion technique (1.0%) reduced

272   anthracnose development while maintaining the quality of fruits within the 28-day storage period (10 ±

273   2 °C and 80 ± 5% relative humidity). Similarly, Zahid et al., (2013) used locally prepared and low-

274   molecular-weight chitosan in the form of nanoemulsions to control anthracnose. The low molecular

275   weight chitosan at 1% concentration with 600 nm droplet size inhibited conidial growth and reduced

276   mycelial dry weight of *C. gloeosporioides* (Zahid et al., 2013; Zahid et al., 2019) compared to the

277   locally prepared chitosan and control (no-nanoemulsions) treatments (Zahid et al., 2013).

278

5.3. Biopesticides

280   Treatment of *Cymbopogon nardus* essential oil in dragon fruits stored in cold room (10°C, RH 85-

281   90% for 21 days) delayed anthracnose incidence without affecting the quality of the fruits at

282   concentrations below 2% oil (Aifaa et al., 2013). At 2% and above, phytotoxicity effects were

283   observed and is therefore not recommended for postharvest treatment. *Cinnamomum zeylanicum,*

284   *Cymbopogon flexuosus, Eucalyptus globulus, Eugenia caryophyllus*, and *Rosmarinus officinalis*

285   essential oils have been also assayed against postharvest diseases caused by *A. alternata. C.*

286   *zeylanicum* and *E. caryophyllus* strongly inhibited mycelial growth at 250 and 500 µg/ml, respectively.

287   On fruits, *E. caryophyllus* reduced mycelial growth of *A. alternata* by 31% compared to the non-

288   treated fruits (Castro et al., 2017). It was found that *E. caryophyllus* and *C. zeylanicum* both contained

289   high amount (90.50% and 80.70%, respectively) of eugenol (Castro et al., 2017), a chemical with

290   known antimicrobial activity. Rain tree (*Samanea saman*) leaf extracts have been also found to inhibit

291   growth of *F. solani* in culture media and at 2.5% inhibited *F. solani* and stem rot development in

292   dragon fruit stem (Rita et al., 2016). Similarly, wild zingiberaceae (*Ellettariopsis slahmong*) CK

293   extracts and its volatile compounds can inhibit the growth of the anthracnose pathogen (*C.*

294   *gloeosporioides*) *in vitro*.

295   The use of silicon to reduce the incidence and severity of various fungal diseases in dragon fruit

296   plants has been also reported. Plants treated with silicon (5.0 ml/L) had lower disease incidence and

297   severity compared to the control treatments and lower silicon treatments (1.5 and 2.5 mL/L) (Faziha et

298   al., 2019). Nevertheless, more research would be needed to determine the impact of silicon uptake of

299   plants on fruit development.

300

301 *5.4. Biological Control*

302   Spent mushroom sawdust applied in disease-conducive soil reduced the incidence of basal stem rot

303 to 3-12%, compared to that of the control which is 44-59% (Choi et al., 2007). Accordingly, the

304 bacterial and fungal populations, in the sawdust, was key to the disease-suppressive ability of the spent

305 mushroom sawdust (Choi et al., 2007). Bae et al. (2013) evaluated 943 microbial isolates against *B.*

306 *cactivora* and identified two bacteria (*Bacillus subtilis* GA1-23 and *B. amyloliquefaciens* GA4-4) with

307 strong antimicrobial activity. The *Bacillus* sp. inhibited mycelial growth and spore germination of *B.*

308 *cactivora*. The effect was comparable to the chemical control treatment difenoconazole. Mixtures of

309 azoxystrobin (200 g/L) and difenoconazole (124 g/L) has been recommended in controlling diseases of

310 dragon fruit, particularly anthracnose and stem canker (Noegrohati et al. 2019). Meetum et al. (2017)

311 also identified two *Bacillus* sp. from the surface of dragon fruit twigs that were able to inhibit growth

312 and conidial germination of anthracnose pathogens. These biocontrol agents were *B. methylotrophicus*

313 strains PB182, PB255 and PB257, and *B. subtilis* PB223. Accordingly, *B. methylotrophicus* produces

314 volatile compounds that inhibit mycelial growth, which also results in reduced virulence of the

315 pathogen in dragon fruits (Meetum et al., 2017). Anthracnose lesion in dragon fruit twigs was reduced

316 by *B. methylotrophicus* PB182 and PB257in both protective and curative tests. Aside from bacteria, a

317 fungus has been also identified that has antimicrobial activity against *C. gloeosporioides*. Crude

318 extracts of *Penicillium oxalicum* T3.3 inhibited the growth of *C. gloeosporioides* in disc diffusion test

319 by 33% and the diffused non-volatile metabolite of this fungus inhibited the pathogen's growth by

320 97% at 7 days post-incubation (Mamat et al., 2018). *Penicillium oxalicum* T3.3 is one of the 7

321 potential biocontrol agents, out of the 126 endophytes isolated from dragon fruit plants, that can

322 suppress the growth of *C. gloeosporioides* (Mamat et al., 2018).

323

324   *5.5. Pesticides*

325   Mixtures of azoxystrobin (200 g/L) and difenoconazole (124 g/L) have been used previously to

326   control diseases of dragon fruit, particularly anthracnose and stem canker (Noegrohati et al., 2019).

327   Several pesticides have a fungistatic effect against the stem canker pathogen *N. dimidiatum.*

328   Hexaconazole, tebuconazole, flusiazole, and pyraclostrobin have had a negative effect on *N.*

329   *dimidiatum* mycelial growth (Xu et al., 2018). Azoxystrobin was also tested but its bioactivity was

330   relatively low compared to the other four chemicals. In the field, 250 g/L pyraclostrobin EC controlled

331   stem and fruit canker of up to 80% and 85%, respectively. Azoxystrobin SC (250 g/L) and

332   tebuconazole (430 g/L) also have had a comparable effect to that of pyraclostrobin EC (Xu et al.,

333   2018). Pre-treatment of imazalil fungicide at 0.4 h/L before storage has been also reported to reduce

334   disease severity by 70.5% (Vilaplana et al., 2017).

335

336   **6. Conclusion**

337   Dragon fruit used to be a backyard plant grown only for table consumption and medicinal uses. But

338   now, it is more than just fruit from one's backyard. There is a global growth of dragon fruit production

339   of which growers are profiting. The export/import market is booming with Vietnam and Israel

340   producing dragon fruits from production areas that rapidly expanded throughout the years. There is an

341   ever-increasing demand for dragon fruit from the US and European import markets due to dragon

342   fruits medicinal and industrial uses. It might be thought that with the increase of supply and demand,

343   dragon fruit production should be very productive and profitable. Unfortunately, there are challenges

344   associated with dragon fruit production that limits its maximum production potential. Among these

345   problems are diseases caused by 22 species of fungi, two species of bacteria, one species of nematode

346   and a virus particle. Making a significant impact on yield reductions are pathogens causing

347 anthracnose, fruit and stem rot, canker, viral disease, and soft rots. Incidence of these diseases is

348 increasing worldwide and in the last five years, this has been the case. Several control options are

349 available for select dragon fruit diseases and the use of biological control agents has been considered a

350 promising sustainable disease control approach. Breeding efforts are being done (Nobel, 2002; Tel

351 Zur, 2015) and it is likely that within the next decade, breeding for disease resistance will be on the

352 table focusing on major diseases. However, it remains a question whether there are more dragon fruit

353 diseases that needs to be identified. If this is the case, increasing pathogen and disease monitoring

354 would be necessary. As fruits are exported and imported, disease monitoring would be vital to ensure

355 plant biosecurity.

356

357 **7. Acknowledgements**

361

362 **8. References**

363

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619   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

620   Source: Nerd et al 2002

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630 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* [1]	-	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 [2], Thailand, Taiwan, US, Korea, Japan	Ben-Ze'ev et al (2011), He et al (2012), Oeurn et al (2015), Wang (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. gloeosoporioides	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 Mohd 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)

631 [1] Also known as *Selenicereus megalanthus*
632 [2] Fruits imported from Vietnam
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641 Figure 1. Dragon fruits. A) *Hylocereus undatus,* B) *H. monacanthus* and C) *H. megalanthus.*