Chapter

Potato Dry Rot Caused by *Fusarium* spp. and Mycotoxins Accumulation and Management

Huali Xue and Zhimin Yang

Abstract

Dry rot of potato (*Solanum tuberosum L.*) is an important postharvest disease during storage. The decay can be caused by several different species of *Fusarium* spp., such as, *F. sambucinum*, *F. coeruleum*, *F. oxysporum*, *F. avenaceum*, *F. culmorum*. The pathogen of *Fusarum* spp. causing dry rot of potato is considerable different in different countries and regions. The typical symptom of potato dry rot is sunken and wrinkled brown to black tissue patch on tuber with less dry matter and shriveled flesh. *Fusarium* spp. only invades host through wound or natural orifice during pre-harvest, storage and transportation period. Some *Fusarium* species infection associated with mycotoxins accumulation, which has phytotoxicity and mycotoxicoses in humans and animals. Synthetic fungicide is the main strategy to control the dry rot of potato, however, there are series of problem, such as environmental pollution, pathogen resistance. An integrated approach to manage the disease includes the introduction of resistant cultivar, appropriate cultural practices, and storage conditions combined with the application of synthetic fungicides pre-harvest or post-harvest. Moreover, some chemical fungicides and microbial antagonists have been integrated into potato dry rot management.

Keywords: *Fusarium* spp., potato dry rot, pathogenic mechanism, mycotoxins, control

1. Introduction

Fusarium is a large fungal genus within the Ascomycota phylum comprising a few hundred species that are mainly distributed in soil and in association with plants [1]. As we know, *Fusarium* spp. can cause dry rot of potato, it is a devastating pathogenic disease that significantly influences potato tubers (*Solanum tuberosum L.*) worldwide [2]. The disease not only causes a significant reduction in potato quality, but also leads to enormous economics losses. It is reported that 90% of potato tubers need to be stored for vegetable and industrial materials, however, the enormous yield losses attributed to dry rot disease during storage ranges from 6 to 25%, with up to 60% of tubers affected in some cases [3]. There are 13 species of *Fusarium* designated globally as causal agents of potato dry rot [4, 5]. Different species *Fusarium* were isolated from dry rot of potato tube and identified in different countries and regions. *F. sambucinum* is the most predominant pathogenic fungus causing potato dry rot in North America, China and some regions

***Fusarium* spp. species**	**Region**	**Source**
F. sambucinum	North Amercian, China and some regions of Europe	[3, 5, 6, 8, 10, 11, 13, 24]
F. coeruleum and	United Kingdom	[6, 14–19]
F. sambucinum		
F. sulphureum,	China, South Africa	[20–23]
F. sambucinem		
F. solani		
F. acuminatum		
F. avenaceum,	Finland and USA	[7, 25, 26]
F. equiseti,	North Dakota	
F. graminearum		
F. oxysporum	Egypt, Norway, Michigan	[27]
F. culmorum		[28]
F. verticillioides	Egypt	[29]
F. incarnatum		

Table 1.
Fusarium *species causing potato dry rot in different countries and regions.*

of Europe [3, 5–13]. *F. coeruleum* is the most prevalent agent associated with the dry rot of potato in cold storage in the United Kingdom and Great Britain [14–18]. Sometimes, *F. sambucinum* occasionally causes severe yield and economic losses in United Kingdom [6, 19]. In North Dakota, *F. graminearum* and *F. sambucinum* were reported to be the most frequent species *Fusarium* causing dry rot. In China, *F. sambucinum* is considered as the most notorious fungus in most potato growing regions [20], in addition, *F. oxysporum, F. avenaceum, F. acuminatum and F. equiseti, F. sulphureum*, *F. sambucinem* and *F. solani* also play the most predominant role in causing potato dry rot [21–23]. Similarly, *F. oxysporum* is the most common pathogen causing dry rot in Michigan. Recently in Egypt, the *F. sambucinum* was reported as the predominant fungus followed by *F. oxysporum*, *F. verticillioides* and *F. incarnatum* (**Table 1**) [29].

The frequency of the *Fusarium* species associated with dry rot is not only affected by crop location, but also by other factors such as potato cultivar, fungicide and seed tuber source [16]. In addition, *F. avenaceum*, *F. equiseti*, and *F. graminearum* are usually being considered lesser importance when compared with *F. sambucinum* and *F. coeruleum*; however, sometimes, they can be the predominant pathogen to cause serious disease in Finland and USA [24–26]. For example, A 2004–2005 survey of potatoes from stores in the north-central potato-producing region of the USA showed that *F. graminearum* along with *F. sambucinum* were the predominant causes of the disease [24].

2. Symptoms of dry rot, infection process of *Fusarium* and potato tuber tissue reaction

The symptom of potato dry rot includes sunken and wrinkled brown to black tissue patch on tuber with less dry matter and shriveled flesh. The initial symptoms of dry rot of potato appear on tubers at wound sites as shallow small brown lesions after approximately one month of postharvest storage. The infected lesions enlarge in all directions, then the periderm sinks and collapses, eventually, the growing lesion may appear as concentric rings as the underlying dead tissue desiccates [1, 4]. Cavities underneath the rotted tissue are usually associated with cottony white, purple, pink or brick orange spore and mycelia of pathogenic fungus [30]. The whole rotted tubers always become shriveled and mummified (**Figure 1**). Dry rot lesions may be infected by some bacterial pathogens and cause soft rot decay, especially when the tubers are wet or stored at high relative humidity storage conditions [3]. *Fusarium* species that causes dry rot can also indicate themselves as seed tuber decay and in-field wilt.

Fusarium spp. cannot infect the healthy potato tuber through the stomata or lenticels when the tuber is in the absence of wounds. The pathogenic fungus successfully infect tuber only if the tuber's skin is ruptured [3], the fungus only invades the tuber through wound or natural orifice during pre-harvest or storage and transportation (**Figure 2**). The pathogenic hyphae are initial at intercellular, then become intracellular in dead cells. Histological studies showed that *F. coeruleum* infected through the intercellular spaces, the adjacent host cells remaining alive for some time; however, *F. avenaceum* infected through killing and penetrating the cells where it came into contact [3]. Lesions at the infected site can be prevented by the accumulation of suberin polyphenolic (SPP) and suberin polyaliphatic (SPA) [3, 31]. SPP and SPA can effectively prevent the spread of hyphae of the pathogen, and as wound periderm can be sealed with SPP and SPA [3]. In fact, the formation of SPP and SPA is the process of wound healing. Wound healing can suppress the development of dry rot by walling off infection sites and preventing lesions from expanding [3]. *F. sulphureum* infected tuber tissues were indicated to accumulate SPP and SPA [31].

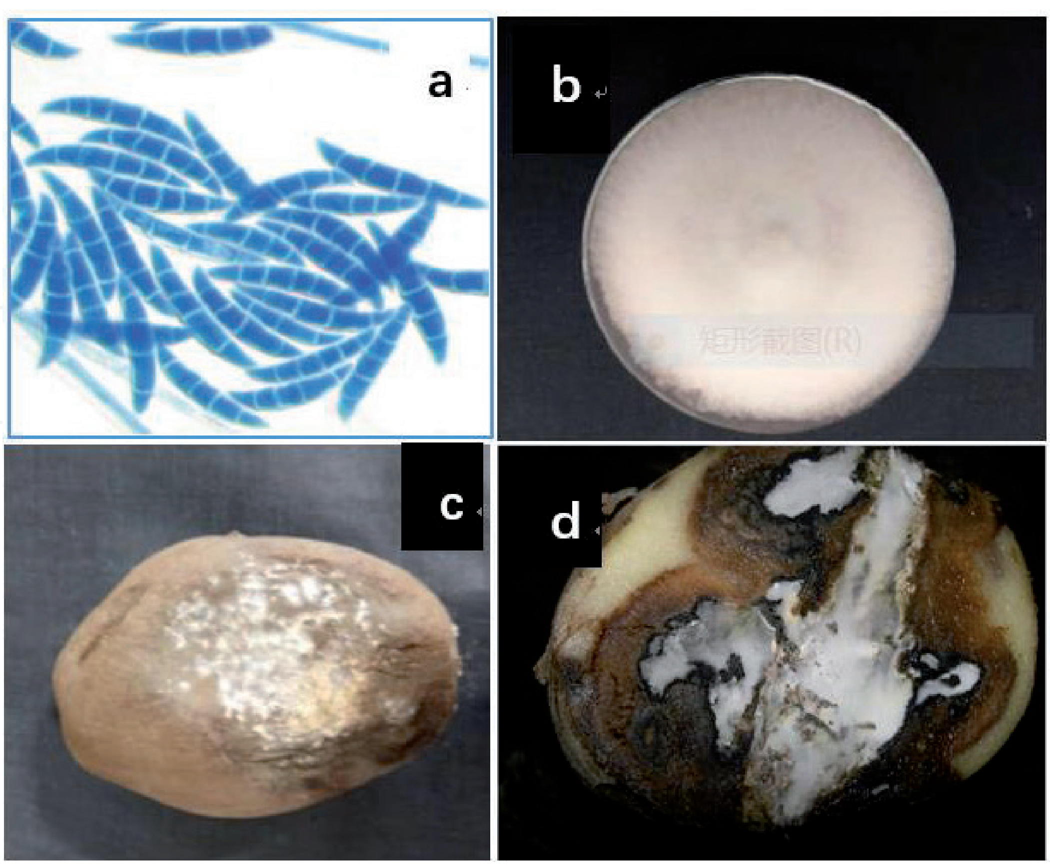

Figure 1.
(a) and (b) Respective spores and mycelia, (c) and (d) Respective typical symptoms of dry rot showing shriveled and mummified tubers.

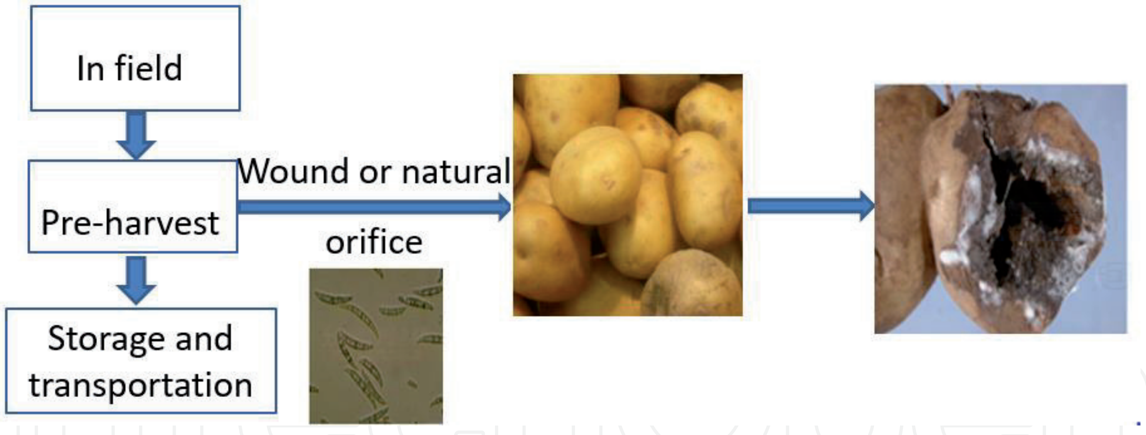

Figure 2.
Fusarium spp. infects potato tuber by wound or natural orifice.

The wound healing process includes two stages of wound-induced suberization: the closing layer formation and wound periderm development, accompanied by deposition of SPP and SPA on the wounded site [32]. It was reported that both SPP and SPA can resist bacteria and fungi invade by the formation of an effective physical barrier [33]. Jiang et al. [31] suggested some synthesis substances, such as benzo-(1, 2, 3)-thiadiazole-7-carbothioic acid s-methyl ester (BTH) can accelerate the wound healing of potato tuber by elevation of phenylpropanoid metabolism.

3. Mycotoxins production associated with dry rot of potato

The dry rot, caused by some species of *Fusarium* spp., is associated with mycotoxins accumulation. Mycotoxins is a kind of secondary metabolites produced by pathogenic fungus under the favorable temperature and humidity condition, which can pose a potential risk to human health and food safety [34]. The mycotoxin produced by *Fusarium* spp. can be divided into two kinds of non-trichothecene and trichothecenes. The typical non-trichothecene produced by *Fusarium* spp. are listed in **Table 2**.

Beauvericin (BEA), enniatins (ENNs), zearalenones (ZEA), fumonisins (FUM), sambutoxin (SAM), fusaric acids (FA) and fusarin C (FUS) are usually detected in dry rot of potato tuber. BEA and ENN are cyclic hexadepsipeptides, which has antimicrobial, insecticidal, phytotoxic and cytotoxic characteristic properties [45]. ZEA belong to non-steroidal estrogenic mycotoxins, accompanied with estrogenic syndromes in some experimental animals [46]. FUM have been linked to leukoencephalomalacia, in horses and rabbits and have hepatotoxic and carcinogenic influences, as well as esophageal carcinoma in human, phytotoxic symptoms in plants [47]. SAM was detected in dry rot of potato caused by *F. sambucinum* and *F. oxysporum* [42, 44], which can lead to hemorrhage in the stomach and intestines, loss of body weight, feed refusal and death in rats. Consumption of FUS produced by *Fusarium* species has been associated epidemiologically with some diseases in human [46]. El-Hassan et al. [27] indicated that a significant positive correlation between FA accumulation and dry rot incidence.

The trichothecenes are the main kind of mycotoxins detected in dry rot of potato, which is a kind of chemically related sesquiterpenes compound. Presently, more than 190 known trichothecenes are detected. According to their chemical structure, they can be classified into four groups: types A, B, C, and D, the chemical structure are shown in **Figure 3**.

***Fusarium* species**	**Mycotoxins**	**Reference**
F. acuminatum	BEA	[35]
F. avenaceum	ENNs	[36]
F. crookwellense	ZEA, FUS	[37–39]
	FA	[40]
F. equiseti	FUM, ZEA	[27]
F. graminearum	ZEA	[37, 41]
F. oxysporum	FA	[40]
	SAM	[42, 43]
	FA, FUM, ZEA	[27]
	ENNs, BEA	[35]
F. sambucinum	SAM	[42–44]
	FA	[40]
	FA, FUM, ZEA	[27]
	ENN	[36]
	BEA	[35]

Note: BEA: beauvericin, ENNs: enniatins, FA: fusaric acid, FUM: fumonisin, FUS: fusarin C, SAM: sambutoxin, ZEA: zearalenones.

Table 2.
Non-trichothecenes produced by Fusarium *species in dry rot of potato.*

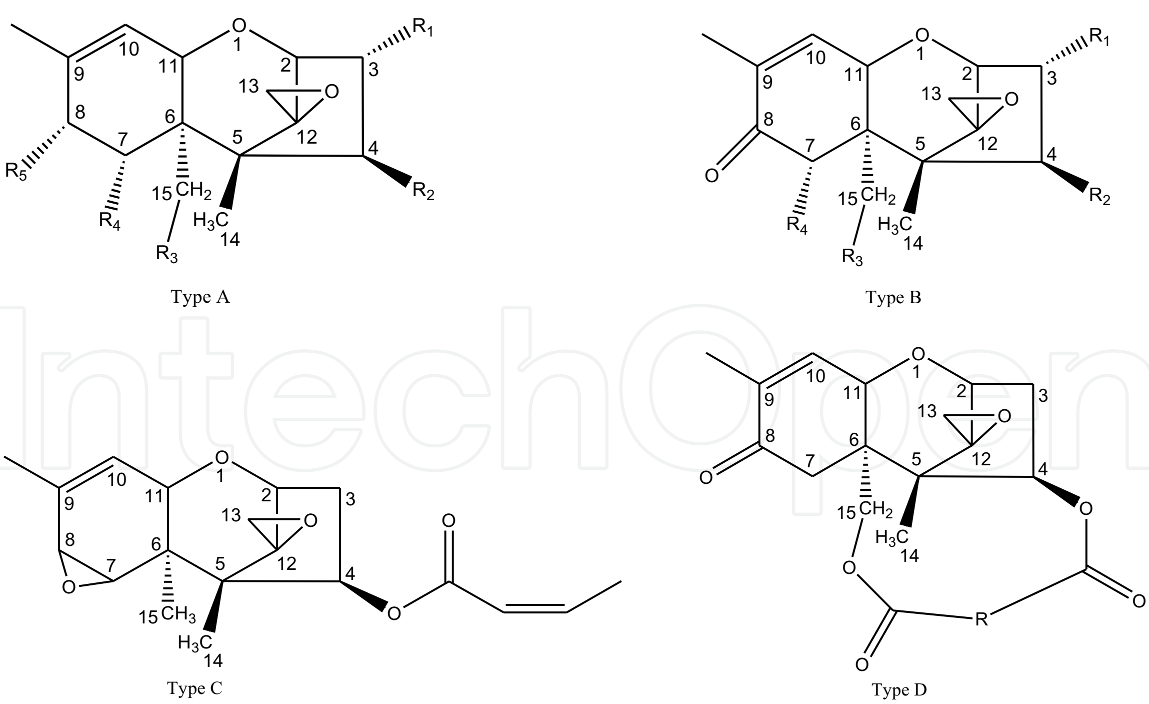

Figure 3.
Basic chemical structure of trichothecenes.

Types A and B are usually found in cereal grains, animal feed, and human food made from contaminated grains. In addition, they were also found in potato tubers infected by *Fusarium* spp. Trichothecenes have phytotoxicity and mycotoxicoses which can pose a severe threat for human and animal health [22]. The typical symptoms are vomiting, feed refusal, and diarrhea when animal intake the food contaminated trichothecene, in severe case, trichothecenes have the potentiality leading to cancer, deformity and mutation [48]. Members of the genus *Fusarium* produce simple or non-macrocyclic trichothecenes while more complex macrocyclic trichothecenes are produced by fungi of the genera *Stachybotrys* and *Trichothecium* as well as other fungi [46]. Some *Fusarium* species associated with dry rot of potato were shown to produce trichothecenes in dry rot of potato tuber (**Table 3**). Type A and B are usually detected in rotted potato tuber tissue. Xue et al. [22] suggested that 3-ADON, T-2, FX and DAS were found in dry rot of potato caused by *F. sulphureum*, *F. solani* and *F. sambucinum*, Meanwhile, these mycotoxins were found not only in the lesion but also in the adjacent asymptomatic tissue, whose concentration showed a strong trend of decline with increase in distance from the infection point. Ellner et al. [55] indicated that 4,15-DAS and DAS were found in not only rotten tissue but also in distant healthy looking tissue in potato tuber infected with *F. sambucinum*, which had a strong decline in trichothecenes concentration with

***Fusarium* species**	**Mycotoxins**	**Sources**
F. coeruleum	DON, HT-2, 3-ADON	[49]
F. culmorum	DON, 3-ADON	[39]
	NIV, FX, DON, 3-ADON	[50]
F. crookwellense	NIV, FX	[37]
	NIV, DAS	[38]
	FX	[50]
F. equiseti	NIV, FX, 4,15-MAS, DAS, SCR	[50]
	T-2,	[27]
F. graminearum	DON, NIV, FX, 3-ADON, 15-ADON	[51]
	DON, NIV, FX	[37]
	NIV, T-2, 3,15-ADON, 15-SCRP	[52]
	NIV, FX, DON, 3-ADON, 15-ADON	[50]
	DON, 3-ADON, 15-ADON	[41]
F. oxysporum	T-2	[27]
F. sambucinum	DAS, MAS, NEO, T-2, HT-2	[53]
	DAS	[39]
	4,15-DAS, 15-MAS, 4-MASc	[54]
	DAS	[40]
	DON, NIV, HT-2	[49]
	T-2	[27]
	MAS, DAS	[56]
	3ADON, DAS, FX, T-2	[22]
F. sulphureum	3ADON, DAS, FX, T-2	[34]
F. solani	3ADON, DAS, FX, T-2	[34]

Note: 3-ADON: 3-acetyldeoxynivalenol, 15-ADON: 15-acetyldeoxynivalenol, DAS: diacetoxyscirpenol, 4,15-DAS: 4,15-diacetoxyscirpenol, DON: deoxynivalenol, FX: fusarenone X, HT-2: HT-2 toxin, MAS: monoacetoxyscirpenol, 4-MAS: 4-acetyl-monoacetoxyscirpenol, 15-MAS: 15-acetyl-monoacetoxyscirpenol, NIV: nivalenol, NEO: neosolaniol, SCR: scirpentriol, 15-SCRP: 15-acetylscripenol, and T-2: T-2 toxin.

Table 3.
Trichothecenes produced by Fusarium *species in dry rot of potato.*

an increasing distance from the visible rotted tissues. Similarly, Delgado et al. [51] reported that DON, NIV, FX, 3-ADON, 15-ADON were detected in dry rot of potato caused by *F. graminearum*, which also had the similar decline trend in trichothecenes concentration with an increasing distance from the rotted tissues.

In order to investigate the stability for heat, the effect of cooking on the trichothecenes was carried with potato tubers infected with *F. sambucinum,* the results indicated that the content of 4,15-DAS reduced 26% and 81% after 1 h and 4 h of cooking at 100°C, respectively [57]. The long cooking times required to degrade the structure of the trichothecens, which make it difficult that thermal treatment can be used as the degradation method for food or feed contaminated with trichothecenes. Although mycotoxins, considered thermally stable [57], are found in tuber invaded by different *Fusarium* spp., no sufficient data are currently available to evaluate the health risk for human health.

4. Dry rot control

4.1 Cultural practices and storage

The excellent cultural practices combined with appropriate of storage conditions are the most important and crucial factors which affect the incidence and severity of potato dry rot. In addition, planting healthy seed tubers in field, avoiding tuber injuries during harvesting, taking some steps to accelerate wound healing, providing appropriate storage conditions, these steps are the crucial factors, which provide good control to dry rot of potato [58]. In most cases, care is indispensable when harvesting that can minimize bruises and wounds for the harvested tubers. The tuber without wound may restrict the fungal spore colonization and germination, finally prevent major rotting. The 10–18°C temperature of the pulp is the suitable period for tuber harvesting [59]. The suitable temperature combined with high humidity (95–99%) and excellent ventilation is crucial for wound healing in tubers after harvest. After 7–14 days of vine killing, it is suitable for tuber to harvest, which has enough time to wound healing and reduce the chances of pathogen attack [59]. Planting certified seed tubers having <2% disease symptoms is recommended. The infected seed tuber is not recommended to introduce into field, because this will lead to pathogen survive during the whole growing period, finally cause dry rot. Moreover, proper disinfection treatment for storage facilities and implements used in handling and cutting of tubers are mandatory. Physiological maturation of the tuber is another important influence factor to affect dry rot development. Heltoft et al. [28] indicated that maturity plays an important role, in generally, late maturing cultivars are much more resistant to *F. sambucinum* than the early maturing one. The reason is maybe that the immature cultivar has high sucrose content and poor skin set, high sucrose can provide nutrition for pathogen growth, and poor skin are easy to bruise and produce wound, whose property make the early maturing cultivar are more vulnerable to pathogen [28]. Harvesting tubers with a high maturity can decrease the incidence rate of dry rot during storages. Harvest date is also an indispensable factor to influence *Fusarium* involved in dry rot incidence. Crop rotation is also very important, which is the most recommended cultural practice in managing soil-borne diseases in potato dry rot management [4]. Because *Fusarium* spores can live for a long term in soil and its broad host range, which makes it very difficult to manage by using crop rotation. Moreover, it is reported that crop infectivity of *Fusarium* isolates in clover and cereal crops that suggests that crop rotation may offer the favorable host and condition to survive for the pathogenic strains, rather than controlling them [13].

As we know, the dry rot of disease can infect through wound, when one single tuber is rotten, it can infect to other tubers around the rotten tuber, which will lead to a disastrous disease during storage. Therefore, it is necessary for any wounds (including pests and disease appearance) to have a thorough examination of tubers before storage, and that is the reason for proper grading before storage [60]. For storehouse, proper circulation of cool air is very crucial as respiration in stored potatoes generates excessive CO_2 and heat that can facilitate the growth of adhering fungal spores. The CO_2 concentration in a well-maintained storage facility is about 1200 to 1500 ppm. When the CO_2 concentration is more than 5000 ppm, which indicates storage rots and/or insufficient ventilation in the storage [60].

4.2 Host resistant

Host resistant play an important role in control postharvest disease. Xue et al. [34] compared two cultivars of Longshu No 3 (susceptible cultivar) and Longshu No 5 (resistant cultivar) susceptibility to dry rot disease and trichothecenes accumulation, the result showed that Longshu No 3 has more lesion diameter and the contents of FX, DAS, 3ADON and T-2 toxin in tubers inoculated *F. sulphureum*, when compared with the resistant cultivar of Longshu No. 5. In fact, resistance to each species of *Fusarium* is independent and genetically distinct [18]. The resistance to a species of *Fusarium* is transmitted to progeny, but appears to be associated with recessive alleles [61, 62]. Despite the fact that numerous potato cultivars and clones have been tested for susceptibility, no one cultivar is resistant to the whole *Fusarium* complex. Jiang et al. [31] suggested Qingshu 168 is resistant to *F. sulphureum*, and Longshu No 3 is susceptible to *F. sulphureum*. Clone B7200–33 from the USDA Potato Breeding Program appeared immune to both *F. sambucinum* and *F. coeruleum* [63]. Esfahani et al. [64] showed that the cultivar Saturna was relatively resistant to *F. sulphureum*, *F. solani*, and *F. oxysporum*. More recently, Yilma et al. indicated that the cultivar of Owyhee Russet was significantly higher resistance to dry rot than Russet Burbank. In general, some cultivars are susceptible to one species of *Fusarium* spp., but some cultivars are resistant to another species of *Fusarium*. Similarly, one strain of *Fusarium* is pathogenic to one cultivar, however, the strain of *Fusarium* is non-pathogenic to another cultivar. Because the susceptibility-resistance difference, on the one hand, was related with the strains and cultivars, on the other hand, the prevailing culture and environmental conditions in different regions of the world also play the important roles. Therefore, to optimize the cultivar to grow in field, it is essential to investigate the populations of *Fusarium* in the field and the pathogenicity.

4.3 Chemical control

The most popular and effective the management of dry rot is pre- and post-harvest management, that is to say, seed piece decay management before planting is combined with post-harvest treatments of tubers before storage. Presently, thiabendazole is the most effective and extensively used benzimidazole fungicide to control the dry rot disease caused by *Fusarium* species [1, 4]. Thiophanate-methyl (benzimidazole group) is widely used to manage seed tuber piece decay in Canada. However, the application of thiabendazole caused the appearance of resistant strains against *F. sambucinum*, but the rest of the *Fusarium* species *viz*. *F. solani, F. oxysporum, F. culmorum, F. equiseti, F. sporotrichioides, F. acuminatum* and *F. avenaceum* were still sensitive to thiabendazole [4]. Some new alternative"low-risk"fungicide, such as fludioxonil (phenylpyrroles) and azoxystrobin (strobilurins) also manifest good effect in managing dry rots [65]. Fludioxonil can be used to control tuber seed piece decay and sprout rot. Daami-Remadi et al. [65] suggested that the synthetic fungicides such as, azoxystrobin, chlorothalonil and fludioxonil effectively reduced the severity of dry rot up to 50% when compared with control during 21 days of storage at 25–27°C. Fungicides mixture of metalaxyl + mancozeb or maneb is found effective in controlling tuber diseases where rotting was reduced by 50 and 91% on tubers inoculated with *F. sambucinum* and *P. erythroseptica* + *F. sambucinum*, respectively. Fludioxonil with mancozeb as seed tuber soaking treatment was effective to control dry rot [66].

The increasing resistance against fungicides, environmental pollution, and food safety problems, it is urgent to explore new and safe strategies to manage dry rot diseases. Some generally recognized as safe (GRAS) compounds, such as several inorganic and organic salts, essential oils and phytohormones, display good effect in sustainably managing dry rot of potato. Potassium metabisulfite and sodium metabisulfite showed 100% control of dry rot while magnesium sulfate, potassium sulfate, ammonium sulfate, sodium carbonate, sodium sulfate, calcium phosphate and potassium phosphites significantly reduced the infection percentage [67]. Li et al. [21] suggested sodium silicate significantly inhibited the growth of *F. sulphureum in vitro*, and suppressed the development of dry rot of tubers *in vivo*.

The use of chitosan as GRAS food additive is approved by the United States Food and Drug Administration. A recent study showed that a concentration of 0.25% chitosan completely inhibited *F. sambucinum* growth and prevented the other physiological losses in tubers. A similar antifungal effect of chitosan was reported against *F. sulphureum* and *F. solani* [68]. Chitosan and β- aminobutyric acid (BABA) applications suppressed the development of lesion diameter and trichothecenes accumulation in potato tuber inoculated with *F. sulphureum*, the involved mechanism is related with the increases in enzyme activities associated with induced resistance, and down-regulated genes involved in trichothecenes biosynthesis pathway [69]. Raigond et al. [70] also indicated that chitosan was effective in managing dry rots in a dose-dependent manner in potato cultivar Kufri Jyoti and Kufri Chipsona. As we know, chitosan can be as coating thin film material, in future chitosan should be used as a kind of coating thin film material to manage postharvest disease in potato tuber.

Recently, some other GRAS compounds, such as essential oils and plant extracts also manifested a good effect in inhibiting growth of fungus and the development of dry rot caused by *Fusarium* spp. *in vitro* and *in vivo* in the form of seed soaking or fumigation treatment [70, 71]. *Zanthoxylum bungeanum* essential oil found effective in reducing the severity of dry rot disease caused by *F. sulphureum* [72]. Similarly, the essential oils of fennel and peppermint also significantly inhibited the growth of *F. oxysporum* and controlled the tuber decay when applied as a protective emulsifiable concentrate [73]. The application of aqueous extracts of cinnamon markedly suppressed the growth of *F. sambucinum* and reduced dry rot [74]. The cinnamaldehyde, a predominant constituent of cinnamon essential oil, manifested excellent effect against *F. sambucinum*, the underlying mechanism revealed that a concentration of 3 and 4 mM inhibited spore germination by restricting the ergosterol biosynthesis, enhancing reactive oxygen species (ROS) accumulation and lead to disrupting cell membrane integrity. The down-regulation of ergosterol biosynthetic genes and the reduction of ergosterol content were analyzed by qRT-PCR and HPLC, respectively [75]. Some essential oils can directly inhibit mycotoxin accumulation, for instance, the essential oils of palmarose and clove inhibited DON and ZEA production in *F. graminearum*. The underlying mechanism maybe the essential oils down-regulate mycotoxin biosynthesis pathway. The essential oils and botanicals as sustainable alternative to synthetic chemicals needs to be further investigated for their on-farm efficacy in future.

4.4 Biological control

Numerous researches focused on the application of antagonistic microorganisms to the control postharvest diseases. Presently, antagonistic microorganisms are considered as an attractive alternative to replace synthetic chemical compounds to manage postharvest diseases. Bio-pesticide is considered more green and safety for the environment and human health than conventional synthetic pesticide. Antagonistic microorganisms can effectively control dry rot during the wound healing period when the potato tuber is at its most vulnerable. The first report that isolates from the genera *Pseudomonas Migula* spp., *Enterobacter Hormaeche & Edwards* spp., and *Pantoea Gavini*. spp. could decrease the incidence of dry rot caused by *F. sambucinum* [76]. Schisler's group also found two-strain mixtures of various antagonists manifested more effect than a single strain alone in controlling dry rot of potato [77]. *Pseudomonas fluorescens Migula* and *E. cloacae* were also effective under field conditions [78]. Glomus irregulare Blaszk., Wubet, Renker & Buscot enhanced defense responses, reduced the disease severity caused by *F. sambucinum* and modulated trichothecene mycotoxin gene expression in the pathogen [79].

Trichoderma is one of the most studied fungal genera, as well as recognized for its ability to inhibit different kinds of fungal pathogens and control both pre-harvest and post-harvest diseases. El-Kot [80] indicated that *Trichoderma harzianum Rifai*, *Epicoccum Link ex Steudel* sp., *Streptomyces endus Anderson & Gottlieb* had a high potential as biocontrol agent to manage dry rot disease caused by *F. sambucinum*. Daami-Remadi et al. [81] found *Trichoderma harzianum* and *Trichoderma viride* showed higher antagonistic activity against potato dry rot in Tunisia caused by *F. oxysporum*, *F. solani*, *F. graminearum*, and *F. sambucinum*. The major modes of action of *Trichoderma* is maybe that mycoparasitism, competition for nutrients, and the production of extracellular enzymes and/or secondary metabolites. Tian et al. [82] reported that antagonistic *Trichoderma* strains were able to detoxify DON, produced by *F. graminearum*, via glycosylation. Xue et al. [83] suggested that T-2 toxin (produced by *F. sulphureum*) at low concentration can be as an elicitor to induced resistance against dry rot of potato by stimulating reactive oxygen species (ROS) metabolism and phenylpropane metabolism. Yu et al. [84] reported that another biocontrol fungus, *Trichothecium roseum*, acting as an elicitor significantly enhanced defense responses in potato tubers against dry rot caused by *F. sulphureum*. During the defense responses, the resistance-related genes was up-regulated, the resistance-related enzymes and level of antifungal compounds significantly increased after treatment. Moreover, an arbuscular mycorrhizal fungus, *Glomus irregulare*, were found to modulate mycotoxin gene expression in *F. sambucinum*, inhibit its growth, and significantly reduce the production of DAS [85]. The application of mycoparasites as biocontrol agents that can manage plant diseases and detoxify/degrade mycotoxins is an ongoing topic of research [86].

5. Conclusion

Dry rot of potato, caused by *Fusarium* spp., is a disastrous disease postharvest during storage, which can cause economic losses and mycotoxin contamination. and the genetic diversity of *Fusarium* varies depending upon the geographical location and growing condition. The host cultivar and storage condition also significantly influence the frequency of occurrence and aggressiveness of potato dry rot. A breeding program is urgent to develop in order to adapt to the different cultivar against *Fusarium* species.

An integrated disease management strategy is necessary in order to efficiently management of dry rot, which includes appropriate harvesting conditions to avoid bruise for tubers, suitable storage conditions, as well as the pre- or postharvest application of registered synthetic chemical fungicides. In addition, the GRAS compounds and microbial antagonists as alternative strategies are being developed to control potato dry rot. The successful management of dry rot will certainly rest on additional research and development efforts between scientists and industry to implement an integrated strategy towards the efficient and durable management of dry rot.

In future, the application of omics technology will supply further functional genes and proteins that can be targeted for designing non-transgenic and transgenic management approaches. The integrated management of dry rot mainly depend on the additional research on the identified gaps and collaborative efforts of stakeholders (including researchers, industrialists and farmers) in developing an succesful management strategy from field to storage.

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