台灣農業研究 (J. Taiwan Agric. Res.) 75(2):185–199 (2026)
https://doi.org/10.6156/JTAR.202606_75(2).0002

Feature Article

Plant Disease Management Strategies for Sustainable Agriculture

Hung-Chang Huang[1,*]

Abstract

Huang, H. C. 2026. Plant disease management strategies for sustainable agriculture. J. Taiwan Agric. Res. 75(2):185–199.

The outbreak and spread of crop diseases result from the interactions among plant pathogens, host plants, and environmental conditions. Improper cultural practices, such as the use of diseased seeds, susceptible varieties, and inappropriate cultivation practices, may lead to the emergence or resurgence of crop diseases. Crop disease management is crucial in modern agriculture. In this era of energy conservation and environmental protection, all crop disease control methods must be effective, economical, and environmentally friendly. Crop disease management methods such as the use of clean seeds, disease-resistant varieties, crop rotation, biological control, organic soil amendment, and cultural practices are considered viable alternatives to synthetic chemical pesticides. The prospects and applications of these environmentally friendly plant disease control methods are further discussed using fungal and bacterial diseases as examples.

Key words: Allelopathy, Biological control, Crop rotation, Disease resistance, Ecology, Epidemiology, Soil amendment, Insect-pathogen relationship.

INTRODUCTION

Plant disease outbreaks require sufficient numbers of virulent pathogens to initiate infection, susceptible hosts to promote disease development, and environmental conditions that favor further spread of the disease. Inappropriate farming practices in modern crop production often lead to the emergence and recurrence of crop diseases. For example, farmers in Alberta, Canada, use sprinkler irrigation to increase crop yields of alfalfa, beans, and sugar beets. This cultivation method has led to serious disease outbreaks in these crops, including Verticillium wilt of alfalfa (*Verticillium albo-atrum*) (Howard *et al*. 1991), white mold of beans (*Sclerotinia sclerotiorum*) (Huang *et al*. 1988), *Pythium* damping-off of sugar beets (*Pythium* spp.), and bacterial wilt of beans (*Curtobacter flaccumfaciens* pv. *flaccumfaciens*) (Hsieh *et al*. 2002). Other cultural practices, such as planting pathogen-infected seeds or susceptible crop varieties, can also lead to disease outbreaks, resulting in severe crop losses.

Verticillium wilt of alfalfa, caused by *V. albo-atrum*, was discovered in Sweden in 1918 and caused severe losses to alfalfa grown in cooler regions of Europe in the 1950s (Bergstrom 1984). In North America, the disease was first reported on alfalfa in the United States in 1977 (Graham *et al*. 1977) and in Canada in 1979 (Sheppard 1979). In 1994, Verticillium wilt of alfalfa was also reported in Hokkaido, Japan

Received: October 2, 2025; Accepted: January 28, 2026.
* Corresponding author, e-mail: hchuang39@gmail.com
1 Research Scientist (Emeritus), Agriculture and Agri-Food Canada, Lethbridge Research and Development Centre, Lethbridge, Alberta, Canada.

(Sato 1994). Results from annual field surveys conducted in Alberta from 1980 to 1994 indicate that Verticillium wilt of alfalfa occurs primarily in irrigated alfalfa but is rarely seen in dryland alfalfa (Table 1). *S. sclerotiorum* is another fungal pathogen with a wide host range that is distributed worldwide (Boland & Hall 1994). In Canada, *S. sclerotiorum* causes disease in many commercial crops, including oilseed crops (sunflower, canola, and safflower), pulse crops (beans, peas, and lentils), and vegetable crops (lettuce, carrots) (Bardin & Huang 2001). This disease is serious in Alberta, especially in irrigated crops such as beans (Table 2). *Pythium* damping-off (*Pythium ultimum*) is an important seedling disease of vegetables and other crops in many countries. In Alberta, *Pythium* damping-off is important on safflower, canola, peas, and sugar beet (Huang *et al*. 1992a; Bardin *et al*. 2003). The purpose of this article is to explore effective and environmentally safe plant disease management strategies using these three high-profile fungal diseases as examples.

BIOLOGY AND EPIDEMIOLOGY OF PLANT PATHOGENS

Basic research to understand the biology and epidemiology of plant pathogens is critical to developing effective and rational crop disease management strategies. For example, the pathogen *S. sclerotiorum* produces black sclerotia that can survive extreme weather conditions. This explains why Sclerotinia disease of crops occurs worldwide, from cold temperate regions to the tropics. In addition, the black sclerotia of *S. sclerotiorum* can germinate myceliogenically to produce white mycelia or carpogenically to produce ascocarps, releasing large numbers of airborne ascospores. Therefore, different sclerotial germination patterns can lead to distinct diseases in plants. For example, the black sclerotia in the soil germinate myceliogenically to produce white mycelia, which either attack the roots of sunflower seedlings, causing damping-off disease, or attack the roots of older plants, resulting in

Table 2. Annual survey of Sclerotinia white mold of bean (*Sclerotinia sclerotiorum*) in Alberta, Canada (1988–2011).

	Diseased/surveyed (%)	
Year	Irrigated fields	Reference
1988	3/5 (60%)	Huang & Phillippe (1989)
1993	31/31 (100%)	Huang & Erickson (1994a)
1994	33/37 (89%)	Huang *et al*. (1995)
1995	18/18 (100%)	Huang *et al*. (1996)
1998	20/21 (95%)	Huang & Erickson (1999)
1999	22/22 (100%)	Huang & Erickson (2000)
2007	27/28 (96%)	Erickson & Balasubramanian (2008)
2009	41/43 (95%)	Erickson & Balasubramanian (2010)
2011	27/30 (90%)	Erickson & Chatterton (2012)

Table 1. Annual survey of Verticillium wilt of alfalfa (*Verticillium albo-atrum*) in Alberta, Canada (1980–1994).

	Diseased/surveyed (%)		
Year	Irrigated fields	Dryland fields	Reference
1980	5/49 (10%)	0/24 (0%)	Howard *et al*. (1991)
1981	22/86 (26%)	0/28 (0%)	Howard *et al*. (1991)
1982	71/791 (9%)	1/247 (0.4%)	Howard *et al*. (1991)
1983	12/56 (21%)	0/24 (0%)	Howard *et al*. (1991)
1984	10/54 (19%)	0/32 (0%)	Howard *et al*. (1991)
1985	16/35 (46%)	2/18 (11%)	Howard *et al*. (1991)
1986	17/65 (26%)	0/28 (0%)	Howard *et al*. (1991)
1993	7/10 (70%)	(No data)	Huang & Erickson (1994b)
1994	18/18 (100%)	(No data)	Huang & Erickson (1995)

wilt of sunflower plants (Dorrell & Huang 1978; Huang & Dueck 1980). On the contrary, black sclerotia in the soil germinate carpogenically to produce ascocarps and release a large number of airborne ascospores, which attack the above-ground tissues of plants and cause diseases such as sunflower head rot, safflower head rot, pea pod rot (Huang & Kokko 1992) and bean white mold. Therefore, understanding the germination behavior of sclerotia of *S. sclerotiorum* is crucial to adopt the correct strategies to control Sclerotinia diseases in crops. Taking the biocontrol of Sclerotinia diseases by *Coniothyrium minitans* as an example, to effectively control Sclerotinia wilt of sunflower, *C. minitans* should be applied via soil treatment (Huang 1980; McLaren *et al*. 1994). However, for effective control of bean white mold, *C. minitans* should be applied as an air-spray (Huang *et al*. 2000) or as a soil treatment before sowing and air-spray during the flowering period (Huang & Erickson 2004a).

Verticillium wilt of alfalfa caused by *V. albo-atrum* is a good example of the versatility of plant pathogens. This pathogen has a narrow host range but can be transmitted through multiple routes (Huang 2003). Since Verticillium wilt is a systemic disease of alfalfa, the pathogen is distributed in the vascular system of infected roots, stems, leaves, pods, and seeds (Huang *et al*. 1985; Huang 1989). Therefore, Verticillium wilt of alfalfa is an important quarantine disease in many countries, including China and Japan. Exports of alfalfa hay or seeds to these countries are strictly controlled by quarantine rules. In addition, under humid conditions in the field, large numbers of *V. albo-atrum* spores (conidia) are produced on old diseased alfalfa plants. These spores can be spread by running water, agricultural machinery, or insect pests such as aphids (Huang *et al*. 1983), grasshoppers (Huang & Harper 1985) and alfalfa weevils (Harper & Huang 1984). These insects are important alfalfa pests in Canadian prairie and are effective vectors of Verticillium wilt of alfalfa (Huang 2003).

The alfalfa leafcutter bee (*Megachile rotundata*) is an important pollinating insect for alfalfa seed production. A field study showed that many leafcutter bees were contaminated with *V. albo-atrum* spores while foraging in diseased alfalfa fields (Huang *et al*. 1986b). Leafcutter bees in the fields also cut leaf fragments infected with *V. albo-atrum* and use them to make cocoons in their hives (Huang & Richards 1983). Contamination of leafcutter bee cocoons with *V. albo-atrum* may pose potential problems for international trade in this pollinating insect. Further studies conducted indoors (Huang & Kokko 1985) and in the field (Huang *et al*. 1986b) showed that alfalfa pollen grains are susceptible to infection by *V. albo-atrum*. Since alfalfa leafcutter bees are important pollinators for alfalfa seed production, infection of alfalfa pollen by *V. albo-atrum* may further affect alfalfa seed production. Therefore, in addition to insect pests, this pollinator may also be a potential vector when foraging in alfalfa seed fields where Verticillium wilt occurs.

Another study also suggested that Verticillium wilt of alfalfa may be transmitted by ruminants (e.g., lambs) grazing on diseased alfalfa pastures (Huang *et al*. 1986a). All these basic studies on the survival, biological behavior, and epidemiology of *S. sclerotiorum* and *V. albo-atrum* will provide the basis for developing effective strategies for the sustainable management of these two important fungal diseases.

STRATEGIES FOR SUSTAINABLE MANAGEMENT OF CROP DISEASES

To minimize the over-reliance on chemical pesticides, some conventional measures and new options for sustainable crop disease management are discussed below.

Phytosanitary measures

Phytosanitary measures are used to prevent the spread of plant diseases between countries. For example, Verticillium wilt of alfalfa (*V. albo-atrum*) is listed as a quarantine disease in China.

All alfalfa hay shipped to China from the USA (Anonymous 2012) or Canada (Anonymous 2021) must be certified Verticillium wilt-free. Bacterial wilt of bean caused by *Curtobacterium flaccumfaciens* pv. *flaccumfaciens* is an important seedborne disease in North America, South America, Europe, and Australia (Huang *et al*. 2009) and is a quarantine disease in many Asian countries, including China (Chun Li, Personal Communication). Four variants of the bacterial wilt pathogen in beans have been reported: yellow, orange, purple, and pink variants (Huang *et al*. 2009). The European and Mediterranean Plant Protection Organization (EPPO) imposes quarantine regulations to prevent the import of bean seeds infected with the bacterial wilt pathogen (OEPP/EPPO 1982). Therefore, phytosanitary measures are a reasonable measure to prevent the spread of plant diseases through commercial trade of seeds or other planting materials such as seedlings or tubers.

The development of rapid detection methods for plant pathogens is critical for the implementation of phytosanitary regulations. Taking bacterial wilt of beans as an example, Tegli *et al*. (2002) developed a rapid, sensitive, and specific PCR-based assay for the detection of *C. flaccumfaciens* pv. *flaccumfaciens* (Cff) in infected bean seeds. McDonald & Wong (2000) developed a cocktail of antibodies to screen commercial bean seeds for the presence of various variants (yellow, orange, purple, or pink variants) of the bacterial pathogen. Another example is Verticillium wilt of alfalfa, for which Christen (1982) developed a selective medium specifically for the detection of the pathogen *V. albo-atrum* in soil, infected alfalfa seeds, and infected alfalfa hay. These two examples demonstrate that the development of rapid detection methods for plant diseases varies by disease, and therefore, focus should be placed on the effectiveness and efficiency of each detection method.

Use pathogen-free seeds or seedlings for planting

Seeds, tubers, or other planting materials infected with plant pathogens have the potential to introduce these diseases into the field. Seed-borne diseases are common in cultivated crops. For example, *V. albo-atrum* (*Vaa*) is a seed-borne pathogen of alfalfa (Sheppard & Needham 1980; Huang *et al*. 1985), and the use of *Vaa*-infected alfalfa seeds may lead to outbreaks of Verticillium wilt. *Erwinia rhapontici* is another seed-borne pathogen that causes pink seed disease in many crops, including peas, beans, lentils, chickpeas, and durum wheat (Huang *et al*. 2003a, 2003b; Hsieh *et al*. 2010). Field studies have shown that planting *E. rhapontici*-infected pea seeds reduces pea emergence, seedling vigor, and seed yield (Huang & Erickson 2004c). The pink seed pathogen survives well under the cold winter conditions of the Canadian prairies (Hsieh *et al*. 2010). *Curtobacterium flaccumfaciens* pv. *flaccumfaciens* is another seed-borne pathogen that causes bacterial wilt of beans in many countries (Huang *et al*. 2009). All these examples suggest that seed-borne pathogens may be the primary source of inoculum for many crop diseases. Therefore, using pathogen-free seeds or seedlings for planting is a prerequisite for preventing crop diseases. It is important to use isolated fields with good field sanitation to produce healthy seeds for planting.

Breeding crops for disease resistance

Plant disease outbreaks are often the result of growing commercial varieties that are susceptible to pathogens. Breeding disease-resistant crops is the most effective and environmentally friendly way to protect crops from plant diseases. For example, Verticillium wilt of alfalfa was discovered in Canada in 1979 (Sheppard 1979), but due to the lack of resistant commercial varieties, it quickly became a major disease spreading across the country. In an effort to find a solution to Verticillium wilt of alfalfa, Agriculture and Agri-Food Canada established the National Alfalfa Breeding Program in 1981, with the specific goal of developing new alfalfa varieties resistant to this disease. This breeding effort resulted in the release of three new alfalfa varieties, 'Barrier' (Hanna & Huang 1987), 'AC Blue J' (Acharya *et al*. 1995) and 'AC Longview' (Acharya &

Huang 2000), that are high-yielding and resistant to Verticillium wilt (Huang *et al*. 1994). The economic benefits of growing these Verticillium wilt-resistant alfalfa varieties in Western Canada are estimated to be CDN$26.6 million per year (Smith *et al*. 1995).

Developing rapid and effective techniques to screen crop varieties or lines for disease resistance is a critical step in ensuring the success of crop breeding programs. For example, Fusarium wilt, caused by *F. oxysporum* f. sp. *chrysanthemi*, is an important disease of cold-tolerant chrysanthemums in Manitoba, Canada (Huang *et al*. 1992b). An indoor screening using chrysanthemum stem cuttings can effectively identify chrysanthemum varieties or lines that are resistant to Fusarium wilt (Huang *et al*. 1993). Another example is the release of three alfalfa varieties resistant to Verticillium wilt (Acharya & Huang 2003), which was attributed to the use of an effective indoor screening technique for this disease (Huang & Hanna 1991). In addition to conventional screening methods for crops disease resistance, other approaches, such as molecular methods, should be explored to accelerate plant breeding programs. At the same time, collaboration among researchers such as plant pathologists, plant breeders, and molecular biologists is crucial to ensure the success of crop breeding programs.

Soil amendment

Some plant species may contain allelopathic chemicals that are harmful to plant pathogens (Patrick 1986). Soil amendment with allelopathic plant tissues or other agricultural wastes (e.g., manure, compost) may help control crop diseases (Huang & Huang 1993). For instance, amending soil with 3% (w/w) lentil, canola, or sweet clover straw not only inhibited the production of apothecia of *S. sclerotiorum* but also promoted the growth of soil microflora (Huang *et al*. 2002a; Huang & Chou 2005). In addition to controlling plant pathogens, Moyer & Huang (1997) reported that 1% aqueous extracts of lentil straw, oat straw, or canola straw inhibited seed germination of flixweed, stinkweed, and downy brome, but not wheat. These reports (Moyer & Huang 1997; Huang *et al*. 2002a) suggest that some allelopathic chemicals in certain crop straws may have the potential to control soil-borne plant pathogens and weeds. In addition, some agricultural chemicals, such as fertilizers and herbicides, may also have harmful effects on plant pathogens. For example, soil amendments using urea effectively controlled apothecia production from sclerotia of *S. sclerotiorum* (Huang & Janzen 1991). Soil amendment with triazine herbicides, atrazine or simazine, at the recommended rates for weed control resulted in the formation of multiple secondary stipes, which failed to form ascocarps and produce asci and ascospores (Huang & Blackshaw 1995). Therefore, agricultural wastes, agrochemicals, and other industrial wastes may have the potential to develop formulated products for the control of plant diseases.

To develop a formulated compound for disease control, the compound should have the following functions: (1) maximize harmful effects on target plant pathogens, (2) increase the number of beneficial microorganisms, (3) maintain or improve soil fertility, and (4) maintain healthy agroecosystems (Huang & Huang 1993). Most formulated soil amendments are composed of fertilizers, agricultural wastes, and industrial wastes. For example, "S-H Mixture" (R.O.C. Patent No. 021096; Inventors: S. K. Sun and J. W. Huang) is the first commercial product developed in Taiwan to control soilborne diseases in crops, including Fusarium wilt of radish, watermelon and cabbage; club root of Chinese cabbage; bacterial wilt of tomato; Rhizoctonia blight of beans; sheath blight of rice; and southern blight of pepper (Sun & Huang 1985). This product is mainly made from agricultural and industrial wastes such as sugarcane bagasse, rice husk, oyster shell, and mineral ash (Sun & Huang 1985). In addition to controlling soilborne diseases, "S-H Mixture" can also stimulate the growth of beneficial microorganisms in the soil. Another formulated product, "FBN-5A" (R.O.C. Patent No. 135447; Inventors: J. W. Huang and S. S. Yang), mainly consists of spent forest mushroom compost, fish meal, bone powder, blood powder, rape seed meal, lime, and allyl alcohol (Shiau *et al*. 1999). Adding 0.1% FBN-5A to soil or BVB#4 growth medium can effectively prevent and control damping-off cabbage and radish caused by *Rhizoctonia solani*. In addition to controlling Rhizoctonia damping-off, FBN-5A stimulates the growth of antagonists such as *Trichoderma* spp. (Shiau *et al*. 1999). The third example is the granular biofumigant “PBGG” (R.O.C. Patent No. I276402; Inventors: J. W. Huang, W. C. Chung, H. C. Huang, and J. H. Shiau). It is used to control soilborne pathogens such as *R. solani*, *Pythium* spp., *S. sclerotiorum*, and *Sclerotium rolfsii* (Chung *et al*. 2002; Chung *et al*. 2005). The main ingredients of “PBGG” are *Pseudomonas boreopolis*, Brassica seed pomace, glycerin, and sodium alginate. Application of 1% (w/w) of “PBGG” to soil infested with *R. solani* significantly reduced the percentage of colonization of cabbage seeds by the pathogen and stimulated the growth of actinomycetes, including *Streptomyces padanus* and *S. xantholiticus*. The control of plant diseases is based on the release of fungal toxic substances, isothiocyanates by “PBGG” (Chung *et al*. 2005). These examples illustrate the potential to develop soil-improvement products that inhibit pathogens while promoting the growth and proliferation of biocontrol agents. The disposal of agricultural waste has become an important global environmental issue. Therefore, utilizing agricultural waste to develop effective disease management products will benefit agriculture and society as a whole.

Crop rotation

Crop rotation has long been considered an effective strategy for excluding and eradicating plant diseases (Walker 1969). Repeated monocultures of the same annual crop may lead to disease outbreaks in that crop. For example, results from a long-term (1959–2000) field trial in Hokkaido, Japan, clearly demonstrated the impact of crop rotation on bean diseases and yields (Huang *et al*. 2002c). In this field trial, a total of seven treatments were set up including: (1) bare land (no crops or weeds planted); (2) monoculture (potatoes, sugar beets, oats, kidney beans, or winter wheat); (3) two-year crop rotation (oats, sugar beets); (4) three-year crop rotation (soy bean, sugar beets, oats); (5) four-year crop rotation (potatoes, sugar beets, oats, soybean); (6) five-year crop rotation (sugar beets, oats, winter wheat, red clover, potatoes); and (7) six-year crop rotation (potatoes, sugar beets, oats, kidney beans, winter wheat, red clover). Each treatment was repeated once. Several reports from studies in this field indicate that *Pythium* damping-off (*Pythium* spp.) of beans is severe in monocultures (Kageyama *et al*. 1981; Huang *et al*. 2002c), while bean plants in the six-year rotation treatment are healthy (Huang *et al*. 2002c). Monoculture also causes severe yield losses in bean seeds. From 1989 to 2000, the annual seed yield of beans under monoculture was 970 kg ha^{-1}, while the seed yield in 6-year rotation was 2,380 kg ha^{-1}, resulting in a 59% yield loss in monoculture (Huang *et al*. 2002c). In addition to reduced seed yields, bean monocultures also resulted in reduced seed quality, such as smaller seed size in monoculture plants.

Allelopathy is another important factor to consider when choosing crops for rotation. Moyer & Huang (1997) reported that aqueous extracts of oat, lentil, or canola straws contained allelopathic chemicals that were toxic to flixweed, stinkweed, and downy brome. The healthy bean plants observed in the six-year crop rotation treatment of the long-tern crop rotation trial in Hokkaido, Japan, may be due to the planting sequence of beans after oats (Huang *et al*. 2002c). Other studies in Canada have shown that rotation of legume crops with cereals is superior to cereal monocultures because legume-based rotation systems increase cereal crop yields (Wright 1990), improve soil fertility and quality (Green & Biederbeck 1995), and increase the abundance of soil microorganisms, including fungi, bacteria, and actinomycetes (Biederbeck *et al*. 1999). Therefore, in every crop rotation plan, it is useful to include legume crops to improve soil fertility and allelopathic crops to control harmful plant pathogens.

Biological control

Many fungal and bacterial plant pathogens have natural enemies or competitors, such as hyperparasites (mycoparasites) or antagonistic microorganisms. These natural enemies of plant pathogens may have potential for biological control of plant diseases. For example, diseases caused by *S. sclerotiorum* are difficult to control because the pathogen has a wide host range, including many important commercial crops, and its black sclerotia survive well even in extreme climatic conditions. Furthermore, black sclerotia of *S. sclerotiorum* can geminate in two different ways: (1) myceliogenic germination to produce mycelia that infect the plant roots, or (2) carpogenic germination to produce air-borne ascospores that infect above-ground tissues of the plant. Therefore, the two sclerotial germination modes of *S. sclerotiorum* may cause distinct crop diseases. For example, sclerotia of *S. sclerotiorum* in the soil germinate myceliogenically to produce mycelia, which infect the roots of sunflowers, causing damping-off of sunflower seedlings (Huang & Dueck 1980) or basal stem rot and wilting of older sunflower plants (Huang & Dueck 1980). On the other hand, when sclerotia in the soil germinate carpogenically to produce apothecia, a large number of ascospores are released into the air and infect the aboveground tissues, causing sunflower head rot and stalk rot, safflower head rot, canola leaf blight, stem blight and pod rot, bean white mold, pea pod rot and alfalfa pod rot (Bardin & Huang 2001).

Studies have shown that *Coniothyrium minitans* is a mycoparasitic fungus, capable of attacking sclerotia (Huang 1977; Huang & Kokko 1987) and hyphae (Huang & Hoes 1976; Huang & Kokko 1988) of *S. sclerotiorum*. *C. minitans* is rich in cell wall degrading enzymes, such as glucanase (Huang *et al*. 2001; Laroche *et al*. 2004), and xylanase (Laroche *et al*. 2000). These *C. minitans* enzymes may play an important role in destroying hyphae and sclerotia of *S. sclerotiorum*. Field trials in western Canada have shown that soil treatment with *C. minitans* can effectively control Sclerotinia wilt of sunflower (Huang 1980), and air spraying of *C. minitans* spores can effectively control bean white mold (Huang *et al*. 2000; McLaren *et al*. 2009) and pea pod rot (Huang & Kokko 1992). In addition to being effective in controlling Sclerotinia diseases, *C. minitans* survives well under the extreme weather conditions of the Canadian prairies (Huang & Erickson 2002). Several studies in western Canada have also shown that compared with other mycoparasites such as *Trichothecium roseum* (Huang & Kokko 1993), *Talaromyces flavus* (McLaren *et al*. 1994, 1996), *Trichoderma virens* (Huang *et al*. 2000) and *Trichoderma atroviride* (Li *et al*. 2005), *C. minitans* is the most effective mycoparasite to control *S. sclerotiorum*. These findings suggest that *C. minitans* is an idea biocontrol agent for controlling Sclerotinia diseases in crops grown in cold regions such as Canada because of the organism's ability to survive cold winters (Huang & Erickson 2002) and can effectively control sclerotia (Huang 1977, 1980) and apothecia (Huang & Erickson 2004a, 2004b) of *S. sclerotiorum* during the crop production season.

The results of research on *C. minitans* as a potential biocontrol agent (Huang 1980; McLaren *et al*. 1994; Huang *et al*. 2000) attracted investment from three Canadian companies- CSP Food Ltd., Saskatoon (1978–1980), PhilomBios, Saskatoon (1986–1988), and Agrium Co., Calgary (1994–1998) to commercialize this mycoparasite; however, all attempts were ultimately unsuccessful. In contrast, commercialization efforts for *C. minitans* have been successful in Europe, including the product Contans WG® from Prophyta, Germany and another product, Koni®, from Bioved Ltd., Hungary (Luth 2001; Whipps & Lumsden 2001). Contans WG® has been distributed to many countries in Europe and North America.

In addition to mycoparasites, many bacterial species such as *Pseudomonas fluorescens*, *Erwinia* spp., *Streptomyces* spp., and *Rhizobium* spp. are antagonists of many plant pathogens. These antagonistic bacteria may have potential for biocontrol of crop diseases. For example, through indoor screening, *Rhizobium leguminosarum* bv *viceae* "strain R21" was selected and tested for the control of damping-off disease in peas and lentils in fields naturally infested with *Pythium* spp. (Huang & Erickson 2007). The results show that treating pea seeds or lentil seeds with *Rhizobium* "strain R21" can not only control *Pythium* damping-off in peas and lentils, but also increase the seedling height, root nodule size, root biomass, shoot biomass, and seed yield (Huang & Erickson 2007). Although pea seeds treated with the fungicide Thiram™ also effectively controlled *Pythium* damping-off disease, the root nodules produced on pea plants were small in size (Huang & Erickson 2007).

In addition to nitrogen-fixing bacteria, other rhizosphere bacteria have potential as biocontrol agents for crop disease management. For example, seed treatments using *Erwinia rhapontici*, *Pseudomonas fluorescens*, *Bacillus cereus*, or *Pantoea agglomerans* can effectively control *Pythium* damping-off in field crops such as canola, safflower, peas, and sugar beets (Liang *et al*. 1996; Bardin *et al*. 2003). These findings suggest that selected rhizosphere bacterial strains may be developed into biocontrol products. However, before microorganisms are selected for use in the development of biocontrol products, a risk assessment is required to ensure the safety of each biocontrol agent. For example, *E. rhapontici* is an effective agent for controlling *Pythium* damping-off in canola, safflower, peas and sugar beets (Liang *et al*. 1996; Bardin *et al*. 2003), but it is also a plant pathogen, that can cause pink seed disease in many crops, including peas (Huang *et al*. 1990; Huang & Erickson 2004c), beans (Huang *et al*. 2002b; Hsieh *et al*. 2010), lentils (Huang *et al*. 2003a), chickpea (Huang *et al*. 2003a), and wheat (McMullen *et al*. 1984). Therefore, *E. rhapontici* is not suitable for making commercial biocontrol products because it is also a pathogen of many crops (Huang *et al*. 2003b). In comparison, *Rhizobium leguminosarum* bv *viceae* 'strain R21' has great potential for producing commercial products because it not only controls plant diseases but also fixes nitrogen to improve soil fertility (Huang & Erickson 2007).

Culture practice

1. Adjust plant spacing

For soil-borne plant diseases, the location of pathogens in the soil is an important factor in determining disease outbreaks in the field. Taking Sclerotinia wilt of sunflower as an example, Huang & Hoes (1980) conducted field studies and determined the impact of sclerotia of *S. sclerotiorum* buried at different vertical or horizontal distances from sunflower seeds on the incidence of Sclerotinia wilt of sunflower. The results show that the distance between sunflower seeds and sclerotia of *S. sclerotiorum* has a significant impact on the occurrence of Sclerotinia wilt of sunflower. When sclerotia are buried 5 cm deep next to the sunflower seeds, more than 50% of the sunflower plants will be killed and wilted by the pathogen. On the other hand, the incidence of Sclerotinia wilt of sunflower is significantly reduced when the sclerotia are buried 4 cm above the seed or 5 cm or 15 cm below the seed. Likewise, the incidence of Sclerotinia wilt of sunflower is significantly reduced when sunflower seeds and sclerotia are buried at seed level (5 cm deep) but horizontally spaced 10 cm or more apart (Huang & Hoes 1980).

Adjusting plant spacing is an important factor affecting the secondary spread of diseases in the field. Hoes & Huang (1985) conducted a study in a field heavily infested with sclerotia of *S. sclerotiorum*, and they concluded that sunflower wilt due to secondary spread from the primary inoculum (i.e., from sclerotia in the soil) was common at the within-row plant spacing of 15 cm. However, sunflower wilt due to secondary spread from the primary inoculum was rare at the within-row plant spacing of 25 cm. There was no increase in disease due to plant-to-plant transmission at within-row plant spacing of 36 and 47 cm, and all wilted plants in both treatments were due to primary infection with sclerotia in the soil (Hoes & Huang 1985). Furthermore, studies in this diseased field have shown that sunflower seed yields are maximized with within-row plant spacing of 36 cm or greater, and at 26,000 to 49,000 plants ha^{-1} (Hoes & Huang 1985). This population range also maximizes yields from sunflowers grown on uninfested soils (Robinson *et al*. 1980). Therefore, uniform spacing between sunflower plants can not only maximize sunflower yield (Robinson *et al*. 1982), but also effectively control the secondary spread of Sclerotinia wilt disease in the field (Hoes & Huang 1985).

2. Use of agriculture chemicals

Chemical fertilizers, herbicides, and pesticides are widely used in crop production. Some of these chemicals can harm the environment, including microorganisms. For example, urea is a nitrogen fertilizer for crops, but it is also a fungicide that can control soilborne plant pathogens such as *Fusarium oxysporum* f. sp. *cubense* (Sequeira 1963), *Sclerotium rolfsii* (Fang & Liu 1988) and *Phytophthora* sp. (Tsao & Oster 1981). Huang & Janzen (1991) reported that non-sterile natural soil amended with 100 kg ha^{-1} urea completely inhibited carpogenic germination of sclerotia of *S. sclerotiorum*, but in sterile soil treated with 100 kg ha^{-1} urea, more than 97% of sclerotia germinated carpogenically to produce numerous apothecia. However, if urea-amended, sterile soil is treated with urease, the soil has a strong inhibitory effect on carpogenic germination of sclerotia of *S. sclerotioum*. These findings suggest that ammonia released from the decomposition of urea is a key toxicant that inhibits carpogenic germination of sclerotia of *S. sclerotiorum* (Huang & Janzen 1991). In addition to urea, other chemicals such as calcium cyanamide (Perlka®, https://www.alzchem.com/en/brands/perlka/), not only provide nitrogen and lime to the soil but also control *S. sclerotiorum* (Huang & Sun 1991).

Triazine herbicides, such as atrazine and simazine, are commonly used in crop production in many countries. Canadian studies have shown that triazine herbicides persist in soils in Saskatchewan (Smith & Walker 1989) and Alberta (Moyer & Blackshaw 1993) and that these herbicide residues have reduced yields of subsequent crops in western Canada (Moyer & Blackshaw 1993). Huang & Blackshaw (1995) reported that the triazine herbicides also affect the plant pathogen, *S. sclerotiorum*. Field soils amended with atrazine or simazine at the recommended field application rates (1500 g ha^{-1} or 7.5 ppm) did not stimulate or inhibit carpogenic germination of sclerotia of *S. sclerotiorum*, compared to untreated controls. However, soil treatment with atrazine or simazine results in the formation of secondary stipes on primary stipes that are unable to form normal ascocarps for ascospore production (Huang & Blackshaw 1995). These examples show that certain chemical fertilizers or herbicides may be effective in controlling plant diseases. However, risk assessments are needed to assess the impact of each disease control strategy, including chemical fertilizers, herbicides, and pesticides, on agroecosystems and the environment.

CONCLUSIONS

Agriculture chemicals, including fertilizers, herbicides, and pesticides, are widely used in crop production. There are many examples of heavy reliance on agrochemicals having negatively impacting agricultural ecosystems and the environment. As a result, the “one chemical kills them all” approach to crop production is no longer acceptable in modern agriculture. To ensure the sustainability of crop production, efforts should be made to develop eco-friendly and environmentally sound pest control measures. These include preventive measures, such as phytosanitary measures to prevent the spread of diseases between countries or regions. Crop rotation is another good cultural practice for plant disease management. Nitrogen-fixing legumes and allelopathic crops are good choices for crop rotation. Crop sequence and crop selection are important factors in determining the success of a crop rotation system. Changing cultural practices, such as irrigation techniques, is an effective way to control plant pathogens that prefer moist, poorly drained soil. Other field management techniques, including the selection of environmentally friendly agricultural chemicals, field sanitation, and insect vector control, can help minimize the impact of crop diseases.

Plant breeding is an effective strategy for plant disease management. Plant breeders should focus on developing new crop varieties with high yield, high quality, and high disease resistance. Biocontrol, using antagonistic or hyperparasitic microorganisms, is considered a good disease management strategy. However, while certain microorganisms may be able to control diseases in certain crops, they may also be harmful plant pathogens in other crops. Therefore, in addition to efficacy trials, risk assessment of the potential harmful effects of biocontrol agents on other crops, farmers, and consumers is crucial to ensure the successful development of biopesticides for practical applications. Commercialization of biocontrol agents remains challenging. More efforts are needed on issues such as formulation, scale-up production, product cost, and user friendliness. Achieving sustainable crop production requires an integrated pest management (IPM) approach that integrates all effective, environmentally friendly disease control measures.

ACKNOWLEDGEMENTS

I would like to thank Dr. Hsueh-Shih Lin, Director of the Taiwan Agriculture Research Institute, Ministry of Agriculture, for inviting me to present the content of this article at the “International Symposium on Biocontrol and Sustainable Cropping Management”, June 25, 2024, Taipei, Taiwan. Information on “Commercial biocontrol products developed in Taiwan” was provided by Dr. Jenn-Wen Huang (Emeritus Professor) and Dr. Cheng-Fang Hong (Assistant Professor), National Chung-Hsing University, Taichung, Taiwan.

REFERENCES

Acharya, S. N. and H. C. Huang. 2000. Registration of ‘AC Longview’ alfalfa. Crop Sci. 40:1823. doi:10.1002/j.1435-0653.2000.tb21498.x

Acharya, S. N. and H. C. Huang. 2003. Breeding alfalfa for resistance to Verticillium wilt: A sound strategy. p.345–371. *in*: Advances in Plant Disease Management. (Huang, H. C. and S. N. Acharya, eds.) Research Signpost, Trivandrum, India. 429 pp.

Acharya, S. N., H. C. Huang, and M. R. Hanna. 1995. Registration of ‘AC Blue J’ alfalfa. Crop Sci. 35:1225–1226. doi:10.2135/cropsci1995.0011183X003500040084x

Anonymous. 2012. The requirements of import of alfalfa hay from US to China. http://kernag.com/caap/phytos/country/china.pdf (visit on 3/3/2024)

Anonymous. 2021. D-03-14: Canadian hay certification program to certify for export. Effective date: June 4, 2021. 3rd revision. https://inspection.canada.ca/plant-health/invasive-species/directives/grains-and-field-crops/d-03-14/eng/1323829800901/1323829873124#aa3 (visit on 3/3/2024)

Bardin, S. D. and H. C. Huang. 2001. Research on biology and control of Sclerotinia diseases in Canada. Can. J. Plant Pathol. 23:88–98. doi:10.1080/07060660109506914

Bardin, S. D., H. C. Huang, L. Liu, and L. J. Yanke. 2003. Control, by microbial seed treatment, of damping-off caused by *Pythium* sp. on canola, safflower, dry pea, and sugar beet. Can. J. Plant Pathol. 25:268–275. doi:10.1080/07060660309507079

Bergstrom, G. 1984. Verticillium wilt of alfalfa. https://hdl.handle.net/1813/42392 (visit on 10/2/2025)

Biederbeck, V. O., N. Z. Lupwayi, W. A. Rice, K. G. Hanson, and R. P. Zentner. 1999. Crop rotation effects on soil microbial populations, biomass and diversity under wheat in a brown loam. p.594–602. *in*: Proceedings of Soils and Crops. February 25–26, 1999. Saskatoon, Canada. Extension Division, University of Saskatchewan, Saskatoon, Canada.

Boland, G. J. and R. Hall. 1994. Index of plant hosts of *Sclerotinia sclerotiorum*. Can. J. Plant Pathol. 16:93–108. doi:10.1080/07060669409500766

Christen, A. A. 1982. A selective medium for isolating *Verticillium albo-atrum* from soil. Phytopathology 72:47–49. doi:10.1094/Phyto-72-47

Chung, W. C., J. W. Huang, and H. C. Huang. 2005.

Formulation of a soil biofungicide for control of damping-off of Chinese cabbage (*Brassica chinensis*) caused by *Rhizoctonia solani*. Biol. Control 32:287–294. doi:10.1016/j.biocontrol.2004.10.011

Chung, W. C., J. W. Huang, H. C. Huang, and J. F. Jen. 2002. Effect of ground *Brassica* seed meal on control of Rhizoctonia damping-off of cabbage. Can. J. Plant Pathol. 24:211–218. doi:10.1080/07060660309506998

Dorrell, D. G. and H. C. Huang. 1978. Influence of Sclerotinia wilt on seed yield and quality of sunflower wilted at different stages of development. Crop Sci. 18:974–976. doi:10.2135/cropsci1978.0011183X001800060017x

Erickson, R. S. and P. M. Balasubramanian. 2008. Survey of diseases of dry bean in southern Alberta in 2007. Can. Plant Dis. Surv. 88:99–100.

Erickson, R. S. and P. M. Balasubramanian. 2010. Survey of diseases of dry bean in southern Alberta in 2009. Can. Plant Dis. Surv. 90:121–122.

Erickson, R. S. and S. Chatterton. 2012. Survey of diseases of dry bean in southern Alberta in 2011. Can. Plant Dis. Surv. 92:117–118.

Fang, H. C. and T. M. E. Liu. 1988. Effect of urea and nitrogenous compounds on the sclerotial germination and viability of the *Sclerotium rolfsii* in soil and its relationship with soil microorganisms. Plant Prot. Bull. 30:235–244. (in Chinese)

Graham, J. H., R. N. Peaden, and D. W. Evans. 1977. Verticillium wilt of alfalfa found in the United States. Plant Dis. Rep. 61:337–340.

Green, B. J. and V. O. Biederbeck (eds.). 1995. Farm Facts: Soil Improvement with Legumes, Including Legumes in Crop Rotations. Can. Sask. Agrmt. Soil Conserv. Bull. Regina, Canada. 20 pp.

Hanna, M. R. and H. C. Huang. 1987. Barrier alfalfa. Can. J. Plant Sci. 67:827–830. doi:10.4141/cjps87-116

Harper, A. M. and H. C. Huang. 1984. Contamination of insects by the plant pathogen *Verticillium albo-atrum* in an alfalfa field. Environ. Entomol. 13:117–120. doi:10.1093/ee/13.1.117

Hoes, J. A. and H. C. Huang. 1985. Effect of between-row and within-row spacings on development of sclerotinia wilt and yield of sunflower. Can. J. Plant Pathol. 7:98–102. doi:10.1080/07060668509501522

Howard, R. J., H. C. Huang, J. A. Traquair, E. R. Moskaluk, M. J. Kokko, and L. M. Phillippe. 1991. Occurrence of Verticillium wilt of alfalfa in southern Alberta, 1980-86. Can. Plant Dis. Surv. 71:21–27.

Hsieh, T. F., H. C. Huang, and R. S. Erickson. 2010. Spread of seed-borne *Erwinia rhapontici* in bean, pea and wheat. Eur. J. Plant Pathol. 127:579–584. doi:10.1007/s10658-010-9622-0

Hsieh, T. F., H. C. Huang, R. S. Erickson, L. J. Yanke, and H. H. Mündel. 2002. First report of bacterial wilt of common bean caused by *Curtobacterium flaccumfaciens* in western Canada. Plant Dis. 86:1275. doi:10.1094/PDIS.2002.86.11.1275A

Huang, H. C. 1977. Importance of *Coniothyrium minitans* in survival of sclerotia of *Sclerotinia sclerotiorum* in wilted sunflower. Can. J. Bot. 55:289–295. doi:10.1139/b77-039

Huang, H. C. 1980. Control of sclerotinia wilt of sunflower by hyperparasites. Can. J. Plant Pathol. 2:26–32. doi:10.1080/07060668009501458

Huang, H. C. 1989. Distribution of *Verticillium albo-atrum* in symptomed and symptomless leaflets of alfalfa. Can. J. Plant Pathol. 11:235–241. doi:10.1080/07060668909501105

Huang, H. C. 2003. Verticillium wilt of alfalfa: Epidemiology and control strategies. Can. J. Plant Pathol. 25:328–338. doi:10.1080/07060660309507088

Huang, H. C., S. N. Acharya, M. R. Hanna, G. C. Kozub, and E. G. Smith. 1994. Effect of Verticillium wilt on forage yield of alfalfa in Southern Alberta. Plant Dis. 78:1181–1184. doi:10.1094/PD-78-1181

Huang, H. C. and R. E. Blackshaw. 1995. Influence of herbicides on the carpogenic germination of *Sclerotinia sclerotiorum* sclerotia. Bot. Bull. Acad. Sin. 36:59–64.

Huang, H. C., E. Bremer, R. K. Hynes, and R. S. Erickson. 2000. Foliar application of fungal biocontrol agents for the control of white mold of dry bean caused by *Sclerotinia sclerotiorum*. Biol. Control 18:270–276. doi:10.1006/bcon.2000.0829

Huang, H. C., K. J. Cheng, J. L. Zantinge, and A. J. Laroche. 2001. Strains of *Coniothyrium minitans* having β-glucanase activity. U.S. Patent No. 6,268,202 B1. U.S. Patent and Trademark Office. https://patents.google.com/patent/US6268202B1/en (visit on 10/2/2025)

Huang, H. C. and C. H. Chou. 2005. Impact of plant disease biocontrol and allelopathy on biodiversity and agricultural sustainability. Plant Pathol. Bull. 14:1–12. doi:10.6649/PPB.200503_14(1).0001

Huang, H. C. and J. Dueck. 1980. Wilt of sunflower from infection by mycelial-germinating sclerotia of *Sclerotinia sclerotiorum*. Can. J. Plant Pathol. 2:47–52. doi:10.1080/07060668009501437

Huang, H. C. and R. S. Erickson. 1994a. Survey of diseases of dry beans in southern Alberta in 1993. Can. Plant Dis. Surv. 74:98–99.

Huang, H. C. and R. S. Erickson. 1994b. Survey of

Verticillium wilt of alfalfa in southern Alberta in 1993. Can. Plant Dis. Surv. 74:59.

Huang, H. C. and R. S. Erickson. 1995. Survey of diseases of alfalfa in southern Alberta in 1994. Can. Plant Dis. Surv. 75:162–163.

Huang, H. C. and R. S. Erickson. 1999. Survey of diseases of dry bean in southern Alberta in 1998. Can. Plant Dis. Surv. 79:111–112.

Huang, H. C. and R. S. Erickson. 2000. Survey of diseases of dry bean in southern Alberta in 1999. Can. Plant Dis. Surv. 80:73–74.

Huang, H. C. and R. S. Erickson. 2002. Overwintering of *Coniothyrium minkans*, a mycoparasite of *Sclerotinia sclerotiorum*, on the Canadian prairies. Australasian Plant Pathol. 31:291–293. doi:10.1071/AP02019

Huang, H. C. and R. S. Erickson. 2004a. Control of white mold of bean by *Coniothyrium minitans*: Comparison of soil and foliar treatments. Plant Pathol. Bull. 13:171–176. doi:10.6649/PPB.200409_13(3).0001

Huang, H. C. and R. S. Erickson. 2004b. Effect of soil treatment of fungal agents on control of apothecia of *Sclerotinia sclerotiorum* in canola and safflower fields. Plant Pathol. Bull. 13:1–6. doi:10.6649/PPB.200403_13(1).0001

Huang, H. C. and R. S. Erickson. 2004c. Impact of pink seed of pea caused by *Erwinia rhapontici* in Canada. Plant Pathol. Bull. 13:261–266. doi:10.6649/PPB.200412_13(4).0003

Huang, H. C. and R. S. Erickson. 2007. Effect of seed treatment with *Rhizobium leguminosarum* on *Pythium* damping-off, seedling height, root nodulation, root biomass, shoot biomass, and seed yield of pea and lentil. J. Phytopathology 155:31–37. doi:10.1111/j.1439-0434.2006.01189.x

Huang, H. C., R. S. Erickson, C. Chang, J. R. Moyer, F. J. Larney, and J. W. Huang. 2002a. Organic soil amendments for control of apothecial production of *Sclerotinia sclerotiorum*. Plant Pathol. Bull. 11:207–214. doi:10.6649/PPB.200212_11(4).0006

Huang, H. C., R. S. Erickson, T. F. Hsieh, R. L. Conner, and P. M. Balasubramanian. 2009. Resurgence of bacterial wilt of common bean in North America. Can. J. Plant Pathol. 31:290–300. doi:10.1080/07060660909507603

Huang, H. C., R. S. Erickson, L. J. Yanke, T. F. Hsieh, and R. A. A. Morrall. 2003a. First report of pink seed of lentil and chickpea caused by *Erwinia rhapontici* in Canada. Plant Dis. 87:1398. doi:10.1094/PDIS.2003.87.11.1398A

Huang, H. C., R. S. Erickson, L. J. Yanke, H. H. Mundel, and T. F. Hsieh. 2002b. First report of pink seed of common bean caused by *Erwinia rhapontici*. Plant Dis. 86:921. doi:10.1094/PDIS.2002.86.8.921C

Huang, H. C. and M. R. Hanna. 1991. An efficient method to evaluate alfalfa cultivars for resistance to Verticillium wilt. Can. J. Plant Sci. 71:871–875. doi:10.4141/cjps91-126

Huang, H. C., M. R. Hanna, and E. G. Kokko. 1985. Mechanisms of seed contamination by *Verticillium albo-atrum* in alfalfa. Phytopathology 75:482–488. doi:10.1094/Phyto-75-482

Huang, H. C. and A. M. Harper. 1985. Survival of *Verticillium albo-atrum* from alfalfa in feces of leaf-chewing insects. Phytopathology 75:206–208. doi:10.1094/Phyto-75-206

Huang, H. C., A. M. Harper, E. G. Kokko, and R. J. Howard. 1983. Aphid transmission of *Verticillium albo-atrum* to alfalfa. Can. J. Plant Pathol. 5:141–147. doi:10.1080/07060668309501615

Huang, H. C., R. Hironaka, and R. J. Howard. 1986a. Survival of *Verticillium albo-atrum* in alfalfa tissue buried in manure or fed to sheep. Plant Dis. 70:218–221. doi:10.1094/PD-70-218

Huang, H. C. and J. A. Hoes. 1976. Penetration and infection of *Sclerotinia sclerotiorum* by *Coniothyrium minitans*. Can. J. Bot. 54:406–410. doi:10.1139/b76-039

Huang, H. C. and J. A. Hoes. 1980. Importance of plant spacing and sclerotial position to development of Sclerotinia wilt of sunflower. Plant Dis. 64:81–84. doi:10.1094/PD-64-81

Huang, H. C., T. F. Hsieh, and R. S. Erickson. 2003b. Biology and epidemiology of *Erwinia rhapontici*, causal agent of pink seed and crown rot of plants. Plant Pathol. Bull. 12:69–76. doi:10.6649/PPB.200306_12(2).0001

Huang, H. C. and J. W. Huang. 1993. Prospects for control of soilborne plant pathogens by soil amendment. Curr. Top. Bot. Res. 1:223–235.

Huang, H. C. and H. H. Janzen. 1991. Control of carpogenic germination of sclerotia of *Sclerotinia sclerotiorum* by volatile substances from urea. Plant Prot. Bull. 33:283–289.

Huang, H. C., F. Kodama, K. Akashi, and K. Konno. 2002c. Impact of crop rotation on soilborne diseases and yield of kidney bean: A case study in northern Japan. Plant Pathol. Bull. 11:87–96. doi:10.6649/PPB.200206_11(2).0005

Huang, H. C. and E. G. Kokko. 1985. Infection of alfalfa pollen by *Verticillium albo-atrum*. Phytopathology 75:859–865.

Huang, H. C. and E. G. Kokko. 1987. Ultrastructure of hyperparasitism of *Coniothyrium minitans* on sclerotia of *Sclerotinia sclerotiorum*. Can. J. Bot. 65:2483–2489. doi:10.1139/b87-337

Huang, H. C. and E. G. Kokko. 1988. Penetration of hyphae of *Sclerotinia sclerotiorum* by *Coniothyrium minitans* without the formation of appressoria. J. Phytopathology 123:133–139. doi:10.1111/j.1439-0434.1988.tb04460.x

Huang, H. C. and E. G. Kokko. 1992. Pod rot of dry peas due to infection by ascospores of *Sclerotinia sclerotiorum*. Plant Dis. 76:597–600. doi:10.1094/PD-76-0597

Huang, H. C. and E. G. Kokko. 1993. *Trichothecium roseum*, a mycoparasite of *Sclerotinia sclerotiorum*. Can. J. Bot. 71:1631–1638. doi:10.1139/b93-198

Huang, H. C., M. J. Kokko, and L. M. Phillippe. 1988. White mold of dry bean (*Phaseolus vulgaris* L.) in southern Alberta, 1983–87. Can. Plant Dis. Surv. 68:11–13.

Huang, H. C., H. H. Marshall, L. M. Collicutt, D. L. McLaren, and M. J. Kokko. 1993. Screening hardy chrysanthemums for resistance to *Fusarium oxysporum* f. sp. *chrysanthemi* Race 2. Plant Pathol. Bull. 2:103–105. doi:10.6649/PPB.199306_2(2).0007

Huang, H. C., R. J. Morrison, H. H. Muendel, D. J. S. Barr, G. R. Klassen, and J. Buchko. 1992a. *Pythium* sp. "group G", a form of *Pythium ultimum* causing damping-off of safflower. Can. J. Plant Pathol. 14:229–232. doi:10.1080/07060669209500881

Huang, H. C. and L. M. Phillippe. 1989. Survey of dry bean for Sclerotinia white mold in southern Alberta in 1988. Can. Plant Dis. Surv. 69:53.

Huang, H. C., L. M. Phillippe, H. H. Marshall, L. M. Collicutt, and G. A. Neish. 1992b. Wilt of hardy chrysanthemum caused by a new race of *Fusarium oxysporum* f. sp. *chrysanthemi*. Plant Pathol. Bull. 1:57–61. doi:10.6649/PPB.199206_1(2).0002

Huang, H. C., L. M. Phillippe, and R. C. Phillippe. 1990. Pink seed of pea: A new disease caused by *Erwinia rhapontici*. Can. J. Plant Pathol. 12:445–448. doi:10.1080/07060669009500990

Huang, H. C. and K. W. Richards. 1983. *Verticillium albo-atrum* contamination on leaf pieces forming cells for the alfalfa leafcutter bee. Can. J. Plant Pathol. 5:248–250. doi:10.1080/07060668309501605

Huang, H. C., K. W. Richards, and E. G. Kokko. 1986b. Role of the leafcutter bee in dissemination of *Verticillium albo-atrum* in alfalfa. Phytopathology 76:75–79. doi:10.1094/Phyto-76-75

Huang, H. C., G. Saindon, and R. S. Erickson. 1995. Survey of diseases of dry beans in southern Alberta in 1994. Can. Plant Dis. Surv. 75:131–132.

Huang, H. C., G. Saindon, R. S. Erickson, and P. Ma. 1996. Survey of diseases of dry beans in southern Alberta in 1995. Can. Plant Dis. Surv. 76:93–94.

Huang, H. C. and S. K. Sun. 1991. Effect of S-H mixture or Perlka™ on carpogenic germination and survival of sclerotia of *Sclerotinia sclerotiorum*. Soil Biol. Biochem. 23:809–813. doi:10.1016/0038-0717(91)90090-7

Kageyama, K., T. Ui, and Y. Narita. 1981. Influence of *Pythium* spp. on the injury by bean monoculture. Ann. Phytopathol. Soc. Jpn. 47:320–326. (in Japanese with English abstract) doi:10.3186/jjphytopath.47.320

Laroche, A. J., T. Y. Huang, M. M. Frick, Z. X. Lu, H. C. Huang, and K. J. Cheng. 2000. *Coniothyrium minitans* xylanase gene cxy1. U.S. Patent No. 6,121,034 A. U.S. Patent and Trademark Office. https://patents.google.com/patent/US6121034A/en (visit on 10/2/2025)

Laroche, A. J., T. Y. Huang, M. M. Frick, Z. X. Lu, H. C. Huang, and K. J. Cheng. 2004. *Coniothyrium minitans* β-(1, 3) exoglucanase gene cbeg1. U.S. Patent No. 6,734,344 B2. U.S. Patent and Trademark Office. https://patents.google.com/patent/US6734344B2/en (visit on 10/2/2025)

Li, G. Q., H. C. Huang, S. N. Acharya, and R. S. Erickson. 2005. Effectiveness of *Coniothyrium minitans* and *Trichoderma atroviride* in suppression of sclerotinia blossom blight of alfalfa. Plant Pathol. 54:204–211. doi:10.1111/j.1365-3059.2005.01119.x

Liang, X. Y., H. C. Huang, L. J. Yanke, and G. C. Kozub. 1996. Control of damping-off of safflower by bacterial seed treatment. Can. J. Plant Pathol. 18:43–49. doi:10.1080/07060669609500653

Luth, P. 2001. The biological fungicide Contans WG®- A preparation on the basis of the fungus *Coniothyrium minitans*. p.127–128. *in*: Proceedings of Sclerotinia 2001. The XI International Sclerotinia Workshop. July 8–12, 2001. York, UK. British Society for Plant Pathology. London, UK.

McDonald, J. G. and E. Wong. 2000. High diversity in *Curtobacterium flaccumfaciens* pv. *flaccumfaciens* characterized by serology and rep-PCR genomic fingerprinting. Can. J. Plant Pathol. 22:17–22.

McLaren, D. L., H. C. Huang, R. L. Conner, T. L. Henderson, R. S. Erickson, and X. He. 2009. Foliar application strategies and use of pollen with *Coniothyrium minitans* to control white mold of bean, caused by *Sclerotinia sclerotiorum*, in western Canada. Plant Prot. Bull. 51:1–18.

McLaren, D. L., H. C. Huang, G. C. Kozub, and S. R. Rimmer. 1994. Biological control of Sclerotinia wilt of sunflower with *Talaromyces flavus* and *Coniothyrium minitans*. Plant Dis. 78:231–235. doi:10.1094/PD-78-0231

McLaren, D. L., H. C. Huang, and S. R. Rimmer. 1996. Control of apothecial production of *Sclerotinia sclerotiorum* by *Coniothyrium minitans* and *Talaromyces flavus*. Plant Dis. 80:1373–1378. doi:10.1094/PD-80-1373

McMullen, M. P., R. W. Stack, J. D. Miller, M. C. Bromel, and V. L. Youngs. 1984. *Erwinia rhapontici*, a bacterium causing pink wheat kernels. Proc. North Dakota Acad. Sci. 38:78.

Moyer, J. R. and R. E. Blackshaw. 1993. Effect of soil moisture on atrazine and cyanazine persistence and injury to subsequent cereal crops in southern Alberta. Weed Technol. 7:988–994. doi:10.1017/S0890037X00038124

Moyer, J. R. and H. C. Huang. 1997. Effect of aqueous extracts of crop residues on germination and seedling growth of ten weed species. Bot. Bull. Acad. Sin. 38:131–139.

Organization Europeennee et Mediterraneenne pour la Protection des Plants-European Plant Protection Organization (OEPP/EPPO). 1982. Data sheets on quarantine organisms No 48. *Corynebacterium flaccumfaciens* pv. *flaccumfaciens*. Bull. OEPP 12(1).

Patrick, Z. A. 1986. Allelopathic mechanisms and their exploitation for biological control. Can. J. Plant Pathol. 8:225–228. doi:10.1080/07060668609501831

Robinson, R. G., J. H. Ford, W. E. Lueschen, D. L. Rabas, L. J. Smith, D. D. Warnes, and J. V. Wiersma. 1980. Response of sunflower to plant population. Agron. J. 72:869–871. doi:10.2134/agronj1980.00021962007200060003x

Robinson, R. G., J. H. Ford, W. E. Lueschen, D. L. Rabas, D. D. Warnes, and J. V. Wiersma. 1982. Response of sunflower to uniformity of plant spacing. Agron. J. 74:363–365. doi:10.2134/agronj1982.00021962007400020024x

Sato, R. 1994. Outbreak of alfalfa Verticillium wilt in Hokkaido. Japan. Agric. Res. Quarterly. 28:44–51.

Sequeira, L. 1963. Effect of urea applications on survival of *Fusarium oxysporum* f. *cubense* in soil. Phytopathology 53:332–336.

Sheppard, J. W. 1979. Verticillium wilt, a potentially dangerous disease of alfalfa in Canada. Can. Plant Dis. Surv. 59:60.

Sheppard, J. W. and S. N. Needham. 1980. Verticillium wilt of alfalfa in Canada: Occurrence of seed-borne inoculum. Can. J. Plant Pathol. 2:159–162.

Shiau, F. L., W. C. Chung, J. W. Huang, and H. C. Huang. 1999. Organic amendment of commercial culture media for improving control of Rhizoctonia damping-off of cabbage. Can. J. Plant Pathol. 21:368–374.

Smith, A. E. and A. Walker. 1989. Prediction of the persistence of the triazine herbicides atrazine, cyanazine, and metribuzin in Regina heavy clay. Can. J. Soil Sci. 69:587–595. doi:10.4141/cjss89-059

Smith, E. G., S. N. Acharya, and H. C. Huang. 1995. Economics of growing Verticillium wilt-resistant and adapted alfalfa cultivars in western Canada. Agron. J. 87:1206–1210. doi:10.2134/agronj1995.00021962008700060028x

Sun, S. K. and J. W. Huang. 1985. Formulated soil amendment for controlling Fusarium wilt and other soilborne diseases. Plant Dis. 69:917–920.

Tegli, S., A. Sereni, and G. Surico. 2002. PCR-based assay for the detection of *Curtobacterium flaccumfaciens* pv. *flaccumfaciens* in bean seeds. Lett. Appl. Microbiol. 35:331–337. doi:10.1046/j.1472-765x.2002.01187.x

Tsao, P. H. and J. J. Oster. 1981. Relation of ammonia and nitrous acid to suppression of *Phytophthora* in soils amended with nitrogenous organic substances. Phytopathology 71:53–59. doi:10.1094/Phyto-71-53

Walker, J. C. 1969. Plant Pathology. 3rd ed. McGraw-Hill Book. New York, NY. 819 pp.

Whipps, J. M. and R. D. Lumsden. 2001. Commercial use of fungi as plant disease biological control agents: Status and prospects. *in*: Fungi as Biocontrol Agents: Progress, Problems and Potential. (Butt, T. M., C. Jackson, and N. Magan, eds.) CABI. Wallingford, UK. 390 pp. doi:10.1079/9780851993560.0009

Wright, A. T. 1990. Yield effect of pulses on subsequent cereal crops in the northern prairies. Can. J. Plant Sci. 70:1023–1032. doi:10.4141/cjps90-125

永續農業之植物病害管理策略

黃鴻章 [1,*]

摘要

黃鴻章。2026。永續農業之植物病害管理策略。台灣農業研究 75(2):185–199。

作物病害的發生與蔓延，乃是植物病原、寄主植物及環境條件三者交互作用的結果。不當的栽培管理措施，例如使用帶病菌種子、選用感病品種或採取不合宜的耕作方式，皆可能導致作物病害的發生或再度爆發。病害管理在現代農業中具有極其重要的地位，在當前強調節能與環保的時代，所有作物病害防治方法皆須兼具高效、經濟與環境友善等特性。病害管理措施，如使用無病原種子、抗病品種、輪作制度、生物防治、土壤改善及良好耕作管理等，皆被視為合成化學農藥的可行替代方案。本文進一步以真菌與細菌性病害為例，探討這些環境友善型植物病害防治方法的發展前景與應用。

關鍵詞：相剋作用、生物防治、輪作、抗病性、生態學、病害流行學、土壤改善、昆蟲與病原關係。

投稿日期：2025 年 10 月 2 日；接受日期：2026 年 1 月 28 日。
[*] 通訊作者：hchuang39@gmail.com
[1] Research Scientist (Emeritus), Agriculture and Agri-Food Canada, Lethbridge Research and Development Centre, Lethbridge, Alberta, Canada.