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Research Article

Etiology of diseases affecting the quality of cruciferous and leafy vegetables – a review

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Abstract

Cruciferous crops, or leafy vegetables, from the *Brassicaceae* family are important gourmet vegetables and among the most widely produced worldwide. These vegetables are consumed worldwide for their high nutritional content, including vitamins, beneficial enzymes, minerals, and fiber. Despite the remunerative market for crucifers, several factors beset the industry. These vegetables are susceptible to destructive field and postharvest diseases. Hence, appropriate control measures must be established to achieve desirable product quality and a high yield. Here, major diseases of commonly cultivated crops belonging to the *Brassica* spp. and *Raphanus* spp. are reviewed. Most diseases of cruciferous crops are caused by soil-borne pathogens that survive and persist in the soil for long periods, posing a significant threat to crucifer production, as these crops are directly cultivated near the soil line. Pathogens mainly affect the foliar parts and heads of cruciferous crops, which are the marketable parts of the plant. Damage to these essential organs results in a reduction in quality and quantity. Preventive control is recommended for most diseases, as pathogens are challenging to eradicate once established. Integrated disease management would require an efficient control strategy to mitigate the adverse effects of diseases.

Keywords: *Brassicaceae*, *Brassica* spp., *Raphanus* spp., Soil-borne plant pathogens, Plant disease

Introduction

Brassicaceae (previously known as Cruciferae), commonly termed "Cruciferous crops, is an economically important family comprising vegetables, condiments, fodder crops, and edible and industrial oilseed species (Warwick, 2011). Crops belonging to the Brassicaceae family are called Crucifers (Latin: "*crux*") due to their flowers having four petals resembling the shape of a cross (CUESA, 2006). This family comprises about 375 genera and over 3,200 species (LeCoz & Ducombs, 2006; Ishida *et al.,* 2014), including the model plant *Arabidopsis thaliana.* Commonly cultivated and consumed cruciferous vegetables belong to the cultivars of the Genus *Brassica*, for *B.rapa*: Chinese cabbage, Chinese mustard, bok choy, turnip, for *B. oleracea*: cabbage (var. *capitata*), broccoli (var. *italic*), cauliflower (var. *botrytis*), Kale (var. *acephala*), brussels sprouts (var. *gemmifera*), for *B. juncea* or mustard greens, and *Raphanus sativus* or radish (Ishida *et al.,* 2014).

Cruciferous crops are important gourmet vegetables and are among the most dominant food crops worldwide due to their nutritional content: high fiber, calcium, and vitamins A and C; low calories; and rich in beneficial enzymes (Meenu *et al.,* 2013). Crucifers are primarily native to Europe, the Middle East, and Asia. In the Philippines, these are commercially important vegetables in the higher-elevation areas of Mountain Province, Negros Occidental, Cebu, and Mindanao.

However, several factors beset the industry despite the remunerative market for cruciferous crops. Such factors include high production costs, handling and distribution losses, and postharvest mishandling. For example, the Philippine Peasant Institute reported a 30% produce loss attributed to spoilage, as crucifers have short storage life and losses due to postharvest handling and processing (Roxas, 2005). Moreover, biological constraints, such as field and postharvest diseases, are a major problem for the industry. Several agents, like fungi, bacteria, viruses, nematodes, and other organisms, cause such diseases. This paper reviews diseases affecting cruciferous vegetables, with a particular focus on the Cruciferae group, *Brassica* spp., and *Raphanus* spp.

Diseases of *Brassica* spp. and *Raphanus* spp.

Phytopathogens have been a persistent problem, significantly constraining food systems worldwide. Some pathogens have a broad host range. Despite decades of studying multidisciplinary approaches to establishing integrated disease management, effective disease management remains challenging. In cruciferous crops, particularly the *Brassica* and *Raphanus* genera, the vast number of organisms causes several diseases that infect crops in the field and affect yield and postharvest quality. Bacteria, fungi, viruses, and nematodes are the major phytopathogens that threaten crop production. Each disease's relative importance and symptoms are described separately in succeeding sections.

Bacterial diseases

Bacterial agents are among the important pathogen groups causing foliar diseases in cruciferous crops. They can spread rapidly and cause significant damage to the marketed portion of the crop. Although the symptoms and causal organisms of different diseases differ, control measures are generally similar.

***Black Rot* (*Xanthomonas campestris* pv. *campestris*)**

Black Rot, a seed-borne disease (Cook *et al.,* 1952), is caused by a gram-negative bacterium *Xanthomonas campestris* pv. *campestris* (Pammel) Dowson. It is considered a severe disease, emphasizing economically important vegetable *Brassica* crops and several other cruciferous crops (Mani *et al.,* 2020), as it renders the heads unmarketable. Moreover, this disease causes considerable yield losses by premature defoliation and reduction in the "curd" and heads on cauliflower and cabbage (Meenu *et al.,* 2013), with 10-50% reported yield losses annually (Sharma *et al.,* 2017), and at 0.03% of infection can lead to epidemics (Tanushree *et al.,* 2020). Typical symptoms of this disease include V-shaped chlorotic lesions, usually starting at the leaf margins and progressing to blacken the veins, indicative of systemic invasion (Shigaki *et al.,* 2002; Vicente & Holub, 2012). Expression of black rot symptoms may be attributed to the ability of the pathogen, *Xcc*, to multiply within the vascular system of the host, since vein plugging in plants infected with *Xcc* triggers the accumulation of fibrillar material in vessels in response to the host to prevent the spread of the pathogen within the vascular system (Ignatov *et al.,* 1998). As a result, water deficiency will be followed by the wilt and death of leaf segments between affected veins. These are the main reasons for the V-shaped lesions, a striking symptom of black rot (Bretschneider *et al.,* 1989). Yuen and Alvarez (1985), as cited by Shigaki *et al.* (2000), reported other foliar symptoms of black rot in cabbage, particularly blight symptoms characterized by the collapse of interveinal tissues at early stages of infection. They emphasized that strains that produce these symptoms were considered highly virulent *Xcc* strains and may be under genetic control (Chen *et al.,* 1994).

Aside from being seed-borne, Black Rot can also be transmitted through infested soil, infected transplanting materials, crop residues, and related weed species. This disease is predominantly found in temperate and subtropical regions worldwide, where copious rainfall and average temperatures range from 25 °C to 30 °C (Meenu *et al.,* 2013). Infection may occur at any stage of the host plant's growth. The bacterium may enter through natural openings or pre-existing wounds within the plant. Infection via hydathode entry is possible only if the fluid surrounding the hydathode is colonized. Another consequence of Black rot infection is the predisposition of the infected plant to another disease, Alternaria Blight (Sharma *et al.,* 1991).

Kamoun *et al*. (1992) classified isolates of *Xcc* into five different races (0 to 4) based on the response of cultivars of Turnip (*B. rapa)* and cultivars of Mustard (*B. juncea*), with races 1 and 4 found to be the most dominant strains from cultivated *Brassica* crops worldwide, especially in cabbage and cauliflower (Ignatov *et al.,* 1998; Vicente *et al.,* 2001).

Controlling black rot is a pressing challenge in selecting appropriate management measures. The primary solution to hamper the spread of *Xcc* in *Brassica* is to use disease-free seeds and implement appropriate multidisciplinary practices, which will reduce the dissemination and number of inocula in the field (Vicente *et al.,* 2002). Hot-water seed treatment at 50 °C for 30 minutes was adequate; however, seed viability was compromised, and the pathogen was not eradicated (Kishun, 1984). Moreover, crop rotation for 3-5 years with non-cruciferous crops was suggested by Meenu in 2013 to break the disease cycle of the pathogen. Mulching was also found to reduce secondary inoculum. It reduces splashing of infested soil, thereby hampering the secondary spread of pathogens (Onsando, 1988). Kashap and Dhiman (2010) emphasized that eco-friendly disease management controls can be sufficient in the field alone or as part of integrated pest management (IPM).

For biological control, Lirio *et al*. (1998) reported inhibitory effects of extracts from 20 Philippine plant species on *Xcc in vitro*. Moreover, the essential oil of *Anacardium occidentale* Linn. showed antibacterial activity against *Xcc* (Garg & Kasera, 1984). Although chemical control should be the last resort in pest and disease management, several reports have shown that chemical control is effective in reducing *Xcc.* In 1940, Hopkins (1940), as mentioned by Meenu in 2013, recommended foliar spraying of Bordeaux Mixture (4:4:50) in combination with Lead Arsenate (1.5 lb/50 gals), mixed with a spreader, to control black rot in cabbages and cauliflowers. For cabbages, Tanase (1978) reported that 2-3 sprays of 0.5% Koside, 0.5% Cuprofix M, 0.5% Copper Oxychloride, and 0.5% Dithane Cupromix were effective for controlling black rot. Three foliar sprays of Cobox (50% Copper, 4 g/L) at two-week intervals were reported to effectively control black rot (Onsando, 1988).

Another important control method is to study and establish resistant varieties against *Xcc*. However, black-rot-resistant cultivars had limited access in practice (Taylor *et al.,* 2002). Inheritance of resistance between crosses of resistant and susceptible lines of *B. oleracea* was studied by Vicente *et al*. (2002), who found that *Xca4* is the first major locus identified and mapped to control race-specific resistance to *Xcc*. For the resistance in both races 1 and 4, the B genome of *B. nigra* (Black Mustard) and BC genome of *B. carinata* (Abyssinian Cabbage) showed high proportions of resistance against *Xcc* (Taylor *et al.,* 2002). Chuaboon and Prathuangwong (2008) reported 82.08% reduction in black rot severity when foliar spraying with *Bacillus* sp. was combined with biological control using microbes and *Pseudomonas fluorescens.*

Bacterial Soft Rot (Pectobacterium carotovorum and Pseudomonas marginalis pv. marginalis)

Soft Rot disease predominantly attacks vegetables during post-harvest storage and transit, resulting in total product loss compared to other bacterial diseases (Agrios, 2007). Bacterial soft rot was suggested to be caused by a complex of bacterial pathogens. However, Hilderbrand (1989) reported that the primary pathogens isolated from diseased *Brassica* heads are *Pectobacterium carotovorum* ssp. *carotovorum* (formerly classified as *Erwinia carotovora* ssp. *carotovora*) and highly pectolytic strains of *Pseudomonas marginalis* pv. *marginalis* associated with the disease. Soft Rot is a widespread and destructive disease of crucifers and other fleshy crops worldwide. Infected hosts appear asymptomatic in the field and do not show any visible symptoms at the harvesting stage. However, soft rot symptoms develop during transit to market (Tsuyama, 1979, as cited by Higashio & Yamada, 2004), and infection may worsen due to rough postharvest handling. Latency in infection is severe at the postharvest stage due to high temperatures and humidity (Bhat *et al.,* 2012). Water-soaked spots are the initial symptoms of bacterial soft rot as the bacteria mainly attack the tender tissues of the host's storage organ. As time progresses, these spots coalesce and enlarge, becoming sunken and soft, indicating that the underlying tissues have become mushy (Lunt, 2013). Commonly, this disease is associated with a strong, pungent odor that accompanies the breakdown of plant tissues. The odor is caused by the secondary infection of invading bacteria inhabiting the decaying tissues. As the disease progresses, the whole plant will collapse a few days after infection (Alvarado *et al.,* 2011).

P. carotovorum and *P. marginalis* pv. *Marginalis* are soil-borne pathogens that enter plant tissues through natural openings, pre-existing insect feeding wounds, and mechanical damage during postharvest handling. Disease development exponentially progresses as the temperature rises, so rapid infection and tissue breakdown happen as the disease proliferates. Soft Rot attacks plant tissues by degrading the pectate molecules. This binding agent holds plant cells together, causing the plant structure to disintegrate slowly. Tissue cells lose water, and thus, plasmolysis follows, destroying cells that are then invaded by bacteria. This disease is often problematic in countries with no appropriate cold storage, poor transportation, and issues with product mishandling (Higashio & Yamada, 2004). Bacteria can spread through contaminated tools, insect vectors, infested soil, plant debris, or water. Lunt (2013) reported that soft rot could be more severe when plants lack sufficient Calcium (Ca). The inoculum of this disease is often spread by rain, irrigation water, and several vectors, such as maggot flies and other insects. Bacterial cells multiply exponentially by dividing in half every 20 to 60 minutes in favorable conditions at temperatures ranging from 18 °C to 35 °C (Babadoost, 1990).

Management of bacterial soft rot is generally hampered by the pathogen's wide host range and its ability to persist in the soil for extended periods. Higashio and Yamada (2004) reported a low-cost, straightforward method for reducing the incidence of soft rot. It was found that storing cabbages freshly indoors for more than 24 hours allowed them to dry and heal, reducing the likelihood that they would serve as entry points for the bacteria. Moreover, they reported that applying cement to cut ends was an effective way to suppress soft rot. It is initially believed that the physiological function of the Calcium hydroxide component of cement would help suppress infection by soft-rot-causing bacteria. Eventually, it was found that the cement acted more as a barrier to bacterial entry at the wounded ends of cabbage heads. Lunt (2013) suggested methods for managing bacterial soft rot, such as avoiding excessively wet conditions for the plant, promoting wider plant spacing, and planting on well-draining soils with controlled watering.

Several papers demonstrated the efficacy of bacterial isolates as microbial pesticides for *Brassica* soft rot. *Bacillus amyloliquefaciens* KC-1 showed strong biological action against *P. carotovorum* pv. *carotovorum* as it was able to survive in the rhizosphere of cabbage and subdue the growth of *Pcc* (Romero *et al.,* 2017; Cui *et al.,* 2019). Diallo *et al.* (2011) reported that *B. amyloquefaciens* represses pathogens through antibiosis (secretion of polyketides), competition, and induction of systemic resistance for the host plant. *Lactobacillus plantarum* strain BY also showed control of soft rot under field conditions, strongly suggesting inhibition of the pathogen at wounded host sites and its proliferation in host tissues (Tsuda *et al.,* 2016).

Antibiotics such as Penicillin, Tetracycline, oxytetracycline, and Ciproflaxin were found to have reasonable control against *Pcc*, with Ciproflaxin found to highly control of the pathogen as a pre-inoculation spray *in vivo* with 84.78% disease control, and *in vitro*, with 21 mm inhibition zone at 200 µg mL^{-1} (Bhat *et al.,* 2012). Furthermore, Bhat *et al*. (2012) reported an efficient control of soft rot using Ciproflaxin in combination with postharvest packaging using net bags, with only 4.5% rot intensity compared with cabbage heads packed in other packaging materials (Polythene, Net, Gunny, Cardboard boxes) alone without biocide treatment, with rot intensity of 77.78%.

Bacterial Leaf Spot (*Pseudomonas syringae* pv. *maculicola* (McCulloch) Young *et al.*

Bacterial Leaf Spot, also called Pepper Spot, in the *Brassica* and *Raphanus* genus, is caused by the bacterial pathogen *Pseudomonas syringae* pv. *maculicola* (Psm). It was first reported on cauliflower and has now been reported in 32 countries where members of the *Brassica* spp. are cultivated (Bradbury, 1986; Zhao *et al.,* 2000b). The disease mainly occurs on cauliflower, broccoli, cabbage, brussels sprouts, and turnips. Typical symptoms of Pseudomonas leaf spots include small, water-soaked, brown to tan necrotic spots surrounded by yellow(chlorotic) haloes and irregular edges. As the disease progresses, spots coalesce into a larger lesion with a brown papery area with yellow borders, giving the plant a ragged appearance (Smith, 2012).

Pseudomonas syringae pv. *maculicola* is a seed-borne pathogen reported to be capable of inhabiting soil and crop debris for up to a year (Gabor *et al.,* 2013). Rain and irrigation water splashes can spread the bacterial inoculum through insects. *Psm* is known to be able to produce Coronatine, a non-host-specific phytotoxin that also serves as a virulence factor for several pathovars of *Pseudomonas* (Bereswill *et al.,* 1994), and production of this phytotoxin has been an important diagnostic tool in identifying *Psm* (Bereswill *et al.,* 1994; Damicone, 2017).

Since disease spread is mainly driven by water splashing from rain and irrigation systems, one control strategy for this disease is switching from overhead or sprinkler irrigation to furrow or drip irrigation to minimize pathogen spread (Mani *et al.,* 2020). In addition, crop rotation with non-host plants where the disease has recently occurred can reduce the inoculum levels present in the field. Finally, the complete elimination of crop debris and potential alternate hosts should also be ensured to remove all potential sources of future crop infections in the field.

***Xanthomonas Leaf Spot* (*Xanthomonas campestris* pv. *armoraciae* (McCulloch) Dye)**

Bacterial Leaf Spot in *Brassica* was first reported by McCulloch (1929) as the pathogen causing nonvascular leaf spots in horseradish (*Amoracia rusticana*). Sahin and Miller (2007) reported that new pathotypes of *X. campestris* pv. *armoraciae* (Xca) was pathogenic to cabbage, kale, radish, and horseradish (Vicente *et al.,* 2006). Symptoms of the disease include the development of small, circular, water-soaked black spots with yellow haloes on the underside of the leaves. The same symptoms were observed on the upper side of leaves and petioles. Pin-point spots enlarge to form gray, water-soaked necrotic spots (Tamura *et al.,* 1994). Furthermore, discrete water-soaked spots were observed on the leaf blades of infected hosts, with the absence of V-shaped lesions, which differ from those of *Xanthomonas campestris* pv. *campestris*, causing black rot. Moreover, *Xca* differs from *Xcc* in that leaf spot develops at lower temperatures than black rot and does not show chlorotic or systemic symptom movement within the plant (Machmud, 1982). *X. campestris* pv. *armoraciae* is used synonymously with *X. campestris* pv. *raphani* (White) (Black and Machmud, 1983 as cited by Tamura *et al.,* 1994). However, a study conducted by Vicente *et al.* (2006) proposed that *X. campestris* isolates causing nonvascular leaf spot diseases on *Brassica* should instead be classified as pv. *raphani* and not pv. *armoraciae* due to differential reactions of several *Brassica* spp., dividing the leaf spot isolates into three races.

Locations of symptoms observed on infected leaves strongly suggest that *Xca* enters *leaves* through natural openings, such as stomata and hydathodes, findings supported by scanning electron microscopy (SEM). SEM revealed abundant bacterial cells in substomatal chambers and hydathodes associated with the lesions observed (Machmud, 1982). Zhao *et al.* (2000a) reported that *Xca* was an aggressive pathogen capable of infecting leaves, stems, and petioles of cultivated *Brassica* crops, rendering the produce unmarketable. Symptoms observed are similar to those of bacterial leaf spots in crucifers caused by *Pseudomonas syringae* pv. *maculicola* (Tamura *et al.,* 1994). However, spots incited by *Psm* were restricted only to the leaves of the infected plant (Zhao *et al.,* 2000a, b).

Since the causal organism causing Xanthomonas leaf spot is closely related to the bacterium causing Black Rot, the seed testing procedure available for Black Rot can detect the bacterium causing leaf spot, whereas the leaf spot seed testing procedure has not yet been developed (Damicone, 2017). Therefore, certified, tested, and disease-free seeds should be sown in a field that has not been previously planted with cruciferous crops for at least 2 years to ensure complete decomposition of residues and debris that may harbor the pathogen. Also, field cultivation while plants are wet should be avoided, as this bacterium is efficiently transmitted by mechanical means (Damicone, 2017).

Fungal and fungal-like diseases

Fungal agents are the other important pathogen group causing a direct effect on the quality of harvested heads and leaves, as even the slightest damage harms marketability. Here, symptomatology and general disease management of each disease are discussed.

***Alternaria Black Spot* (*Alternaria brassicae* (Berk.) Sacc, *A. brassicicola* (Schwein.) Wiltshire, *A. japonica* (Groves & Skolko)**

Alternaria Black Spot is an important fungal pathogen causing destructive effects on *Brassica* crops worldwide. It is a complex of *A. brassicae, A. brassicicola,* and *A. japonica,* which can infect singly or by mixed infection, contributing to a vast number of yield losses to affected crops as the result of several physiological processes of the plant, such as reduced photosynthetic activity, hastened senescence, premature death of pods, and shriveling of seeds (Shrestha *et al.,* 2000). Symptoms of the disease include chlorotic black lesions found on leaves and stems, and yellow-black spots with target-like concentric rings appearing on infected leaves that coalesce as the disease progresses. Symptoms of the black spots are visible on both sides of the leaves and typically appear first on older, lower leaves. The development of Alternaria Black Spot is favored by cool temperatures, high humidity, and prolonged leaf wetness. Infection reduces crop quality at any growth stage of the host and during storage of vegetable crops (Scheufele, 2013), as several factors are affected, including photosynthetic capacity, early defoliation, florescence abortion, premature ripening, and seed shriveling (Kumar *et al.,* 2014). In seeds, infection results in low germination rates, and if germination persists, seedlings will grow already infected.

Alternaria spp. spores are disseminated by wind, rain, contaminated materials, and equipment, thus classifying them as seed-borne, soilborne, and airborne (Kumar *et al.,* 2014). Crop debris colonized by *Alternaria* spp. is an inoculum source in the field. It plays an important role in disease epidemiology. Kutcharek (1985) reported that *Alternaria* species could be seed-borne, as fungal mycelium can live within the seed and transitory spores can be present on the seed. Moreover, spores are produced at night and released during the day as relative humidity decreases. Finally, the movement of infested equipment and materials aids the field's release and spread of spores. Infection and lesion length caused by *Alternaria* spp. have a positive linear relationship with prolonged leaf-wetting periods at a relative humidity of more than 90% and an optimal temperature of 25 °C (Kutcharek, 1985; Saharan *et al.,* 2016). Primary infection initially appears on cotyledonary leaves, now serving as secondary inoculum for secondary infection. The pathogen spreads throughout the plant due to dew at a favorable temperature (Saharan *et al.,* 2016).

Methods for controlling Alternaria diseases on crucifers combine cultural practices with chemical control. Certified clean seed, efficient weed control, total elimination of crop debris, crop rotation, and control of potential weed hosts are good cultural practices recommended to reduce inoculum and slow disease development. For chemical control, Chlorathonil and Azoxystrobin are commonly used against Alternaria Leaf Spot (Smart, n.d.). Heat treatment was proven to eliminate spores on the seed coat. However, this method suppresses seed germination. The most economically feasible method for disease control is the development of resistant varieties; however, highly resistant genetic resources have not yet been established in cultivated *Brassica* species (Nowicki *et al.,* 2012).

Black Leg (*Phoma lingam* (Tode) Desmaz)

Black Leg is caused by *Phoma lingam* (teleomorph: *Leptosphaeria maculans*), a widely distributed fungal disease affecting cabbage, broccoli, brussels sprouts, cauliflower, kale, mustard greens, a few strains of radish, and some varieties of turnip. Symptoms of this disease may affect all parts of susceptible plants, whether above or below ground. Early indications of the disease are noticeable in the seedbed upon sowing of infested seed. At the cotyledonary stage, infection is characterized by gray lesions that later cause the plant's early death, often going unnoticed in the field. However, many conidia produced on the prematurely killed seedlings cause secondary infection as these microscopic asexual spores are deposited on the hypocotyls, cotyledons, and the first true leaves (Babadoost, 1989).

On stems and leaves, the initial symptom is the formation of a circular, depressed canker, which eventually surrounds the stem. Over time, fungal structures called "pycnidia," appearing as black dots, will eventually cover the infected area (Mani *et al.,* 2020). Severely infected hosts eventually fall over, as the pathogen can destroy the plant. In *Brassica* heads, the late infection may appear at storage, characterized by the development of deep, sunken, black lesions at the base of the heads, again covered with pycnidia, indicating the presence of the pathogen (Babadoost, 1989). Infected roots are gradually destroyed, characterized by black discoloration of the root system. However, new roots formed above the diseased area may keep the plant alive, allowing the heads to grow into suitable sizes. Eventually, these may topple over, as the roots can no longer support the head weight (MacNish, 1963, 1966).

Phoma lingam can overwinter in the soil, persist on infected crop debris for at least 3 cropping seasons, and serve as a source of inoculum for subsequent seasons. In seeds, the fungus is reported to penetrate the seed coat and remain dormant until the seed is sown (Mani *et al.,* 2020). Seeds that are severely colonized shrivel and do not germinate. However, when the infected seed is planted, pycnidia of *P. lingam* are situated on growing hypocotyls and cotyledons, causing the movement of the pathogen aboveground, eventually predisposing nearby plants to possible infection. Dissemination of this pathogen relies heavily on rain splashes, dew, and irrigation water, promoting the discharge of asexual spores from an infected plant to a susceptible, healthy host. In addition, infested materials such as manure, contaminated tools, and farming equipment, and, in some cases, insects, may also spread the disease. New lesions are observed 10-14 days after infection (Mani *et al.,* 2020). Damages may be severe if wet, moist field conditions and poor soil drainage (MacNish, 1966).

Control of Black Leg mainly revolves around physical and cultural control, such as the usage of hot water-treated seeds, which are incorporated by treatment of protective fungicides, and are proven to eliminate seed-borne infections such as black leg, black rot, Alternaria leaf spot, downy mildew, and scab (Babadoost, 1989). Crop rotation of at least 4 years between non-host and cruciferous crops is also used to break the pathogen's disease cycle. Proper field conditions should also be observed, including proper plant spacing, a well-draining field, and keeping the field free of cruciferous weeds, which may serve as a reservoir for the pathogen. However, if crop rotation is not possible, disinfection with a soil fumigant or heat is also advisable (Babadoost, 1989).

Damping-Off, Wire Stem, and Basal Stem Rot (*Rhizoctonia solani, & Pythium sp*)

Damping-off diseases in seedlings are caused by more than 40 organisms living in the soil (Tjosvold, n.d.). However, the most common organisms are fungal (*Rhizoctonia solani*) and fungal-like (*Pythium* spp.) pathogens that persist indefinitely in soil and plant debris. These organisms generally infect seedlings of many vegetable genera, including *Brassica* crops. Infection may occur either at pre- or post-emergence of the seedlings by attacking the embryo, hypocotyl, and radicle (Schroeder *et al.,* 2013). If at pre-emergence, poor germination is evident, and at post-emergence, rotting at the basal stem or root of the infected plants causes the seedlings to topple over or die, generally termed as "damping-off" (Pscheidt & Ocamb, 2021a, b, c). On Brassicas, damping-off is also known as wire stem (Wellman, 1932; Mani *et al.,* 2020), attributed to a constriction at the base of the stem running upwards of the infected plant, giving off a wire-like appearance (Lancaster, n.d.) as decaying of the outer stem exposes the fibrous inner xylem intact (Mani *et al.,* 2020).

Other symptoms of the disease appear as a necrotic, sunken lesion on the basal stem of the seedlings right above the soil line. As lesions develop around the stem, the seedling will collapse and eventually die. Abundant pathogens favor this disease in cool, highly saturated, compacted, and acidic soil; high humidity; and overcrowding of plants in the field**.** Causal pathogens causing these diseases are thriving soil organisms that permanently reside in infested soil systems. *Rhizoctonia solani*, present on natural soils, can survive indefinitely in the soil living saprophytically through mycelial growth or a specialized resting structure called "sclerotia," a small, round, brown to hard black body. In mature plants, *R. solani* can cause root rot and has been reported to cause bottom and head rot on cabbages (Wellman, 1932), bok choy, and Chinese cabbage (Mani *et al.,* 2020). Species of *Pythium* survive in the soil through the production of different types of spores (Koike & Wilen, 2019), either by chlamydospores, an asexual resting structure that has thick walls, or by oospores, sexual spores capable of undergoing dormancy and able to withstand long periods of drying (Schroeder *et al.,* 2013).

As persistent soil organisms, damping-off-causing pathogens are difficult to control once established in a field. Intensive management of soil conditions and cultivation practices must be maintained to minimize infection until the seedling has passed the vulnerable growth stage (Tiosvold, n.d.). Soil conditions such as good drainage, neutral pH, structure, aeration, good water-holding capacity, and plant nutrition must be attained to avoid conducive environments for the progression of the disease (Meadows *et al.,* 2017; Mani *et al.,* 2020; Pscheidt & Ocamb, 2021a, b, c). Crop rotation with cereals and observing proper plant spacing were also considered preventive measures for the disease (Mani *et al.,* 2020; Pscheidt & Ocamb, 2021a, b, c). If preventive measures fail, several fungicides for soil and treatment are effectively applied as a drench or heavily sprayed on crop seedlings showing early signs of damping off. However, it is recommended to avoid using fungicides unless damping-off has already become a problem. It is advised to wait as long as possible, as young seedlings are more vulnerable to chemical injury than older seedlings (Meadows *et al.,* 2017).

***Cercospora Leaf Spot* (*Cercospora brassicicola* Henn.)**

Cercospora White Leaf Spot, also called Frog-eye leaf spot, is a common disease in the *Brassica* family, causing severe infection on turnip, mustard, and turnip x mustard hybrids. It is a minor disease in collards and kale (Damicone, 2017). Symptoms may appear circular or angular, pale brown to white, with a dark margin measuring up to 8mm in diameter (Jackson & MacKenzie, 2017). The impact of disease on production is generally considered low as it affects mature leaves. It occasionally causes defoliation when the infection is severe. This disease has a worldwide distribution, generally in tropical and subtropical regions. Wet, cool conditions favor disease development, and the pathogen is dispersed by rain and wind surges. The pathogen may be seed-borne. Spores are produced on either side of the leaf spot and disseminated by rain and wind (Jackson, 2017). Fungal spores persist on crop debris, weeds, and in neighboring fields, potentially spreading the disease to new fields. Preventive control measures for Cercospora leaf spot include the use of certified seed treated with captan, thiram, and mancozeb (Jackson & McKenzie, 2017), avoiding overlapping crops, and preventing splashing of spores from infected crops onto healthier crops. In addition, during growth and harvest, removing cruciferous weeds that may serve as hosts for the pathogen is recommended, allowing plant debris to thoroughly decompose below the soil and allowing 2–3 year intervals before planting related crops again to reduce carryover of inoculum.

***Clubroot* (*Plasmodiophora brassicae* (Woronin))**

Plasmodiophora brassicae is a protist pathogen causing clubroot in different members of the *Brassicae* family, primarily Broccoli, cabbage, cauliflower, Chinese Cabbage, Kale, Mustard greens, Pakchoi, Radish, Turnip, etc. Primary symptoms include swelling of roots and rootlets, called "clubs," and aboveground. Secondary symptoms include stunting and yellowing of host plants, as the roots cannot absorb sufficient water and nutrients. In severe cases, clubroot causes premature death in hosts. Yield losses are around 10-15%, but in favorable environments they may reach 50% (CABI, 2019). Members of the Plasmodiophoraceae family infect host cells intracellularly through a unique infection mechanism in which an encysted zoospore produces a tubular structure termed "Rohr," containing a dense structure termed "Stachel," and the zoospore contents pass into an outgrowth of the zoospore itself called "Adhesorium." Formation of the structures mentioned above takes about 2 hours, allowing the zoospore contents to be injected into the host cell wall and the plasma membrane into the host cytoplasm (Aist & Williams, 1971, as cited by Braselton, 1995; Kageyama & Asano, 2009).

Plasmodiophora brassicae is a soil-borne pathogen that enters the host through wounded roots, causing abnormal enlargement and root decay even before crop maturation. Thick-walled resting spores from the infected roots remain viable in soil or crop debris underground for an extended period (15 years or more) (CABI, 2019) without a susceptible host. Inoculum spread may be attributed to contaminated irrigation water, rain splashes, infected transplants, infested soil, and infested planting materials. In a conducive environment where the soil is acidic (pH 4.5-8.1), high in moisture, and a range of favorable temperatures (18-25 °C), and in the presence of root exudates, the production of motile zoospores follows, allowing the movement of *P. brassica* to move and infect susceptible plant rootlets (Heinrich *et al.,* 2016). Gahatraj *et al.* (2019) reported the important role of soil acidity in the pathogen's life cycle, as this condition promotes proliferation and enzyme secretion and affects the pathogen's metabolic system. Kageyama and Asano (2009) intensively studied the life cycle of *P. brassicae* and reported the pathogen's life cycle. The primary phase of infection is called the root hair infection stage, in which the pathogen forms primary plasmodia within root hairs, followed by a series of nuclear divisions that occur in synchrony with plasmodia formation. Cleavage then forms zoosporangia. Four to sixteen zoospores are formed in each zoosporangium, which are then released into the soil. Cortical infection is characterized by the penetration of the secondary zoospores into the cortical tissues of the primary roots. Inside, secondary plasmodia form, leading to cellular hypertrophy and gall, or "club," formation in host tissues. As a result, a new generation of resting spores is produced from the plasmodia and released into the soil, serving as survival structures.

Control of clubroot is challenging because it is almost impossible to eradicate the pathogen once the field is fully infested (Gahatraj *et al.,* 2019). Therefore, an integrated approach combining varietal resistance, crop rotation, and improved agronomic practices is recommended to mitigate the effects of the disease. Heinrich *et al*. (2016) proposed a 3-way approach to clubroot management: disease identification through routine scouting, disease containment, and economically friendly disease management practices to reduce disease pressure. Such practices include the elimination of alternate hosts on the field, crop rotation with non-host crops for at least five years, applying lime to a neutral pH of 7.0 before planting, and planting clubroot-resistant cultivars. Several agrochemicals provided promising control against *P. brassicae*. However, the threat of pathogen resistance arises from the chemicals' effect on non-target organisms. With this, Gao and Xu (2014) reported a nonchemical method for controlling clubroot in *Brassica* by combining heat treatment with biological control agents, which resulted in 91.7% inhibition of *P. brassicae* infection in cabbage.

***Downy Mildew* (*Peronospora parasitica* (Pers))**

Downy Mildew of crucifers is caused by *Peronospora parasitica*, a fungus that thrives in cool, moist conditions. The fungus mainly attacks broccoli, cabbage, cauliflower, radish, and turnip. Based on molecular, phylogenetic, and morphological studies, this pathogen is synonymous with *Hyaloperonospora parasitica* (Gaum). In crucifers, three species are known to cause downy mildew: *H. parasitica, H. brassicae,* and *H. arabidopsidis* (Saharan *et al.,* 2017). Leaf symptoms include irregular dark specks on the underside of young leaves. They may appear net-like as the disease progresses. Upon close examination, spots are scattered over the leaf's abaxial and adaxial surfaces. They may coalesce to form patches of diseased tissue (MacNish, 1966). A distinct disease symptom is the formation of white tufts on the diseased areas or affected tissues.

In cauliflowers and broccoli, downy mildew causes discoloration on curds, rendering damaged heads unmarketable. In addition, the infection may become systemic, affecting the inner curd and allowing the stem tissue to turn dark. In cabbage, greyish discoloration is also observed, and infection makes the crop susceptible to secondary infection (Wukash, 1985). Kucharek (1985a, b) also noted infection in radish "roots," which appear distorted and blackened, with a netted appearance.

Through specialized resting spores known as Oospores, the pathogen can overwinter mainly on crop debris and cruciferous hosts and remain viable from one season to another (Kucharek, 1985a, b). Secondary spread of the pathogen through the dispersion of conidia by water and wind. Wet conditions, High humidity, and Low temperatures are conducive to the sporulation and rapid disease development of downy mildew. Common disease management for Downy Mildew mainly involves integrated methods involving cultural, chemical, and resistant varieties. However, the pathogen's life cycle remains poorly understood, making it difficult to document the use of resistant varieties (Kucharek, 1985a, b). Therefore, the best method to follow in the avoidance of this disease is to minimize conditions that would be conducive to the disease's development. Such an example is implementing proper plant spacing practices to avoid overcrowding of cruciferous crops in the field, and to avoid prolonged moist conditions. Another way is to use disease-free materials, practice crop rotation in the field, and eliminate the field of weeds and other crop residues that may harbor downy mildew (Wukasch, 1985). Using fungicides has also been reported to control downy mildew outbreaks in fields. Seed treatments and foliar spraying with Metalaxyl at 0.4% are recommended, as well as using Methyl Bromide as a soil fumigant (MacNish, 1966). The use of systemic fungicides was also reported. However, the downside of this control method is the development of new strains that would likely render them resistant to these chemicals.

***Phytophthora Root Rot* (*Phytophthora megasperma* (Drechs.)**

Phytophthora Root Rot is a worldwide-distributed root-rotting disease caused by the fungal-like organism *Phytophthora megasperma*. This disease causes severe losses in Apples, Stone Fruits, and Brassicas (Cabbage, Cauliflowers, Mustards, and Brussels Sprouts). Symptoms of the disease in cauliflower and brussels sprouts include red to purple discoloration on stems and mature leaves. As the disease progresses, the whole plant wilts. Purple canker forms on the head's stem, just above the soil line, and discoloration and pith rot are also observed (Kontaxy & Rubatzky, 1983). Infection of the root system is indicated by an entirely decayed tap root or dark lesions along the root length, and in the absence of lateral roots or early signs of decay. All growth stages of susceptible plants are susceptible to infection by *P. megasperma* (CABI, 2021). Although poorly drained, excessively wet field conditions are conducive to the development of this disease, infection hotspots are visible in field low spots and at the tail ends of irrigation runs (Mircetich & Matheron, 1976; Koike & Subbarao, 2017). *Phytophthora megasperma* is a soil-inhabiting fungus-like organism that can overwinter freely in the soil or within host tissues for up to 5 years via oospores (Mircetich & Matheron, 1976). These oospores give rise to structures called zoospores. Zoospores of *P. megasperma* are motile and can travel through the rhizosphere under wet conditions, thereby locating the roots of susceptible plants. *P. megaserma* is generally considered a less aggressive species that causes debilitation rather than complete plant death (CABI, 2021).

Eradication of this disease is difficult, as oomycete-active fungicides do not generally eradicate the disease but only slow disease development (Erwin & Ribeiro, 1996). That is why management strategies focus on good soil management to prevent root rot by avoiding conditions conducive to the pathogen. Good soil cultivation practices, such as aerating and preventing soil compaction, can help reduce the risk of the disease. This method promotes good soil drainage and moderate field saturation (Koike

& Subbarao, 2017). In addition, planting in a field with a history of Phytophthora Root Rot should be avoided as the pathogen persists in the field for long periods.

***Powdery Mildew* (*Erysiphe polygoni* DC) (syn. *Erysiphe cruciferarum* Opiz: Junell)**

Powdery Mildew is a minor disease of cabbage, cauliflowers, and other crucifers. A biotrophic pathogen requires a living host to grow and reproduce (Eckardt, 2002). Infection with *E. cruciferarum* is evident if the infected plant is covered with a white, powdery, patchy mycelial growth growing superficially on the upper surface of the leaves, living ectophytically (Chattopadhyay *et al.,* 2016). Fungal growth patches coalesce as the disease progresses, eventually invading the entire leaf surface. If the disease is severe, fungi may also grow on the underside of leaves. Affected leaves eventually senesce and, in severe cases, may result from planting stunting, depending on the crop's growth stage. The development of the disease is favored by low relative humidity and water stress within the host. The availability of free moisture on the leaf surface favors spore germination (Howard *et al.,* 1994). Cleistothecial formation of this fungus is favored by low to moderate temperatures, low relative humidity, dry soil, and aging of the infected host (Chattopadhyay *et al.,* 2016).

In fungal nomenclature, *E. polygoni* was previously used to refer to the pathogen of rutabaga, turnip, and other economically important hosts. However, authors restricted the name to *E. cruciferarum* to refer to the pathogen that attacks members of the *Cruciferae* and *Papaveraceae* families, emphasizing *E. cruciferarum* as the primary source of powdery mildew infections on crucifers (Koch & Slusarenko, 1990). *Erysiphe cruciferarum* has been reported to infect numerous crop species in the families *Capparidaceae, Fumariaceae, Papaveraceae, Resedaceae*, and *Brassicaceae*, with a global distribution (Tam *et al.,* 2016). The life cycle of this pathogen has two distinct infecting stages: asexual spores (conidia) and sexual spores (ascospores) (Deacon, 1997). At the asexual stage, hyphae from the fungal mycelia grow towards and penetrate plant tissues, forming a haustorium, a nutrient-absorbing structure (Reed, 1913; Deacon, 1997). As mycelia grow, conidiophores bear conidia (Reed, 1913). The primary source of inoculum is conidia settling on plant debris and on off-season hosts living in and around the field. In contrast, a secondary source of inoculum may be the conidia dispersed by the wind (Saharan, 2005). At the sexual stage, ascospores are produced inside an ascocarp called a cleistothecium. Cleistothecia produced by the fungal pathogen serve as survival structures that can overwinter (Silverside, 2001; Chattopadhyay *et al.,* 2016).

Management of Powdery Mildew ranges from resistance breeding, cultural methods, and chemical control last resort. For resistance, resistance against powdery mildew has been reported in *B. alboglabra* (Chinese Kale), *B. rapa* var. brown sarson (Field Mustard), *B. chinensis* (Bokchoy), and *B. alba* (White Mustard) (Kolte, 1985), while transgenic plants of *B. napus* (rapeseed) had shown inhibition on the growth of *E. cruciferarum* by expressing bacterial catalase katE in the chloroplast (Chattopadhyay *et al.,* 2016). For biological control, confirm the efficacy of *A. sativum* (Garlic) extracts and *T. viride* as seed and foliar sprays. For chemical control, Kolte (1985), as reported by Cattopadhyay *et al*. (2016), achieved reasonable control of the disease when Karathane was sprayed three times at 10-day intervals. Chattopadhyay *et al.* (2016) suggest dusting with sulfur if the disease becomes serious.

Sclerotinia Stem Rot* (*Sclerotinia sclerotiorum)

This disease is caused by the pathogen *Sclerotinia sclerotiorum*, a cosmopolitan fungus with a broad ecological distribution and a wide host range, including members of the cruciferous family such as broccoli, cabbage, and cauliflower, as well as other crops belonging to other plant families. Symptoms of the pathogen are noticeable on the aboveground parts, as its presence is strongly indicated by white cottony growth. As the infection progresses, dense white fungal bodies develop and soon become black and hard as they mature. A pale brown to gray-brown lesion is produced upon the fungus's colonization of host tissues. The infection causes severe tissue degradation and rot (Dillard, 1987; Laemmlen, 2002). In cabbage, the infection may initiate on the stem near the soil line, at the bases of leaves, or on foliage that meets the soil. The infected tissue becomes soft and watery, eventually colonizing the entire cabbage, and sclerotia may be observed. This disease, also called white mold, can be severe in the field, during storage, and during transit (Dillard, 1987).

Sclerotinia sclerotiorum is a necrotrophic plant pathogen that attacks its host through the soil. However, it was also found to produce airborne spores. Thus, infections can also be observed on the heads of cabbage, broccoli, and cauliflower (Laemmlen, 2002). Moreover, this pathogen was reported to colonize senescent flower parts and can quickly invade the healthy leaves and stems of the infected host. Sclerotial bodies are asexual structures that can survive in the soil and infect susceptible hosts by producing ascospores and mycelia (Kamal *et al.,* 2016). There are two modes of sclerotial germination: Carpogenic (Apothecial) and Myceliogenic (Hyphal). Carpogenic germination produces apothecia, which encase ascospores, a product of the sexual process that the wind may disseminate in the aerial portions of the plants. Ascospores may survive only a few days after release. In myceliogenic germination, hyphae grow from sclerotial bodies, which are stimulated by host plant exudates, and infect plant parts below ground. Infection subsequently spreads to the aboveground parts (Link & Johnson, 2007).

In controlling this disease, crop rotation with corn, small grains, and other non-host crops was reported to reduce *S. sclerotiorum* populations in the soil (Laemmlen, 2002) and to reduce sclerotial viability over time. However, Morrall and Dueck (1982) reported insufficient control of crop rotation alone in the infection of *S. sclerotiorum* on rapeseed. Nevertheless, avoiding sclerotia buildup in the soil remains a good practice. Canopy management and proper irrigation systems must also be observed and maintained at moderate levels to avoid conditions that favor disease development (Link & Johnson, 2007). Hua *et al*. (1994) found effective control of the disease in sunflowers by establishing an integrated control approach combining 2-year crop rotation, delayed seeding, increased potassium fertilizer levels, and fungicide spraying. For biological control, the mycoparasite *Coniothyrium minitans* was shown to reduce sclerotia in soil when incorporated into crop rotation (Gerlagh *et al.,* 1999). In addition, Kamal *et al.* (2016) reported a reduction in stem rot in *B. napus* using a sclerotial-inhibiting strain of *Bacillus cereus* SC-1, indicating a sustainable management strategy for *S. sclerotiorum.*

***Verticillium wilt* (*Verticillium albo-atrum* (Reinke & Berthier), *Verticillium dahliae* (Kleb.))**

Verticillium Wilt is primarily caused by two fungal pathogens, *Verticillium albo-atrum*, and *Verticillium dahliae*. It is a fatal disease commonly affecting Solanaceous and Cucurbits plants. However, it also infects *Brassica* plants (Frost & Hudelson, 2013), most commonly in Cauliflowers and Chinese Cabbage. Symptoms of this disease include sudden yellowing of foliage, followed by wilting and leaf death. However, this symptom is mistaken for natural leaf aging. Fradin and Thomma (2006) reported varying symptoms among hosts, with no unusual symptoms observed in infected plants. Symptoms may vary, producing wilting, chlorosis, stunting, necrosis, and vein-clearing. For cabbages and cauliflowers, symptoms resemble black rot-producing, V-shaped lesions with yellowing borders traversing the leaf margins. At the same time, vascular tissues develop brown discoloration running from the stems down to the roots. Dumin *et al*. (2021) observed the yellowing of the edges of foliage at an early stage. Disease progression led to a wilted, dried, and detached infected leaf from the plant. Soft rot on leaf tissues and root tissues, causing leaf detachment, was also observed as a disease symptom.

Verticillium albo-atrum and *V. dahliae* are soil-borne pathogens with a broad host range of over 200 dicotyledonous plant species (Agrios, 2007), specifically attacking plants through the roots. The life cycle of both species can be divided into dormant, parasitic, and saprophytic phases. In the parasitic stage, *Verticillium* spp. enters susceptible plants through root tips or areas where lateral roots form (Bishop & Cooper, 1983). The conidial formation results from budding when the pathogen successfully invades the host's vascular tissues. Colonization continues as the conidia formed are carried through the sap stream, traversing pit cavities and vessel end walls. Sporulation follows, starting another infection cycle (Bishop & Cooper, 1983). In the dormant phase, resting spores undergo mycostasis, which inhibits germination for a short time and is overcome only when root exudates from host and nonhost plants are released in the rhizosphere, leaving available carbon and nitrogen conducive to spore germination (Huisman, 1982). The saprophytic phase of the pathogen occurs during plant senescence and tissue necrosis, during which the conidia formed on the surface of dead tissues are quickly disseminated by wind, initiating another disease cycle (Jimenez-Diaz & Millar, 1988). Microsclerotia formation is a known survival strategy for *V. dahliae*, which can survive in the soil for 10-15 years (Wilhelm, 1955), while for the short-term survival structure of *V. albo-atrum*, it is through the dark, melanized resting mycelium living within asexual plant propagules (Fradin & Thomma, 2006).

Verticillium Wilt is generally considered a monocyclic disease, and management strategies are based on reducing initial inoculum in the field. Preventive rather than curative control strategies are used for this disease, as the pathogen is difficult to eradicate from the field. However, maintaining the right moisture and nitrogen levels in the field can help tone down the initial symptoms of the disease. Before planting susceptible hosts in the field, several measures should be taken to ensure the pathogen is absent, such as using certified, pathogen-free planting materials to prevent the introduction of *Verticillium* spp., and sourcing healthy transplants grown aseptically in greenhouses. If already present in the field, soil fumigation with Metam Sodium reduces the impact of Verticillium wilt (Dung & Weiland, n.d.). However, limitations on soil fumigation with chemicals arise from environmental and health concerns and from the development of pathogen resistance to the applied chemical. A desirable preventive measure against this disease is the use of resistant *Brassica* cultivars, which limit colonization and subsequent *Verticillium* spp. production inocula from the field.

***White rust and staghead* (*Albugo candida* (Pers) Kunze)**

Albugo candida, an economically important plant pathogenic oomycete, causes white rust. Yield loss of 90% worldwide and infection of over 400 species of plants, including cruciferous crops, ornamental, and several weed species, make this disease one of the most destructive and widespread diseases of crucifers (Saharan *et al.,* 2014). It is characterized by a symptom termed "staghead," a malformed inflorescence caused by the accumulation of white rust. At this stage of infection, yield loss is evident. *A. candida* attacks mustard, radish, horseradish, turnips, and other cruciferous family members. Symptoms initially appear as necrotic, pinpoint spots on the upper leaf surface or on infected tissue. Then, white blisters form on the adaxial part of the leaves, and a corresponding yellow patch forms on the abaxial part of the infected leaves. General and systemic infections of *A. candida* include distortion, hypertrophy, hyperplasia, and sterility of inflorescences. Severe infection by this pathogen often leads to leaf distortion, reduced marketability, and the host's premature death.

Pustules of white rust are round and smooth. When ruptured, powdery dust from sporangia containing oospores of *A. candida* is exposed, quickly disseminated by wind, and splashed onto neighboring susceptible plants (Mani *et al.,* 2020). Suppose the environment is conducive, with moisture and a favorable temperature present. In that case, it produces motile spores called "Zoospores," which can travel to neighboring hosts and enter through young tissues. Another unique structure, called "Oospores," can be produced by *A. candida* as a mode of survival in soil or crop debris, both in and out of the field. Oospores can overwinter in the soil and be a potential source of infection. Germ tubes from oospores can penetrate the cotyledons of host plants through the stomata and feed on the host through a specialized structure called a haustorium.

Although considered the best way to control White Rust, resistant crucifer cultivars are not yet available, so control measures rely heavily on cultural strategies and good agricultural practices, such as reducing leaf moisture, thereby reducing disease severity. However, a recent study by Santos *et al.* (2006) showed that resistance inheritance in Pak Choi was observed through cross-breeding between *B. rapa* and Pak Choi. Although chemical control is the last resort in pathogen management, fungicides that control downy mildew are also effective against white rust (Mani *et al.,* 2020).

Viral diseases

Worldwide, at least several viral species have been reported to infect crucifers (*Alfalfa mosaic virus* (AMV), *Beet western yellows virus* (BWYV), *Tomato spotted wilt virus* (TSWV), *Cucumber mosaic virus* (CMV, *Cauliflower mosaic cirus* (CaMV), *Turnip mosaic virus* (TuMV), *Broad bean wilt virus 1* (BBWV-1), and *Pea seed-borne mosaic virus* (PSbMV) (Moreno *et al.,* 2005), but the two most important are *Cauliflower mosaic virus* (CaMV) and *Turnip mosaic virus* (TuMV) (Zitter, 1984) with 60% and 40% disease incidence, respectively (Raybould *et al.,* 1999). TuMV is considered the most widespread viral disease of domesticated crucifers. It is a member of the most prominent virus family, *Potyviridae*, with a broad host range. Symptoms of turnip mosaic include mosaic in distorted leaves, necrosis on the lower leaves in turnip, radish, mustard, and cabbage, and mosaic with black necrotic rings on cabbage, cauliflowers, and brussels sprouts (Zitter, 1984). Although some symptoms may only show up for 2-5 months in storage due to infection during the growing season. Infection with CaMV, a member of the family *Caulimoviridae,* is often confused with TuMV symptoms, as it induces mosaic symptoms and veinal chlorosis in its host. However, high temperatures may conceal infections in chronically infected crops.

Turnip mosaic virus and *Cauliflower mosaic virus* are both prevalent in temperate zones of Africa, Asia, New Zealand, the USA, and several EU countries as long as susceptible hosts are present (Sutic *et al.,* 1999). Both are efficiently transmitted by green peach aphids (*Myzus persicae*) in a non-persistent and semi-persistent manner, respectively (Spence *et al.,* 2007). Furthermore, Spence *et al.* (2007) reported that simultaneous infection with TuMV and CaMV resulted in a 20-fold reduction in marketable harvested cabbage heads compared with CaMV alone, implicating early management of TuMV at the seedling stage and TuMV as an incitant in CaMV infection. Transmission Activation (TA) of both viruses was shown to be highly reliant on calcium- and reactive oxygen species (ROS)- mediated signaling, as a plant response to aphid presence (Berthelot *et al.,* 2019).

General management for TuMV and CaMV is deeply rooted in prevention rather than control, as commercial chemicals do not prevent the disease from spreading. Management primarily focuses on eliminating cruciferous weeds in the field, as they may serve as alternate hosts and inoculum reservoirs for these viruses (Moreno *et al.,* 2005). As aphids vector these viruses, early aphid control should be imposed on the crop field and neighboring areas (Zitter, 1984). However, insecticides against these vectors have no significant effect in controlling viral spread, as non-persistently transmitted viruses (TuMV) are difficult to control with insecticides (Walsh & Jenner, 2002). Furthermore, insecticides take time to kill the insects, implying that by the time the insects are dead, virus transmission has already transpired (Tsatsia & Jackson, 2017). Combining genes based on viral determinants could be achieved by identifying viral genes that confer virulence or avirulence to pathotype-specific resistance genes (Jenner *et al.,* 2000). The most environmentally favorable and sustainable control would ultimately be deploying plant resistance genes (Walsh & Jenner, 2002).

Diseases caused by nematodes

Plant-parasitic nematodes are microscopic worms that inhabit the rhizosphere of host plants. They mainly feed on plant roots, resulting in problems with plant growth because they reduce rooting volume and root efficiency in taking up water and meeting nutrient requirements for efficient growth. Alongside this, nematodes induce secondary or aboveground symptoms, which render the crop unmarketable. In crucifers, the main nematode genera affecting crucifers are *Meloidogyne* spp., causing root-knot, and *Heterodera* spp., causing cyst, with the former considered as the most problematic and widely distributed (Monfort *et al.,* 2007). Several species of *Meloidogyne* spp. induces severe prolific root branching and galling on infected roots while subsequently causing stunting, chlorosis, and wilting aboveground. Although infected plants may survive, the quality of the products may be severely affected, rendering them unmarketable in the long term. Two species of *Heterodera* spp. are known to infect crucifers. High numbers of both species present at seeding and transplanting can cause plant stunting, yield reduction, and delay crop maturity (Westerdal & Ploeg, 2018). Aboveground symptoms caused by nematode invasion of roots are not diagnostic, as they are similar to nutrient deficiencies, specific plant pathogens, and some root-feeding insects. Hence, soil sampling is crucial in confirming the presence of nematodes in the field.

Generally, aboveground symptoms of the cyst and root-knot nematodes are similar, such as yellowing of foliage, reduction in the size of head and curds, and visible patches in the field of stunted and dying plants. However, distinct differences in the below-ground environment between the two are observed. *Heterodera* species do not cause galling on roots. Instead, signs of the organism are visible on the root surface as small, lemon-shaped females, which are white initially and turn into black cysts (egg-filled) at maturity. In *Meloidogyne species*, gnarled roots and root galls are present at J3 and J4 stages, and adult females are usually embedded within root tissues (Westerdal & Ploeg, 2018).

Although root-knot and Cyst nematodes belong to the same family, differences are evident in parasitism, invasion, migration, and the induction of different types of nurse cells (Wyss & Grundler, 1992). Furthermore, Wyss and Grundler (1992) reported differences in the feeding behavior of *H. schachtii* and *M. incognita* infection on *A. thaliana*. Juvenile stage 2 (J2) of *H. schachtii* was found to migrate intracellularly, thrusting its stylet on the vascular cylinder before establishing a permanent feeding site called the syncytium. At the same time, for *M. incognita*, the J2 reaches the permanent feeding site by intercellular migration. It then reaches the apex, turning around to the differentiating site of the vascular cylinder. Ibrahim *et al*. (2013) tested the susceptibility of several cruciferous plant cultivars. The researchers reported that cultivars of cabbage (cvs. Balady, Brunswick, and Ganzouri), cauliflower (cv. Balady), and turnip (cv. Balady) were susceptible to infection by both cyst and root-knot nematodes. In contrast, radish (cv. Balady) was moderately susceptible to cyst nematode (*H. schachtii*) and root-knot nematode species.

Preventive measures should be considered to limit nematode movement from infested to non-infested fields. Usage of pest-free planting materials which are grown in fumigated soil medium (Noling, 2009) is reported, as well as thorough cleaning equipment used to prevent the introduction of pests in soil and monitor and prevent the flow of irrigation water from an infested field going to other fields, in which impounding and diverting of run-off should be done (Westerdahl & Ploeg, 2018). Cultural control for cyst nematode, such as crop rotation, is an effective way to control the nematode population in the soil as the pest has a narrow host range (sugarbeet, cabbage, cauliflower, brussels sprouts, broccoli, rape, turnip, rutabaga, radish, and cruciferous weeds) crops that may be used in short-term rotation are beans, corn, grains, peas, potatoes, and tomatoes. A small field population may require a 2-year program. In contrast, high populations may cause 5-6 years of rotation before re-establishing hosts in the field (Pscheidt & Ocamb, 2021a, b, c). On the other hand, crop rotation is ineffective in controlling root-knot nematodes due to the broad host range. For biological control, soil treatment with abamectin and a crude suspension of *Bacillus thuringiensis* reduced the cysts of *H. schachtii* and the egg masses of *M. incognita* on cabbage roots (Ibrahim *et al.,* 2013), as did treatments with marine algae (*Botryocladia leptopoda* and *Ulva fasciata*).

Conclusion and general disease management

Brassica spp. and *Raphanus* spp. crops are susceptible to various diseases caused by different pathogenic organisms. Bacterial and fungal pathogens are the most common agents causing diseases on crucifer crops; however, viruses and nematodes can also be problematic. Most of these diseases are soilborne and are easily disseminated by wind surges and water splashes from rain and irrigation systems. These diseases pose a significant threat to the crucifer industry, as they hamper the growth and development of seedlings and young crucifers. Diseases also damage the leaves, curds, and heads, which are marketable products. As a result, the quantity and quality of the products are reduced. Thus, appropriate disease management is needed to mitigate reductions in quality and yield.

The control strategies for the diseases reviewed focused mainly on preventive cultural measures, as most are difficult to manage once established in the field. However, if the problem arises, the most economically feasible and ecologically acceptable way is to use crop varieties with reported disease resistance. However, sources of resistant lines are still limited. Therefore, before establishing crops on the field, it is crucial to ensure that the seeds used are certified and disease-free and that the equipment and materials used are clean and pathogen-free. The complete decomposition of crop debris in the field must be ensured to prevent pathogens attacking crucifers from persisting.

Crop rotation with a non-host plant is a general control measure in most diseases to break the life and disease cycle of phytopathogens. Moreover, optimum growing conditions in and around the field shall be applied. Proper plant spacing and avoiding plant overcrowding improve plant ventilation, promoting the drying off of excess moisture on the leaf surface and in the soil. Thus, the proliferation of fungal and bacterial infections, favored by moist conditions, would be prevented and curtailed. It is also important to be wary of possible alternate hosts of these pathogens, such as cruciferous weeds and volunteer plants. These plants may serve as a rich reservoir of pathogens and a primary source of inoculum for the next cropping season of the host plants.

The last resort for disease control is the use of chemicals to eradicate plant pathogens. However, chemical resistance management must also be carefully considered and monitored, as pathogens may develop resistance to the chemicals applied.

Author contributions

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