ISSN 2518–2021 (Print) 2415–4474 (Electronic)

Fundamental and Applied Agriculture

Journal home page: https://www.f2ffoundation.org/faa/index.php/home

Vol. 8(4), pp. 655 – 667: 2023, doi: https://doi.org/10.5455/faa.136385

PLANT PATHOLOGY | REVIEW ARTICLE

An Extensive Review of Strawberry (*Fragaria×ananassa*) Diseases and Integrated Management Approaches: Current Understanding and Future Directions

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ARTICLE INFO

Article history
Received: 04 Jan 2023
Accepted: 09 Apr 2023
Published online: 31 Dec 2023

Keywords
Strawberry, Disease cycle, Sustainable production, non-chemical, Epidemiology, Climate change

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ABSTRACT

Strawberry production has increased by more than double in the past two decades. Meanwhile, it is also susceptible to various diseases which have become a limiting factor in its yield increment. Indiscriminate use of chemicals in the management of diseases has brought several adverse effects to the environment and human health. Thus, this review aims to present the different diseases of strawberries including their epidemiology, disease cycle, and symptoms. Moreover, the focus has been given to integrated disease management. More than ten dozen of literature including journal articles, books, websites, and organizational reports were thoroughly reviewed to get the related information. Botrytis grey mold rot, anthracnose, strawberry leaf spot, powdery mildew, and red stele are the major fungal diseases whereas angular leaf spot is the serious bacterial disease of strawberry. It is severely infected by viruses such as strawberry mottle virus and crinkling and vein banding virus. In addition to this nematode causes ring spots, root-knot, and root lesions on strawberries. Integrated disease management approaches should be adopted for their effective and sustainable management. It may include the cultural methods, physical methods, use of bio-control agents, botanical fungicides, and at last chemicals if the disease is severe.

1. Introduction

Strawberry is the most popular fruit among berry that belongs to the Rosaceae family and its cultivation is in increasing trend. Many wild species of strawberry are found worldwide, but among them, *Fragaria* × *ananassa* is the most popular one which is the hybrid between *F.* × *virginiana and F.* × *chiloensis* produced in North America (Stewart, 2010). There is no doubt that *Fragaria* × *ananassa* is the legendary fruit in temperate regions, but nowadays it is ruling over tropical and sub-tropical regions too (Kumar et.al., 2018). Strawberry is highly appreciated for its attractive and distinctive red color, enjoyable taste, characteristic aroma, juicy and succulent texture. Besides these, it has high nutritive and medicinal value and is also a relevant source of antioxidant compounds including Vitamin C (Velde et al., 2014), and phenolic compounds, mainly flavonoids such as flavanols, anthocyanin, and hydrolyzable tannins (Terefe et al., 2013) and also in phenolic acid and ascorbic acid (Giampieri et al., 2012). Most of the people have admired it due to its health improvement activity. These bioactive compounds present in the strawberry can reduce cardiovascular diseases, neurodegenerative diseases, cancer (Moreno et.al., 2014). Furthermore, they have an inhibitory effect on mutagenesis and carcinogenesis; preventive action against some forms of cancer (Ho et al., 2002).

Strawberry is highly nutritious and healthy but meanwhile, it is also susceptible to many diseases which have significantly decreased its economical and nutritious value. The disease is one of the leading factors for decreasing its value among the human world and can infect its roots, crown, leaves, flower, fruit, and even may collapse the plant. Various fungi, bacteria, viruses, nematodes, etc. are responsible for causing disease and mostly fungal diseases are of economic importance in strawberries. The fungus can infect almost every part of

Cite This Article

Dholi PK, Khatiwada P, Basnet B, Bhandari S. 2023. An Extensive Review of Strawberry (*Fragaria×ananassa*) Diseases and Integrated Management Approaches: Current Understanding and Future Directions. *Fundamental and Applied Agriculture*, 8(4): 655–667. https://doi.org/10.5455/faa.136385

plants. In fruit, different fungal pathogens cause fruit rot and they include Botrytis grey mold rot (most studied one (Sesan, 2003; Boff, 2001), anthracnose and strawberry leak (Timudo-Torrevilla et al., 2005); foliar diseases include strawberry leaf spot (most common foliar disease), powdery mildew, Verticillium wilt and on root it causes red stele, black root rot, etc. Similarly, angular leaf spot and bacterial wilt are some bacterial diseases. In the case of the virus, we can find more than 30 viruses and virus-like diseases which are vectored by aphids and whitefly (Tzanetakis, 2006). These viruses, if act together on the same plant, can cause strawberry decline.

Nowadays, strawberry is being an apple in many people's eyes due to its aroma, flavor, and potential health benefits but at the same time, it could not able to protect itself from different diseases.Therefore, the most effective major has to be found to make them healthy. Relying only on chemical methods of disease management will affect the environment and human health and also bring several negative impacts to the non-targeted micro-organisms in soil (Bhandari et al., 2021). In this regard, integrated disease management approaches should be adopted for the sustainable and eco-friendly production of strawberries. Furthermore, most of the papers have been published only on particular diseases of Strawberry. Thus, this review provides a compiled idea about any structural abnormalities caused by a disease-causing pathogen and sustainable management practices for yield enhancement of strawberries. This study aims to present all the identified diseases of Strawberry with their symptoms, epidemiology, disease cycle, and integrated management practices. Moreover, it will also identify the constraints lying behind effective disease management of Strawberry and their solutions through critical analyses of the related literature.

2. Materials and Methods

Data releated to the diseases of strawberry were collected through secondary sources. Google Scholar, Research gate, PubMed and Wikipedia were utilized as search engines. Different journal articles, book chapters, thesis, websites, and other governmental and non-governmental reports were thoroughly reviewed to gain information on symptoms, disease cycle, epidemiology, and integrated management practices of the diseases of Strawberry. Production data from FAO were retrieved and the graph was generated using Microsoft Excel software. Problems behind sustainable disease management were identified, and solutions and future research works were recommended through critical analyses of the situation.

3. Results and Discussion

3.1. Production status of strawberry

The global production of strawberries is in an increasing trend. Its production has been increased by more than two folds in these past two decades as shown in Figure 1.

3.2. Diseases of strawberry

Moajor diseases, their pathogen and distribution are given in Table 2 and Table3.

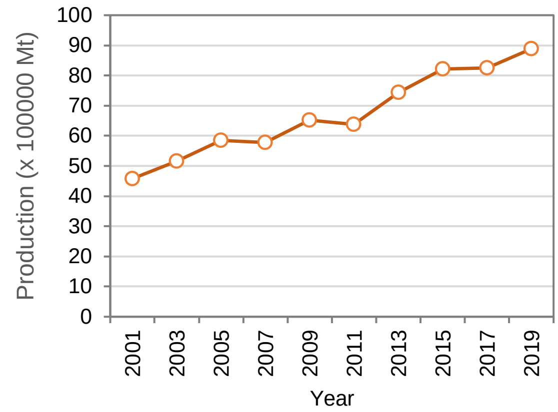

Figure 1. Global production trends of strawberries from 2001 to 2019 (FAO, 2021)

3.2.1. Fungal disease of strawberry

Botrytis gray mold rot: Botrytis gray mold rot is one of the most important diseases of strawberries and also the most studied one (Sesan 2003, Boff 2001). *Botrytis cinerea* can infect more than 1000 plant species including strawberry (Figure 2 A and B) (Elad et al., 2016).

Symptoms: In botrytis gray mold rot, the surface of the fruit shows velvety gray growth but the surface growth also may be cottony or white during the high humid condition where spore formation is very low (Paulus, 1990). The fruit of the infected crop has a water-soaked lesion with brown or tan color which gradually becomes grayish or dry and the disease causes severe pre-harvest losses (Vagelas et al., 2009).

Epidemiology: For the disease development, temperature (15°C-20°C) and relative humidity (more than 90%) should be maintained for more than 28 hours (Devaux, 1978).

Management

a) Chemical: Protective fungicides can be used during moderate disease development and the commonly used fungicides are benomyl or thiophanate-methyl, benzimidazole, and dicarboximide (Paulas, 1990).

b) Biological: Botrytis grey mold in strawberries can be prevented by using the formulation of a bio-control agent, *Bacillus licheniformis* N1 (Kim et al., 2007).

c) Physical: Botrytis fruit rot after harvesting can be controlled by storing fruits at 5°C or below or a combination of 10% to 15% CO_2 in the atmosphere (Sommer et al., 1973).

d) Cultural: Agronomic and horticultural practices such as removal of infected plants parts can reduce inoculum buildup (Daugaard, 1999). Moreover, drip irrigation and micro-sprinklers irrigation can reduce the spread of inoculum and reduction of water films on fruit (Dara et al., 2016; Terry et al., 2007) whereas short spacing can increase incidence (Legard et al., 2005).

Table 1. Major disease of strawberry based on plant parts affected

Disease	Causal organism	References
Leaf disease		
Angular leaf spot	Xanthomonas fragariae	Kennedy & King, 1962
Powdery mildew	Sphaerotheca macularis	(Wallr. ex Fr.) Jacz.
Strawberry leaf spot	Mycosphaerella fragariae	Tul.
Leaf scorch	Diplocarpon earliana	E & E
Leaf blight	Phomopsis obscurans	Ellis MA, 2008, Ohio State University
Fruit disease		
Botrytis gray mold	Botrytis cinerea	pers. ex. Fr
Anthracnose	Colletotrichum acutatum Colletotrichum fragariare Colletotrichum gloeosporioides	J. H. Simmonds A. N. Brooks (Penz) Penz. & Sacc.
Leather rot	Phytophthora cactorum	(Leb. & Cohn) Schroet.
Root diseases		
Red stele	Phytophthora fragariae	Hickman
Blackroot rot	Fungi complex: Rhizoctonia fragariae Idriella lunata Pythium ultimum Pythium irregulare And various other species like Pythium spp, Pyrenochaeta spp, Cylindrocarpon spp & Fusarium spp.	(Husain & Mckeen) Nelson et Wilhelm Trow Buis

Table 2. Distribution, host range, and yield loss of major strawberry diseases

Diseases	Distribution	Host range	Yield loss	References
Botrytis gray mold	Found worldwide where strawberries can be grown	Infects more than 1000 plant species	More than 80% of the flowers and fruits and flowers can be lost under wet condition	(Elad et al., 2016; Petrasch et al., 2019)
Anthracnose	Warmer climatic zone with an optimal temperature of 26.7-32°C	Infects a wide range of crops such as strawberry, apple, almond, citrus, peach, eggplant, tomato, bean, and so on	Up to 50%	(Forcelini et al., 2015; Morkeliune et al., 2021; Afanador-Kafuri et al., 2003)
Strawberry leaf spot	Mostly prevalent in the northern hemisphere	Cultivated and wild Fragaria species	13% decrease in berry weight	(Marcoux, 1996; Louws et al., 2014)
Powdery mildew	Prevalent where strawberry is grown	Red raspberry and different species of strawberry	Up to 70%	(Keep, 1968; Xiao et al., 2001: Liu, 2017)
Red stele	Egypt, India, Japan, Austria, Belgium, Denmark, Ireland, Netherland, Russia, Serbia, Nova Scotia, Florida, and United States	Strawberry and raspberry	Up to 78%	(EPPO and CABI, 2012;
Angular leaf spot	Mostly in Ethiopia, China, South Korea, Austria, Bulgaria, France, Italy, and Netherland	Specific to fragariae species	Reduced marketable yield of up to 7 to 8%	(Roberts et al., 1997)

Table 3. Diseases with their inoculum and mode of dispersion

Disease name	Source of inoculum	Primary inoculum	Secondary inoculum	Mode of dispersion	References
Botrytis gray mold rot	Infected plant tissues	Dormant sclerotia, conidia, and mycelium	Conidia	Wind and rainwater	Jarvis, 1962; Bristow et al., 1986
Anthracnose	Pathogen from soil, Infected plant part	Acervuli	Conidia	Splash dispersion	Paulus, 1990; Madden et al., 1992;
Strawberry leaf spot	Nearby infected plants	sclerotia and perithecia	Conidia	Water splashing due to rainfall	Hammel, 2016; Paulus, 1990; Fulton, 1958
Powdery mildew	Infected leaves	Cleistothecia	Conidia	Wind	Reid, 2015; Gadoury et al., 2010; Louws et al., 2019
Red stele	Infected stock	Sporangia	Secondary sporangia	Soil saturated with water	Hickman, 1940;
Crown rot and leather footrot	Infected mummified strawberry and infected transplant	Oospores	Microconidia	Soil saturated with water	Paulus, 1990
Verticillium wilt	Infected plant debris	Microsclerotia	Absent	No secondary infection	Ellis M.A, 2008; Paulus, 1990
Charcoal rot	Soil and infected crop debris	Microsclerotia	Absent	No secondary infection	Peres et al., 2018;
Angular leaf spot		Contaminated transplant	bacterial ooze	Rain, overhead sprinkle irrigation, and human when they carry out intercultural and harvesting operations.	Natalia et al.,2014; Mass, 1998

Anthracnose: It is another important fungal disease of strawberries. Almost all part of the plant is affected by this disease (Figure 3) (Mass, 1998).

Symptoms: Circular sunken lesions with dark brown color are seen in anthracnose that gradually turns black (Paulus, 1990). Some other symptoms associated with the disease are flower blight, buds rot, irregular leaf spots, and black spot on both green and ripe fruit causing the entire plant to die (Howard et al., 1992). As it affects almost all parts, it causes root necrosis which further causes dwarfism in the plant (Freeman & Katan, 1997). During the crown infection, initially gray to black streaks are seen in vascular tissues where a pocket of cinnamon brown tissue develops in advance case (Horn, 1963; Gubler, 1988).

Epidemiology: The optimum temperature for disease development is 15°C-30°C (Freeman, 2008). Most of the infection procedures during the disease cycle are all favored by the period of wetness of more than 4 hours (Smith, 2008).

Management:

a) Chemical: Proper identification is required for the proper management of disease as C. acutatum is tolerant to benomyl but C. gloeosporiodes (Freeman et al., 1997). Switch 62.5 WG, quadris 2.08F, and captan 80WP, 500WP, or 80WDG are the most effective fungicides against anthracnose. (Turechek, 2004)

b) Physical: Plant protection can be done by using plastics (Freeman & Gnayem, 2004).

c) Cultural: Plastic mulching, soil solarization, fumigation, and removal of infected plants to avoid the source of inoculum are the common management practices (Freeman, 2008). Disease-free planting material should be used. Drip irrigation can be used as it will avoid splash dispersion and also benefit the IPM program (Durner et al., 2002).

Strawberry leaf spot: It is the common foliar disease of strawberries. It also affects other parts such as stems, fruit stalks & fruit calyces (Paulus, 1990).

Symptoms: Small purple circular spots on young leaf whose center gradually becomes gray to white with reddish-brown borders and spot in other parts are also similar to that of the leaf except for stem & stalks with elongated spots (Paulus, 1990). In severe conditions, discoloration occurs in the seed of a fruit and underlying flesh (Fulton, 1958). Dark brown, hard & leathery area is seen under and around the spot and degrades the quality of berry (Carisse et al., 2018).

Epidemiology: More rainfall with prolonged wet periods favors disease development (Paulus, 1990). The production and germination of conidia are favored by the temperature range from 13°C to 21°C (Fall, 1951; Plakidas, 1931). Germination of conidia wasn't seen at the relative humidity below 98% (Elliott, 1988). Without considering temperature, the minimum leaf wetness period must be 12 h and moderate infection was seen when the wetness period was less than 48 h (Carisse et al., 2000).

Management:

a) Host-plant resistance: The use of resistant cultivars is the most economical and sustainable way to manage this disease (Janick and Williams, 1959; Nemec, 1971).

b) Chemical: Chlorothalonil can be used as a plant dip or foliar spray and hot water dip (52°C) for 3 minutes can kill sclerotia with any detrimental effects (Paulus, 1990).

Powdery mildew: It is another important disease of strawberries. It can be seen in every place where strawberries are grown (Xiao et al., 2001).

Symptoms: Symptoms are mainly seen in leaves but fruits are also affected in susceptible cultivars (Jordan et al., 1972). Powdery mass is seen in the lower leaf surface, leaves cup in an upward direction and in advance case burnt margin may be seen (Paulus, 1990). Reddening of the infected fruit is delayed and in severe cases white powdery mass is seen on the surface of the fruit (Wilhelm, 1961).

Epidemiology: Conidial germination on host leaves take place at temperature 15°C to 25°c and relative humidity of 80% (Paulus, 1990). Free water has a lethal effect on conidia and rainwater has a drastic deleterious effect on spore dispersal (Peries, 1962; Jhooty and Mckeen, 1965).

Management:

a) Chemical: Sulfur or benomyl fungicide can be used. Proper use of sulfur should be done as it causes foliage to burn above 27°C (Paulus, 1990).

b) Biological: The use of bio-control agents such as Ampelomyces quisqualis, Bacillus subtilis, and Trichoderma harzianum T39, alternating with chemical fungicide can control powdery mildew reducing its detrimental effects (Pertot et al., 2007).

Red stele: It is one of the serious fungal diseases of strawberries (Mass, 1998).

Symptoms: Plants are stunted, leaves wilt and dry and fruit quality deteriorates or no formation of fruit takes place (Paulus, 1990). Causes the death of tip of crown roots which is known as rattail and cutting it lengthwise exposes red stele (Bain and Demaree, 1945; Wilhelm, 1961). Frequent wilting and poor growth of the plant, bluish-green cast of younger leaves, and yellow or red coloration of older leaves are some other common symptoms (Mass, 1998).

Epidemiology: Heavy rainfall, water logging condition, and frequent irrigations are some favorable conditions for disease development (Paulus, 1990). High moisture with low temperature favors disease development and dispersion (Morita, 1975 & Montgomerie, 1977). Minimum, optimum, and maximum temperatures for disease development are 3°C, 18-22°C, and 30°C respectively (Hickman, 1940; Ho & Jong 1988, Erwin & Ribeiro 1996).

Management:

a) Chemical: Application of ridomil gold at planting, spring when the plant grows and after harvest can help to manage red stele disease in the strawberry field.

b) Physical: Increase PH of the soil as the disease is severe in acidic soil.

c) Cultural: Healthy planting material on a high bed must be used (Paulus, 1990).

d) Host plant resistance: Resistant cultivars with numerous physiological races of fungus must be selected (Anderson & Colby, 1942).

Crown rot and leather footrot:

Symptoms: Xylem and Phloem tissues of crown get degenerate rapidly with severe burning. Plants finally wilt and collapse. Fruit is covered with dark brown or green spots having a brown border. As the case becomes severe whole fruit changes into brown and leathery. High moisture conditions favor white moldy growth in fruit surface finally giving the fruit a hard structure. (Wilhelm & Nelson, 1980). One can identify the disease by seeing brown discoloration of the crown. Generally, symptoms are first seen in the upper portion which gradually moves downward. (Seemular, 1998)

Table 4. Epidemiology of crown rot and leather foot rot disease of strawberry

Temperature	Wetness	Infection type
15°C - 25°C	3 hours	Diseased fruit shows sporangia
15°C - 25°C	16 hours	≥100 sporangia/fruit
17°C - 25°C	1 hour	80% infection of fruit

Epidemiology: Oospores of *Phytophthora cactorum* remain dormant in the soil for a very long time and also survive in the infected mummified fruit for several seasons. It germinates to produce sporangia in the spring season.

Management:

a) Cultural: Well-drained condition with proper soil aeration. Mulching can also help to reduce the disease infestation. It should be done using straw and polythene. (Paulus, 1990)

b) Chemical: Leather rot and gray mold appear together in the strawberry field. So, their proper management requires the combined application of two fungicides. Folpet, captan, or thiram can be used for the management of the disease. An effective fungicide for the control of this disease is Metaxyl but not registered world widely. (Tanbool-EK, 1983; Grove et al., 1985)

c) Biological: Use of *Trichoderma* spp. along with soil solarization can help to manage the disease effectively. (Porras, et al., 2007)

Verticillium wilt

Symptoms: Margin of the leaves turns dark-brown or reddish-yellow. This symptom is also seen between veins. The infected leaves wilt and become dry. (Ellis M.A, 2008). Growth of new leaves retard and plants become stunted at the severe case. (Paulus, 1990)

Epidemiology: Soil temperature of 21°C to 24°C is favorable for disease development. (Ellis M.A, 2008)

Management:

a) Host plant resistance: Avoid susceptible cultivars.

b) Physical: Well-drained soil should be selected for plantation.

c) Chemical: Mix application of methyl bromide and chloropicrin can help to control the disease. After the application of the mixture, the soil must be covered with polythene film. (Paulus, 1990).

Blackroot rot:

Symptoms: Older leaves of the plants are dead. Plants become stunted. Fruit cannot attain its marketable size. New roots become fibrous and whitish that gradually turn dark brown or black (Lows F. & Cline B, 2014). A decline in vigor and productivity of the plants. (Paulus, 1990)

Epidemiology: Soil having high clay content is favorable. Anaerobic conditions in the soil can also help in disease development. (Paulus, 1990)

Management:

a) Physical: During site selection, avoid soil with high clay content.

b) Cultural: Use healthy planting material. Monitoring of the field must be done.

c) Chemical: As the disease involve a fungus complex. It is hard to manage. The fungicide Azoxystrobin can be used in drench applications and transplant root dip in established fields. Foliar application of phosphorus acid products is also effective. (Schilder, 2011)

Charcoal rot:

Symptoms: Sign of water stress is seen initially and the plant gradually collapses. Reddish-brown vascular discoloration in the crown region of the affected plant is a typical symptom of the disease. (Peres et al., 2018). Wilting of the foliage and stunting of plants are some common symptoms. Symptoms can be seen when the plant is cut at the crown region.

Epidemiology: It is seen more at the high soil temperature ranging from 33°C to 47°C with low soil moisture content. (Zveibil et al., 2012). Infection is more in hot and dry weather. They survive as microsclerotia in the soil. Microsclerotia do not survive much in wet soil. (Shukla et al., 2019)

Management:

a) Cultural: Use of white striped plastic mulch, removal of crop debris at the end of the season, and use of fumigants at crop termination. These three methods can be integrated for getting a better result. (Juliana et al., 2019)

b) Chemical: Metam potassium can be used as a pre-plant fumigant to reduce disease infestation. Furthermore, a combination of physical, cultural, and chemical can reduce disease. (Juliana et al., 2021)

3.2.2. Bacterial Diseases of strawberry

Angular leaf spot (ALS):

Etiology: The causative agent of angular leaf spot of strawberry disease is *Xanthomonas fragariae* (Kennedy & King, 1962) which is an international quarantine disease of considerable concern to strawberry growers (Roberts et al., 1997).

Symptoms: At first small, light green, water-soaked lesions are seen on the lower surface of the leaf which enlarges to give angular structure and translucent spots can be easily observed with reflected light (Natalia et al., 2014; Dye and Paula, 1973). During high moisture content (or if we observe its leaves during morning hours), sticky droplets of bacteria can easily be visualized (Howard et al., 1985).As the disease progress, the lesions enlarge and coalesce to form reddish-brown angular spots which later become necrotic and lesions can easily be seen from the upper surface of the leaf (Natalia et al.,2014; Dye and Paula,1973). Sometimes yellow halo may also be present (Dye and Paula,1973). When the plants are affected severely, similar lesions can be observed on calyx (causing black cap or brown cap of fruit), which can reduce the fruit marketability (Legard et al., 2003Epidemiology: There is not much information regarding the epidemiology of ALS (Funt et al., 1997; Mass 1998); however, the warm days (20°C) and cool nights (2-4°C) favored the disease development (Howard et al., 1985).

Management:

a) Cultural: The best method of preventing ALS is using certified disease-free planting material (Barun and Hildebrand, 2013; Smith et al., 1992). We can also prevent them by avoiding intercultural and harvesting operations when humidity is high, avoiding sprinkle irrigation, proper disposal of plant debris, etc. (Natalia et al.,2014).

b) Chemical: Use of antibiotics (such as streptomycin and oxytetracycline) and induction of systemic resistance (with analogs of salicylic acid) have shown effective control but these treatments are not registered for the use on strawberries (Robert et al., 1997; Barun and Hildebrand, 2013). Foliar application of copper-based fungicide can control the disease to some extent but it should be used at low rates since it causes phytotoxicity with repeated spray (Robert et al., 1997; Barun and Hildebrand, 2013).

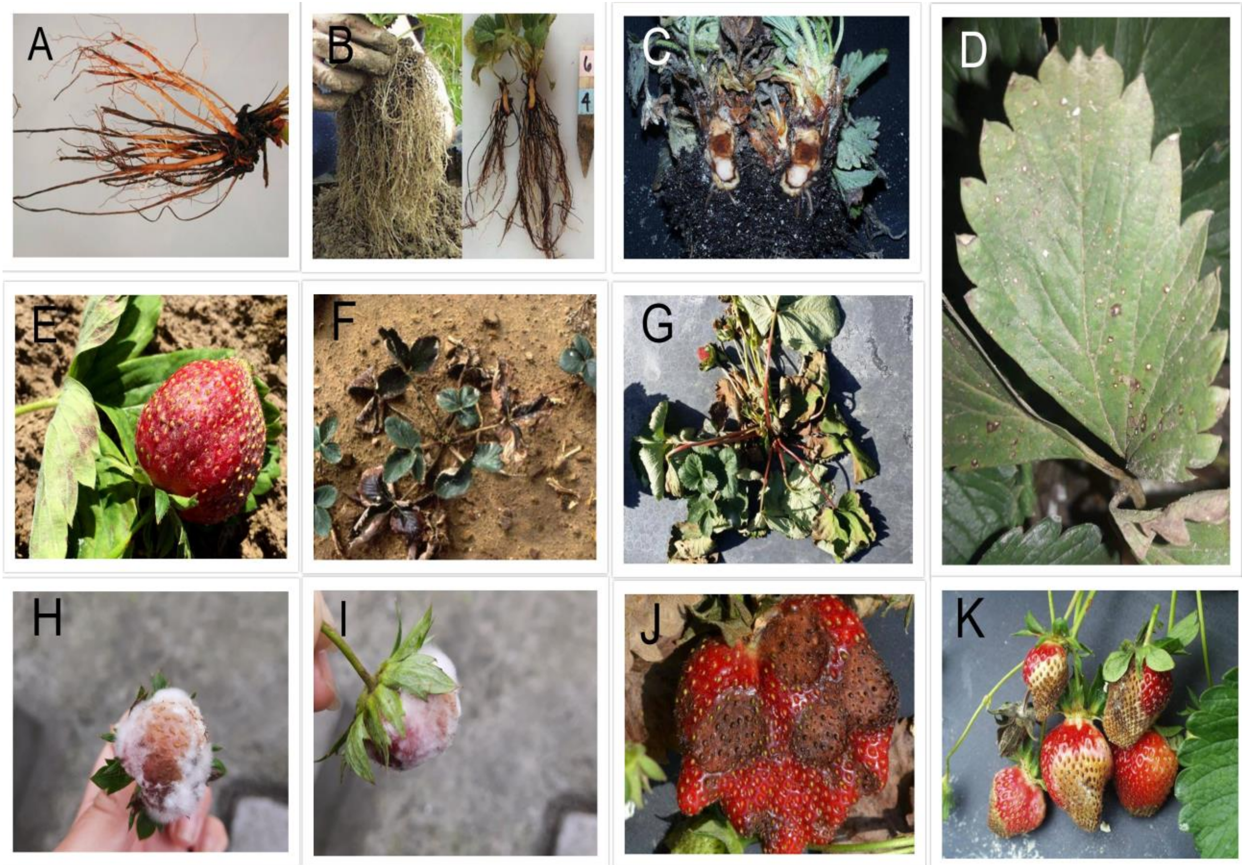

Figure 2. Photographs showing the strawberry disease symptoms caused by fungi (A) Red stele (photo curtsey from (Putnam, 2010), (B) Blackroot rot (photo curtsey from (leandro, 2014), (C) Crown rot (photo curtsey from (Louws, 2014c), (D) Strawberry leafspot (photo curtsey from author), (E) Powdery mildew (photo curtsey from (Bernadine, 2015), (F) Verticillium wilt (photo curtsey from (Ellis, 2008), (G) Charcoal rot (photo curtsey from (Peres et al., 2018), (H) and (I) Botrytis gray mold (photo curtsey from author), (J) Anthracnose (photo curtsey from (Louws, 2014b), and (K) Leather rot (photo curtsey from (Louws, 2014d)

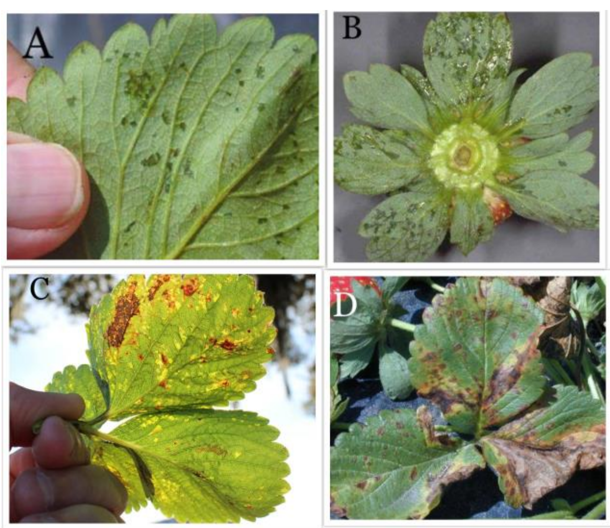

Figure 3. Photographs showing angular leaf spot disease in strawberry caused by bacteria (A) Water-soaked lesions on the underside of an infected leaf (photo curtsey from (Anco, 2011), (B) Water-soaked lesions on the calyx (Peres et al., 2018), (C) Translucent spot of ALS (Gauthier, 2017), and (D) Reddish-brown spot of ALS (Peres et al., 2018)

3.2.3. Viral Diseases of strawberry plant:

Strawberry mottle virus and Strawberry mild yellow virus: These viruses are generally transmitted by wing aphids (*Chaetosiphon fragaefolii C. Jacobi, C. minor)* in a semi-persistent and persistent manner (Moyer et al., 2010). Strawberry mottle virus (SMV) is transmitted through the semi-persistent manner in which viruses get to enter on foregut only but not colonized inside the gut of aphid due to this infested plant inoculated the viruses up to 2 to 3 hours but in case of Strawberry Mild yellow virus (SMYEV); viruses transmitted from foregut to midgut and multiply inside the host so 8 to 9 hours required to inoculate the virus entity (Hildebrand and Lewis, 2014). These viruses are more prevalent in both established and new planting (Bonneau et al.,2019).

Symptoms: Stunted growth of plant chlorosis and necrosis occurs in new leaves, leaf size distortion, reddening of older leaf finally, yield decreases (Lewis and Hildebrand, 2014; Moyer et al., 2010; Koloniuk et al., 2018; Hunda and Sharma, 2018).

Management:

a) Physical: Used yellow sticky traps to capture the wing aphid and whitefly (Moyar et al., 2010).

b) Heat treatment: In this method, well-rooted as well as established plants are grown at 37°C about 4 to 6 weeks after that meristematic in vitro culture propagated plant give virus-free and healthy mother plant (Moyer et al., 2010; Nishi and Ohsawa 1973).

c) Used IPM based aphid control through regular monitoring and field sanitation (Lewis and Hildebrand, 2014; Mortain et al., 2013).

d) Chemical: Use a systemic insecticide to control aphid-like organophosphate pyrethroid (Rondon et al.,2017). Use biological predators like Lacewing (*chrysoptera spp)* and predator mites (*Aphidoletes aphidimyza)* are voracious predators of Aphid (Heinz,1988).

Crinkle and vein Bending Diseases of strawberry: This virus is transmitted by an aphid vector *(Penta trichopus potentillae)* reported by Vaughan (1933).

Symptoms: The plant decreases the production of runner and plant rigidity (Vaughan, 1933).

Distortion and crinkling of leaves, the petals of flowers show abnormal streaking and deformed (Posthuma et al.,2001). Poor leaf growth. when we see older leaves, we can see a premature purplish discoloration pattern but young leaves appear chlorotic and reduced sized with a marked yellow edge on both sides of the leaf vein (Routi et al, 2009).

Management:

a) Cultural: Remove immediately the infected plant (Posthuma et al.,2001). Plant the planting material over silver plastic mulch with proper spacing (single or double row) 25cm× 35 cm and apply the GA3 solution 50 ppm after 4 days of flowering, Increase the plant vigor and yield up to 31 to 41 percent (Dhakal, 2019). Elimination of the virus from mother plants by runner tip culture (Miller and Belkengren, 1963) or by heat treatment for 10 days at 42°C (Bolton, 1967) has been reported. The elimination of the type strain of SVBV from experimentally infected Hood plants by meristem tip culture was 100% whether or not the plants were pre-heat-treated for 6 weeks at 37°C (Mullin and Schlegel, 1978).

b) Physical: Used the planting materials propagated through heat treatment and meristematic culture (Nishi and Oshawa, 1973; p.3).

c) Host plant resistance: Use a virus-resistant variety suitable for geolocation (Hunda and Sharma, 2018). In Nepal, suitable cultivars are king seedling, sweet sensation, Florida beauty, EMCO 32(Dhakal, 2019).

Pallidosis and phytoplasma (witches broom) diseases of strawberries: Transmitted through graft as well mechanical manner (Ioannise et al., 2003), Seed borne virus, also transmitted by greenhouse whitefly (*Trialeurodes vaporarium)* reported by Dura (2013). Witches broom causing mycoplasma is transmitted by leafhopper (*Macrosteles orientalism)* reported by Shiomi and Sugiura (1983).

Symptoms: The plant shows stunted growth, the whole plant gets collapsed because the root cannot supply the required nutrients (Frison, 1994). The plant shows a dwarf bushy appearance consisting of multi branches crown and spindly arrangement whorl shaped small leaves (Zellers, 1927). The main problem of witches' broom diseases is no fruit formation occurs.

Control measures: IPM based agriculture practices.

Nematode Diseases of strawberries: Lots of Nematodes can cause diseases in the strawberry plant and also have the potential vector for carrying the virus. Different types of nematodes borne diseases and their management practice is described below:

Strawberry latent ringspot is a nematode-born virus transmitted through dagger nematodes (*Xiphinema diversicaudatum)* reported by Listes (1964).

Lesion nematode also known as *(Pratylenchus penetrans),* make lesions on roots and stunts the growth of the strawberry plant (Browning et al., 2005). Sting nematode (*Belonolaimus longicaudatus)*.

Root-knot nematodes (*Meloidogyne incognita)* are also the severe nematode of strawberry (Watson et al., 2019; Elgawad, 2019).

Control measures of nematodes in the soil during strawberry farming:

a) Chemical: Drenching of butyric acid on Strawberry cultivated field @ 0.1 to 1M concentration against lesion nematode reduces the nematode density up to 98 to 100 percent (Browning et al., 2005). Preplant soil fumigation of 1,3 dichloropropene + chloropicrin gives the enhancement of plant vigor and fruit yield (Watson et al., 2019). Soil application of fluopyram controls the sting nematode population in soil (Watson, 2019). Preplant application of methyl bromide decreases the population of Nematode (Shennanamdj et al., 2014).

b) Cultural: More plant-parasitic nematodes are present in sandy soil so proper soil maintenance by adding well-decomposed organic matter reduces such problems (Watson et al., 2019).

c) Biological: Vermicompost associated with Trichoderma spp. per kg per meter, square suppress the attack of root-knot Nematode (Ahmed, 2017).

4. Effect of Climate Change on Diseases of Strawberry

Simply, plant disease is the result of interaction among virulent pathogen, susceptible host, and conducive environment. Climate change has directly or indirectly affected the host plant and pathogen (Elad, 2013). Changes in climate and weather potentially affect the epidemiology of pathogens (Garret et.al, 2006). There will be huge influences on the growth, spread, and survival of plant diseases due to changes in weather variables such as light, temperature, precipitation, and humidity (Rosenzweig et al., 2001).

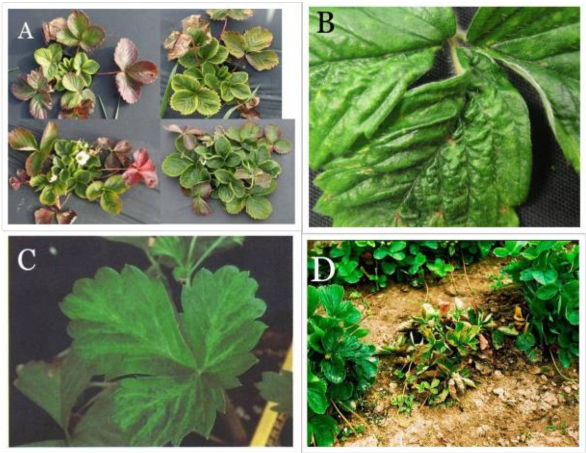

Figure 4. Photographs showing angular leaf spot disease in strawberry caused by bacteria (A) Water-soaked lesions on the underside of an infected leaf (photo curtsey from (Anco, 2011), (B) Water-soaked lesions on the calyx (Peres et al., 2018), (C) Translucent spot of ALS (Gauthier, 2017), and (D) Reddish-brown spot of ALS (Peres et al., 2018)

There are several ways that climate change affects the host-pathogen interaction, particularly by increasing the development rates of pathogen and modifying susceptibility of the host to infection (Harvell et al., 2002).

Severe winter is the period when most of the pathogen mortality takes place, most probably killing more than 99% of the pathogen population annually (Harvell et al., 2002). Climate changes modify the plant host, rather than any direct impact on the organism (Chakraborty et al., 2002; Ziska and Runion, 2007). A strawberry plant(host) could have altered chemical composition and physiology, which may make it more susceptible to pests or diseases due to a change in concentration of defensive compounds if it is stressed by the environment (Ziska and Runion, 2007).

Calleja (2011) found evidence that climate change is already destroying the strawberry sector in the UK and was predicted that due to climate change, the incidence of powdery mildew in strawberries will across most of the UK and is in increasing trend in Scotland, western Wales, and north of England. Also, the incidence of grey mould was predicted to change across most of the UK and is increasing in the north of the midlands. Similarly, the occurrence of black spots of strawberries was predicted to increase drastically across most of the UK (Calleja, 2011). It was also reported that high temperatures and low soil water potentials are important factors causing crown rot disease in strawberries which is important from the perspective of climate change (Olaya and Abawi, 1996). Moreover, cool-climate favors the root rot of strawberries caused by Pythium species, and, fusarium wilt development is favored by high temperature (Mass, 1998).

5. Future Recommendations

- Impacts of climate change on the management of strawberry diseases
- Assessment of the efficacy of different botanicals in the management of strawberry diseases
- Development of resistant cultivars against the specific disease of strawberry
- Post-harvest management of strawberry diseases
- Non-chemical method of strawberry disease management for organic strawberry production
- Assessment of yield loss associated with different diseases of strawberry
- Participatory strawberry diseases identification and management

6. Conclusion

The commercialization of strawberries is gaining momentum worldwide. It is highly nutritious and also possesses medicinal value containing ascorbic acid, flavonoids, and phenolic acid. Nevertheless, its production is limited due to different fungal, bacterial, viral, and nematode diseases. The disease can cause significant yield loss. In this regard, approaches like cultural, biological, and chemical methods can be viable and sustainable approaches for integrated disease management. Fungal diseases infecting strawberries are botrytis gray mold rot, anthracnose, leaf spot, powdery mildew, red stele, crown rot, verticillium wilt, and black rot. Non-chemical management for them is using resistant cultivars, proper spacing, removal of infected plant/plant parts, soil solarization, removing crop debris, maintaining proper soil PH and drainage, and mulching. Different biocontrol agents like *Bacillus subtilis, Trichoderma harzianum,* and *Ampelomyces quisqualis* can be used for the management of fungal diseases. Similarly, a bacterial disease of Strawberry is an angular leaf spot that can be controlled by non-chemical methods such as the use of resistant varieties, destruction of plant debris, avoiding intercultural operations during high humidity, and avoiding sprinkler irrigation. Viral diseases associated with strawberry cultivation are strawberry mottle virus, strawberry mild yellow virus, crinkle disease, vein bending disease, pallidiopsis, and phytoplasma disease. Viral diseases can be controlled by using resistant varieties, destroying infected plants, controlling insect vectors such as aphids and whitefly. The problem of nematode is also serious in strawberries causing diseases like ring spot, lesion, and root-knot. They can be controlled by using tolerant cultivars like Sanibel, use of biocontrol agents like *Trichoderma sp.,* using well-decomposed manure, and soil application of garlic oil. Focuses should be given towards non-chemical control methods and chemicals can be used only in severe cases when all the other methods are not applicable for the management of that particular disease. This practice will help to maintain healthy soil and environment, cause less harm to the non-targeted organisms and ultimately help in effective and sustainable disease management of strawberries. Furthermore, climate change has caused several effects in the management of strawberry diseases. Diseases such as powdery mildew, grey mold, and black spot are becoming severe because of changing climate. Different economical approaches should be developed for the cultivation of strawberries under the protected condition to minimize the effects of climate change.

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