Journal of Agricultural Science; Vol. 12, No. 10; 2020
ISSN 1916-9752 E-ISSN 1916-9760
Published by Canadian Center of Science and Education

Hot Pepper Fusarium Wilt (*Fusarium oxysporum* f. sp. *capsici*): Epidemics, Characteristic Features and Management Options

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Received: June 13, 2020 Accepted: August 28, 2020 Online Published: September 15, 2020

doi:10.5539/jas.v12n10p347 URL: https://doi.org/10.5539/jas.v12n10p347

Abstract

Hot pepper (*Capsicum annum* L.) is one of the important cash crops to Ethiopian smallholder farmers and an important agricultural commodity which contribute to export earnings. In Ethiopia, this high value crop is constrained by powdery mildew, Phytophthora leaf blight, Fusarium wilt, bacterial leaf spot, bacterial wilt, bacterial soft rot and pepper motile virus. Among this diseases, wilt disease caused by *Fusarium oxysporum* f.sp. *capsici* (FOC) is one of the major pathogen that constrained production and productivity of hot pepper in Ethiopia mainly the Central Rift valley. In Ethiopia, hot pepper fusarium wilt is reported in all production regions in different magnitude. The highest wilt incidence due to fusarium is 90% in some Farmers association of Alaba districts in South Nation Nationalities and peoples of Ethiopia. The economic yield losses due to Fusarium wilt has been estimated at 68 to 71%. Infection and disease development in Fusarium wilt is favored by warm soil temperature, low soil moisture, susceptible host, virulent pathogen and 5.0 to 6.0 pH levels; are some of epidemic factors. Fusarium is reproduced by sexually by teleomorphs and asexually by microconidia, macroconidia and chlamydospore. From the Central rift valley of Ethiopia, 49 FOC isolates were identified based on micro and macroscopic characteristics and the isolate having pink colony color, 3-5 septa forming conidia on potato dextrose agar, perform the most pathogenic ability to Mareko Fana Variety. This pathogen has an over wintering stage called chlamydospore which can exist in the soil for more than ten years without the host. Hot pepper fusarium wilt can be managed by host resistance, biological agent, botanicals and fungicide. In Ethiopia, pepper screening for resistant source, in vitro evaluation of bioagents and fungicides were done. In this review attempt has been made to summarize relevant scientific studies on this economically important crop, hot pepper fusarium wilt and associated factors in Ethiopia as well as its different disease management options, challenges and future prospects.

Keywords: epidemics, Fusarium wilt, hot pepper, management options

1. Introduction

Hot pepper (*Capsicum annum* L.) is native to Latin America and belongs to the family *Solanceae* (Rodriguez et al., 2008). The exact time of pepper introduction to Africa in general and Ethiopia in particular is not known. Probably Portuguese had introduced hot pepper to Ethiopia in early 17th century (Huffnagel, 1961). Nowadays, pepper is produced as vegetable and spice nearly in most parts of Ethiopia and the southern Rift valley regions are the major production areas (Tameru, 2004; Berke, 2002). In Ethiopian, hot pepper is one of the cash crops to smallholder farmers and contributes to export earnings (Beyene & David, 2007). The nutritional value of hot pepper merits special attention. It is rich source of vitamin A, E and contains five to six times as much vitamin C as an orange or a lemon; this makes an ideal vegetable to prevent flu colds more than any other vegetable crop (Boselad & Votava, 2000). The average daily consumption of hot pepper by an Ethiopian adult is estimated to be 15 g which is higher than tomatoes and most other vegetables (MARC, 2004), indicating the significance of the crop in the country.

According to FAOSTAT (2017), a world average production of 32.3 t/ha green and 3.8 t/ha dry pepper have been reported. In Ethiopia, average dry and green hot pepper production is 1.6 t/ha and 10.7 t/ha, respectively (Abraham et al., 2016), which is far below the world's average. In 2018, the total area used for cultivation of green and red pepper in Ethiopia was 152, 7523 ha with an estimated total production of 2,647, 22.5 t. Interestingly, this data shows that hot pepper covers 73.1% of all the area under vegetables in Ethiopia (CSA, 2018).

Despite the importance of hot pepper in Ethiopia, total crop failure due to diseases has been common and sometimes farmers are forced to abandon their production due to excessive disease pressure in the field (Tameru et al., 2003). Among hot pepper diseases, Powdery mildew, Leaf blight, Wilt and *Pepper mottle virus* (BARC, 2000; Kassahun et al., 2016; Korobko et al., 1986) have been reported in Ethiopia. Recently, wilt causing pathogens are becoming the leading problems reported by causing 86.4% wilt incidence due to fusarium wilt in Ethiopia (Assefa et al., 2015). The stated diseases vary based on environmental, varietal and pathogen factors. Regarding fusarium wilt, its significance depends on host reaction, virulence level of the pathogen, soil type and soil micro-climate (Goldberg, 2010). For instance, high temperature and moisture play a great role for FOC epidemics (Sanogo, 2003). In Ethiopia, clay loam soil type was found to be favorable for fusarium wilt disease development (Assefa et al., 2015).

In plant disease management, there is a world-wide need to adopt the practice of sustainable agricultural strategies which is environment-friendly, less dependent on agricultural chemicals and less damaging to soil and water resources. Regarding fusarium wilt, effective means of control in general include the use of soil disinfestations and resistant/tolerant plant materials. In particular, the management options so far recommended for the control of fusarium wilt of pepper in Ethiopia include the use of crop rotation, fallowing, resistant varieties, and in the severe cases application of chemicals (EARO, 2004). Nevertheless, these management options should be evaluated to be applicable and bring tangible changes to the end users. The use of resistant varieties is the best strategy for disease control and one of the most effective alternative approaches to control wilt diseases (Sheu et al., 2006). This paper discusses the Fusarium wilt disease and the pathogen, Epidemics, management options and prospects to improve research methods in systemic pathogens.

2. Fusarium Wilt of Hot Pepper and Associated Factors in Ethiopia

Hot pepper production and productivity is in decreasing trend even though it is a highly profitable commercial spice and vegetable crop. Currently production of pepper is under severe threat by several biotic and abiotic factors. Improper agronomic practices and inappropriate use of fertilizers lead to the low yield of chilli (Jack et al., 2006). These problems are causing major issues with the supply of pepper and threaten the sustainability of farmer livelihood as reported by (Thijs, 2010).

Table 1. Important diseases of hot pepper in Ethiopia, 2018

Disease	**Causal pathogen**	**Reference**
Powdery mildew	*Leveillula taurica*	Mengistu (1994)
Anthracnose	*Colletotrichum gloeosporioides*	Fekadu and Dandena (2006)
Fusarium wilt	*Fusarium oxysporum*	BARC (2000)
Root rot	*Rhizoctonia solani, Fusarium* spp.	BARC (2000)
Verticillium wilt	*Verticillium* spp.	BARC (2000)
Phytophthora blight	*Phytophthora capsici*	BARC (2000)
Bacterial leaf spot	*Xanthomonas campestris*	Fekadu and Dandena (2006)
Bacterial wilt	*Ralstonia solanacearum*	Fikre (2006)
Virus	*Pepper mottle virus*	Bos (1974)

Note. BARC: Bako Agricultural Research Center.

In Ethiopia among hot pepper diseases, fungi caused by *Fusarium* spp., *Phytophthora* spp., *Rhizoctonia solani* and *Cercospora capsici* (Shiferaw & Alemayehu, 2014); bacterial diseases caused by *Ralstonia solanacearum* (Kassahun et al., 2016) and viral disease caused by *pepper mottle virus* have been reported as major ones (Korobko et al., 1986). The most recent report by Gabrekiristos (2020) indicates that, in the Central Rift valley of Ethiopia, Farmers respond, the production of hot pepper is threaten by 'Adriq' means dry and 'Ametmet' means softening for about twenty years. The terms are Amharic and associated with the symptom caused by Fungi and bacteria respectively.

3. *Fusarium oxysporum* f. sp. *capsici*

Causal agent: Fusarium wilt disease, caused by the soil-borne fungus, *F. oxysporum* f. sp. *capsici* is the most important disease on hot pepper that reduces growth, fruit yield and quality (Sahi & Khalid, 2007; Wongpia & Lomthaisong, 2010). The pathogen causes vascular wilt on large variety of economically important crops worldwide (Ortoneda et al., 2004). This fungus is a necrotrophic, soil-borne with worldwide distribution in tropical to sub-tropical areas (Booth, 1971).

F. oxysporum f. sp. *capsici* was found to be specific to vascular wilt of bell pepper (Black & Rivelli, 1990). The teleomorphs/sexual type of *Fusarium* species are mostly classified in the genus *Gibberella* and for a smaller number of species; *Hemanectria* and *Albonectria* genera are the teleomorphs (Moretti, 2009). While all strains are capable of saprophytic growth, some are pathogenic to different plant species, resulting in wilts, crown, and root rots (Burgess, 1981). Pathogenic strains typically are extremely host specific and are classified into > 150 formae speciales based on the plant host(s).

3.1 Morphological Characteristics

Morphological characteristics are by far and away the most commonly used criteria for identifying *Fusarium* species. Macro-conidia are the single most important cultural character in the identification of *Fusarium* species. In many cases the morphology of this spore alone is sufficient to identify a culture to species. Kelaniyangoda et al. (2011) reported that white to pink color colony of the culture and macroconidia were hyaline and sickle shaped on potato dextrose agar (PDA). The colony color of *Fusarium* varies from white to pink and the hyphae are septated and branched (Kaushal, 2016). Similarly, Endriyas et al. (2019) reported that, out of 49 FOC isolates, 35 (71.4%) had Pink colony color and the remaining 14 isolates (28.6%) had white colony color on PDA. Ferniah et al. (2014) reported that, morphological characters of *F. oxysporum* with white cottony aerial mycelium and purple on the reverse side with 4-5 cm diameter at 5 days incubation on potato dextrose agar. The hyphae of fusarium are septated, branched and produce microconidia, macroconidia and chlamydospores (Endriyas et al., 2019). The micro- and macro-conidia are formed externally on hypha-like conidiophore, which categorizes *Fusarium* as a Hyphomycete. Chlamydospores are formed single or in pairs from normal hypha which undergoes increased growth and thickening of their cell wall (Nelson et al., 1994). Conidia were grown from short phialid with a false head. Macroconida were straight fussiform, pedicellate basal cell, 3-5 septate. Microconidia were abundant, ellipsoid or fussiform without or with 1-2 septa.

3.2 Geographical Distribution

Fusarium spp is distributed not only to tropical and temperate regions but these are also reported in harsh climatic conditions like desert, alpine and arctic areas (Nelson et al., 1994). Their widespread distribution may be due to their ability to colonize diverse ecological niches in most geographical areas of the world.

Pepper Fusarium wilt was first reported in New Mexico (Leonian, 1919), It was also reported from Pakistan (Kamal & Moghal, 1968; Hafiz, 1986), Avery Island, Louisiana (Black & Rivelli, 1990), Central Java (Agrios, 2005) and Spain (Serrano-Alonso et al., 2014). FOC is the major devastating and destructive disease, affecting production of pepper in Egypt (Attia & Abada, 1994). In India, occurrence of Fusarium wilt in bell pepper and chilli has been reported in various parts of country and causes up to 25 per cent losses (Madhukar & Naik, 2004). Naqvi (2004) reported 35 percent wilt incidence in many states of USA and it is also reported that after 30 days of soil infestation, *Fusarium oxysporum* kills 56% chilli seedlings (Mona et al., 2012). The yield loss due to the disease is known to vary from 10-80 percent worldwide (Loganathan et al., 2013).

3.3 Current Status of Fusarium Wilt in Ethiopia

Currently hot pepper fusarium wilt is big agenda for researcher, Agricultural expertise at different level and Farmers having long experience in pepper production. There is variability among pepper wilt in district and region wise. Regarding the variation of hot pepper fusarium wilt, within and across districts, relatively higher incidence [maximum ≥ 50%; 90.5% (Alaba), 79.4% (Meskan), 63.6% (Mareko), 50% (Dugda) and 50% (Adama)] has been recorded in all districts of the Central Rift Valley of Ethiopia except Adami Tullu Jiddo Kombolcha districts which had a maximum HPFW incidence of 19.4% (Gabrekiristos et al., 2020). Wilt disease caused by Fusarium is the leading one having wide distribution wherever pepper is produced in Ethiopia. The most recent report on pepper fusarium wilt at district level in Ethiopia indicated, 46.5% in Mareko, 46.0% in Alaba, 42.9% in Meskan, 40.0% in Adama, 30.9% in Dugda and 15.1% in Admi Tullu Jiddo Kombolcha (Gabrekiristos et al., 2020). Wilt disease of hot pepper caused by *Fusarium* spp have been reported in Bako and Nejo areas (BARC, 2000). Fusarium wilt has been known to account the losses up to80% around Dugda (Shimeles et al., 2007).

In Ethiopia relative yield loss of 68-71% was obtained due to the effect of fusarium wilt from un-treated Marako-fana variety (Teshome et al., 2012). Further more recent study by Shiferaw and Alemayehu (2014) indicated that the occurrence of fusarium wilt was the highest at Abeshge (55%) followed by Halaba (41%), Hawassa zuria (36%), Dalocha (32%) and Lanfro (30%) and in other location mainly western Ethiopia (Assefa et al. 2015) reported 86.4% wilt incidence. This report indicates that there is variation in level of infection and wilt causing pathogens in different localities of Ethiopia. Wilt causing pathogen of pepper is common problem in Amhara Region now days (personal communication, 2018).

3.4 Symptoms of Fusarium Wilt on Pepper

Most of wilt causing pathogens including fusarium wilt of pepper have Primary and secondary symptom.FOC infects plant from roots and grow from inside towards the cortex (Beckman, 1987). Symptoms are quite variable but wilting of plant parts as a consequence of xylem dysfunction is the most conspicuous symptom of vascular wilt disease. The wilting symptoms appear as a result of severe water stress, mainly due to the vessel plugging/occlusion. Primary symptom of the pathogen is brown vascular discoloration followed by upward and inward rolling of the upper leaves and subsequently wilting of the plants is as secondary symptom (MacHardy & Beckman, 1981; Rivelli, 1989).

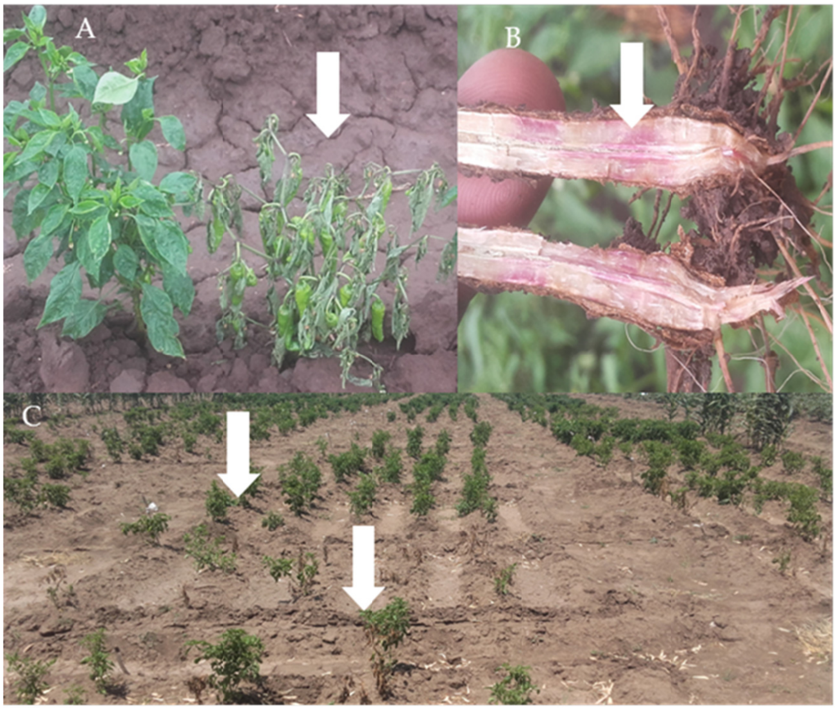

Figure 1. Symptom of hot pepper Fusarium wilt; A: wilted plant due to Fusarium wilt; B: stem discoloration, C: Severely infected plot due to FOC

Source: Endriyas (2018) (unpublished).

Symptoms of Fusarium wilt first appear as slight vein clearing on the outer portion of the younger leaves, followed by epinasty (downward drooping) of the older lower leaves. Slight yellowing of lower leaves and wilting of upper leaves followed by permanent wilting of entire plant and browning of the vascular tissue are the characteristic symptoms of the disease (Smith et al., 1988; Black & Rivelli, 1990). The most common symptoms caused by *F. oxysporum* infection included leaf chlorosis, vascular discoloration, wilting of the plants, root rot, crown rot, stunting, wilting and death of the plants (Lefebvre & Palloix, 1996). At the severe infection the lower leaves wilt and drop, which leads to decrease the number of leaf per stem this leads to bare stems.

3.5 Ecology and Epidemiology

Environmental conditions like temperature, spore density and water potential influence the germination of *Fusarium* conidia (Stakheev et al., 2011). Foc is a typical soil-borne pathogen and the fungus survives for long period of time in the soil in the form of chlamydospores (Garret, 1960). *Fusarium* spp. produces different types of spores, *i.e.*, macro-conidia, micro-conidia and chlamydospores (Nelson et al., 1981), which act as asexual spore and help in survival of the pathogen. Spore production is triggered by the factors like nutrient sources, lights, metals, lipid signals and the chemistry of the plant host (Brodhagen & Keller, 2006). The optimum growth of the genus *Fusarium* is found between 25 to 28 °C, while the maximum growth is generally obtained at 28 °C, inhibited above 33 °C and not favored below 17 °C (Cook & Baker, 1983). High temperature and high moisture plays a significant role in disease development (Sanogo, 2003). Fusarium wilt disease significance also varies with host susceptibility, pathogen virulence, soil type, and environmental conditions (Goldberg, 2010). The pathogen enters the plant through root tips and can remain viable in the soil for up to 30 years (Sally et al., 2006; Thangavelu et al., 2003). The mycelium grows in the xylem vessels where they cut off water supply resulting to wilting (Stephen et al., 2003). There is often an association of *Fusarium* wilt and nematode colonization where the nematodes provide entry route for the fungus. Enzymes may also facilitate *Fusarium* penetration into plant host (Babalola, 2010).

Infection and disease development in *Fusarium* wilt is favored by warm soil temperature and low soil moisture (Lewis, 2003). The disease tends to be most severe in sandy soils and generally less of a problem in heavier clay soils (Larkin et al., 2002) but in Ethiopia type of soil texture with high disease intensity was observed on the clay loam soil this might be due to high water holding capacity that may indirectly favor wilt causing pathogens in the area (Mekonnen et al., 2015). The effect of pH has been shown to influence the growth and sporulation of *Fusarium* spp. and most suitable pH level for growth of fungus was 5.0 and 6.0 (Gangadhara et al., 2004).

Table 2. Relationship between soil characteristics and fusarium wilt incidence, 2018

Soil Factor	Favoring condition	Reference
Soil texture	Sandy soil	Larkin et al. (2002)
Soil temperature	25 to 30 °C	Tu (1994)
Air temperature	25 to 30 °C	Kumar et al. (2012)
Soil moisture	20%	Sekhon and Singh (2007)
pH	5.0 to 6.0	Gangadhara et al. (2004)

3.6 Disease Cycle

Fusarium wilts are generally presumed to be monocyclic because, the disease does not exhibit plant-to-plant spread during the season (Egel & Martyn, 2007). This is primarily because there are no propagules capable of dissemination to other plants to cause secondary infections that form above ground until very late in the season. There is some evidence that suggests some *Fusarium* wilts, for example, *Fusarium* wilt of tomato, may be a polycyclic disease capable of significant secondary spread during the season (Egel & Martyn, 2007).The life cycles of most *Fusarium* wilts are similar and resemble that of the *Fusarium* wilt of tomato (Agrios, 2005). Like that of *Verticillium* wilt, the life cycle of *Fusarium* species can be divided into dormant (resting stage), parasitic and saprophytic stages when the host is absent (Beckman, 1987). The dormant stage comprises inhibition and germination of resting structures in soil. Report by Endriyas (2019), indicated that chlamydospore is formed in the petri-plate when there is scarcity of medium. Report by Garret (1960), indicates that fusarium wilt is extremely adaptable, variable and capable of long persistence in soil in the form of chlamydospores.

The parasitic stage comprises penetration, colonisation of the root cortex and endodermis, colonisation of the xylem of stems and leaves, symptom expression and, later on, death of the host.

Fusarium species enter the parasitic phase when germ-tube (Appressorium) of spore, penetrates the host through cracks formed by emerging lateral roots, wounds or at the root cap, root hairs or branch roots (Mandeel, 2007). Penetration process increases by certain hydrolysing enzymes secreted by *Fusarium* (Walter et al., 2009). Stover (1970) also reported that mycelial growth and cell wall degrading enzymes and toxins produced by the pathogen may contribute to vascular occlusion, which leads to the development of a systemic vascular disease in the host plants. There has been report by Morrell and Bloom (1981), on association of *Fusarium* wilt and nematode colonisation, where the nematodes provide a potential entry point (wound) for the fungus.

3.7 Spread Method of Pepper Fusarium Wilt

Depending on the species, *Fusarium* can be dispersed by one of several means including the movement of contaminated seed, corms and bulbs; water-borne and wind-borne soil; and in infected cuttings and transplants. This pathogen spreads in two basic ways: it spreads short distances by water splash, and by planting equipment, and long distances by infected transplants and seeds. Spores are disseminated by the wind, in ground water, or by movement of the contaminated soil, stake, or equipment (Jaywant, 2016).

4. Host Range of *Fusarium oxysporum*

Fusarium oxysporum is the most widespread and destructive species causing vascular wilt diseases on many plants including pepper (Mushtaq & Hashmi, 1997).The pathogen is known to cause severe losses to a large array of agricultural crops such as tomato (*Lycopersicon esculentum* L.), banana (*Musa acuminata* Colla), cabbage (*Brassica oleracea* var. *capitata* L.), pea (*Pisumsativum* L.), chickpea (*Cicer arietinum* L.), water-melon [*Citrullus lanatus* (Thunb.) (Matsum & Nakai)], cotton (*Gossypium hirsutum* L.) and spinach (Hungerford, 1923; Nelson, 1981; Padwick, 1940). Other commercially important plants affected include basil, beans, carnation, chrysanthemum, peas and watermelon. Woody ornamentals are infected, but are usually not killed by Fusarium wilt alone. Palms, however, are the exception, and there are many species that can die from *F. oxysporum* infection (Dreistadt & Clark, 2004). Pathogenic strains within the species have a limited host range, and strains with similar or identical host ranges are assigned to the same formae speciales (Armstrong, 1981). *Fusarium oxysporum* was found in association with the wilt disease of *C. annuum* (Kraft & Papavizas, 1983; Kucuk & Kivanc, 2003; Siddiqui & Akhtar, 2007). The high level of host specificity of pathogenic strains in *F. oxysporum* led to the development of the “formae specials” concept to enable better differentiation of these morphologically similar strains (PADIL, 2011).

5. Mechanism of Infection

Once Foc is inside the plant, the mycelium grows through the root cortex intercellulary and when it reaches the xylem, it invades the vessels through the xylem's pits (Agrios, 1988). Due to the growth of the fungus within the plant's vascular tissue, the plant's water supply is greatly affected and this results the leaves' stomata to close, the leaves wilt, and the plant eventually dies. It is at this point that the fungus invades the plant's parenchymatous tissue, until it finally reaches the surface of the dead tissue, where it sporulates abundantly. The resulting spores which on their turn act as new inoculum for further spread of the fungus (Agrios, 1988). Vascular wilt pathogens satisfy their nutritional requirements by efficiently acquiring the scarce nutrients available in the xylem sap, by enzymatic digestion of host cell walls, by invading neigh-boring cells, or by inducing nutrient leakage from surrounding tissues (Divon et al., 2005; Mobius & Hertweck, 2009; Klosterman et al., 2011). Nitrogen is one of the limiting nutrients in the xylem sap for vascular wilt pathogens (Divon et al., 2005). The fungus can invade a plant with its sporangial germ tube or mycelium by invading plant roots, through wounds or directly through the root tip or at the formation point of lateral roots (Koste, Thomma, & Bart, 2013).

6. Management Options

Attempts to contain and minimize the diseases caused by Fusarium wilt has been made by using various kinds of control measures in the greenhouse and the field conditions. An important point to remember is that the control procedures should be applied before planting because there are no rescue treatments. Moreover, once the disease becomes existent, an important part to minimize the losses is to avoid stress on the plants (Ozbay et al., 2004). Wilt causing pathogens can be managed by cultural, biological, chemical means and by screening of germplasms/lines for resistance (Mamta et al., 2012). It is also reported that effective means of controlling *F.oxysporum* include: disinfestation of the soil and planting material with fungicidal chemicals, crop rotation with non-hosts of the fungus, or by using resistant cultivars (Jones et al., 1982; Smith et al., 1988). It is observed that application of fungicides is a quick method to manage Fusarium wilt disease but fungicides are not eco-friendly and adversely affected human beings, microorganisms and environment with its toxic residues (Parker et al., 1985) and also, it has been observed that pathogen has developed genetic resistance against the fungicides (Sela-Buurlage et al., 2001). In Ethiopia the use of crop rotation, fallowing, resistant varieties, and in the severe case application of chemicals is stated options to manage pepper fusarium wilt (EARO, 2004).

6.1 Host Resistance

Host plant resistance has been a choice in all crop improvement programs and it is perhaps the best method available to tackle soil-borne diseases.Use of genetic resistance for the management of pepper diseases in general and fusaruim wilt in particular is the simplest and most cost-effective method (Sanogo, 2003). When dealing with soil-borne diseases, cultivar resistance is the preferred method for control because it can be highly effective and is the least damaging to the environment (Fravel et al., 2003).

Research in Ethiopia by Endriyas et al. (2020) indicated that, performance of ACC 80061 and Oda Haro under infection with the highly potent isolate 4DGK was promising. In Ethiopia Significantly, ($P \leq 0.05$) lowest wilt (4.66%) incidence and AUDPC (279%-day) were obtained by integration of the moderately resistant variety Oda-haro with solarization-fungicide-flat seedbed (Teshome et al., 2012). This finding is good indication for the screening of hot pepper cultivar for their reaction to fusarium wilt. Thus, currently available pepper cultivars should be tested for the identified wilt causing pathogens (Mekonnen et al., 2015).

Screening of genotypes/hybrids is an important aspect in resistant breeding program for the management of soil-borne diseases worldwide, especially against *Fusarium* wilt disease of economically important several crops (Ahmed et al., 1994; Nayeema et al., 1995; Madhukar et al., 2002; Naik et al., 2008; Morid et al., 2012; Purna, 2013; Kumar et al., 2014; Shafique et al., 2015). Studies by Mamta et al. (2012) indicates that, Among thirty varieties screened, only two varieties CO-4 and DLC-352 were found 100% resistant, while five varieties, *viz*., Ajeet-3, DLC-524, F-112-5-83, KCS-2013 and Nun-2060 of hot pepper were moderately resistant (83.34). Jaywant et al. (2017) screened chili genotype against fusarium wilt and cultivar CO-4 showed resistant reaction (6.67% wilt), however, six cultivars *viz*., HC-1, GC-1, GC-2, Kashi Gaurav, Ajeet-6 and DKC-8 were moderately resistant (15.56 to 24.44% wilt), whereas, three cultivars *viz*., Pant C-1, Punjab Lal, Kashi Sinduri were moderately susceptible (33.33 to 48.99% wilt) and the remaining twelve cultivars were either susceptible (> 50% wilt) or highly susceptible (> 75% wilt), which could not survive against the pathogen.

6.2 Use of Antagonists

The different mechanism of bio-control of plant pathogens using antagonists may be through competition for space and food or by stimulating host plant by inducing tolerance or resistance to the pathogen, or antibiosis that means production of low molecular fungi toxic compounds or enzymes (Matar et al., 2009). Singh and Zaidi (2002) reported that some bioagent enhanced the growth of some crop species. Use of antagonistic species is environmentally oriented, ecologically and economically sound method as depicted in benefit/cost ratio and expresses less environmental haphazard and toxicity as compared to other conventional disease controlling methods. Now a day’s biological control is considered as an important approach of agricultural biotechnology in recent years for controlling many fungal plant pathogens (Zaher et al., 2013, Abada & Eid, 2014).

In Ethiopia, *in vitro* antagonistic evaluation to manage 4DGK isolate results; *T. Asperellum* provided the highest growth inhibition (85.2%) followed by *T.viride*, *T.longibiracher* and *T. harzianum,* which reduced mycelial growth up to 80.4%, 77.6% and 77.3%, respectively (Endriyas, 2020).

Fusarium genera were diverse in species and even some strains of *Fusarium oxysporum* are not pathogenic and may even antagonize the growth of pathogenic strains and can be used as biological agents (Fravel et al., 2003). Singh and Zaidi (2002) reported that root dipping in antagonists (*i.e.*, *Trichoderma* spp.) suspension (10^6 cfu/ml) not only reduced the rate of disease severity but also enhanced the seedling growth in rice, tomato, brinjal, chilli and capsicum which is double advantage. Sahi and Khalid (2007) reported that among the *Trichoderma* species, *T. viride* showed the best performance (62%), followed by *T. harzianum* (36%), *T. aureoviride* (24%), *T. koningii* (18%) and *T. pseudokoningii* (6%) in reducing the colony growth of *F. oxysporum* in sweet pepper (*Capsicum annuum*). Oyetunji and Salami (2011) observed the effect of arbuscular mycorrhiza (AM) (*i.e.*, *Glomus mosseae*) and *Trichoderma koningii* as antagonists against Fusarium wilt of pepper. Amaresan et al. (2014) investigated the antagonistic potential of endophytic bacteria against *Fusarium oxysporum* and the results revealed that most of the isolates showed antagonistic activity against *F.oxysporum*. A combination of *T. herziamnum*, *T. asperellum* and *T. virens* has the highest capacity of control (80-87%), followed by a binary combination of *Trichoderma* species (79-82%), while *T. virens* alone has the lowest control rate of 65% (Akrami & Yousaefi, 2015).

6.3 Botanicals

Botanicals show antifungal activity against a large number of fungal diseases (Javaid & Rauf, 2015). The plant extracts provide an effective measure for Fusarium wilt disease management and it can be one component of integrated disease management. The fungitoxic properties of different plant extracts against *Fusarium* spp. have been investigated by Shivpuri et al. (1997) and the results indicated that the maximum inhibition (80-85%) of the pathogen was observed with *Allium sativum* and *Allium cepa*. Singh and Kumar (2011) reported that the soil treatments with botanicals *viz*., *Mentha arvensis* significantly reduced the *Fusarium* wilt of *Chrysanthemum* with the maximum (70.0%) disease control, followed by *Tagetus patula* (61.0%) and *Datura stramonium* (50.0%). The botanicals like garlic oil was highly effective (100%) even at 5 per cent concentration, whereas, neem oil was comparatively less effective (59.63%) at 5 percent concentration (Jaywant, 2016). It is also reported that mustard oil (93.75%) and *Datura* (90.94%) reduce the growth of fusarium wilt *in vitro*. Among other management options use of botanical can be a solution for wilt causing pathogens and garlic shows 100% control of fusarium wilt which should get due attention.

6.4 Fungicides

Use of pesticides is an important tool for managing different diseases including soil-borne pathogens. Various systemic and non-systemic fungicides have been reported effective against the fungus. Evaluation of carbendazim and benomyl under *in vitro* and *in vivo* by soil drenching at different depths *viz*., 5, 10 and 15 cm (Naik et al., 2007) which resulted maximum inhibition of Fusarium wilt disease in pepper. Sharma et al. (2002)

studied inhibitory effect of carbendazim, copper oxychloride, captan and metalaxyl + mancozeb (Ridomil) against *F. oxysporum* and other pathogens associated with wilt disease of bell pepper under *in vitro* conditions and reported that carbendazim (Bavistin) and captan completely inhibited the growth of fungus. Fungicides such as Ridomil Gold, Carbandazim, Metalaxyl and Mancozeb are being used to control the *Fusarium* wilt (Sitara & Hasan, 2011). The increased use of pesticides in past has led to several problems, such as environmental degradation, health hazards, pest resistance and decrease in population of beneficial insects (Groenewald, 2006). So, pesticide should be used in safe and care method to decrease the hazard occurred on human and environment.

To manage soil borne pathogens through fungicide is not practiced in Ethiopia. Some effort was made to *in vitro* evaluate fungicides having different group of active ingredient (Gabrekiristos & Ayana, 2020). The recent finding by Gabrekiristos and Ayana (2020) indicates, URGI 75% WP, Nativo SC 300 and Twinstar75 WG led to 98.8%, 94.0% and 92.3% mycelia growth inhibition, respectively (Gabrekiristos & Ayana, 2020). This can be good news to Ethiopian hot pepper producer. The Master isolate, 4DGK were used since the isolate showed as highly pathogenic to Marako Fana variety and some fungicides are not effective in inhabiting. So, Mancodex Super 72 WP (2.9%) and Agro Laxyl MZ 63.5 WP (6.5%) that was not effective in inhibiting the mycelial growth of hot pepper fusarium wilt (Gabrekiristos & Ayana, 2020). Gabrekiristos stated that, URGI 75% WP (Carbendazim and Mancozeb; 120+640 g/Kg), inhibit *in vitro* mycelial growth of FOC and it can be use to evaluate *in vivo*.

7. Conclusions and Future Prospects

Hot pepper serves as important sources of income to smallholder farmers and as exchange earning commodity in Ethiopia. It is a rich source of vitamin A, C and E. This crop is grown in many regions of Ethiopia and is an important ingredient for some of the most famous dishes of Ethiopian cuisine and besides its popularity; pepper can be used as raw material for extraction of oleoresin capsicum and paprika by the Ethiopian Spice Extraction Factory.

It is summarized that, in Ethiopia this high value crop is constrained by powdery mildew, Phytophthora leaf blight, Fusarium wilt, bacterial leaf spot, bacterial wilt, bacterial soft rot and *pepper motile virus*. Wilt disease caused by *Fusarium oxysporum* f.sp. *Capsici* is the top pathogen and reported from where ever pepper is produced in the country. Fusarium wilt is the major constraint causing high damage in Oromia, South Nation Nationalities and peoples and Amhara regions of Ethiopia. Within and across districts, relatively higher incidence [maximum ≥ 50%; 90.5% (Alaba), 79.4% (Meskan), 63.6% (Mareko), 50% (Dugda) and 50% (Adama)] has been recorded in all districts. The occurrence of hot pepper fusarium varies based on host susceptibility, virulent pathogen and environmental condition.

This review concludes that, wilt causing pathogens can be managed by cultural, biological, chemical and by Screening of germplasms/lines for resistance. Endriyas et al. reported that, performance of ACC 80061 and Oda Haro under infection with the highly potent isolate 4DGK was promising. In Ethiopia, *in vitro* antagonistic evaluation to manage 4DGK isolate results; *T. Asperellum* provided the highest growth inhibition (85.2%) followed by *T. viride*, *T. longibiracher* and *T. harzianum,* which reduced mycelial growth up to 80.4%, 77.6% and 77.3%, respectively. Gabrekiristos stated that, URGI 75% WP (Carbendazim and Mancozeb), inhibit *in vitro* mycelial growth of FOC up to 98.8% and it can be used after evaluating *in vivo*.

It is recommended that, hot pepper materials should pass through quarantine system to the county. Varietal screening should be intensively done to replace susceptible one and Country wide survey is important for early detection. Integrated disease management strategies should have to be developed by using compatible management options. Grafting hot pepper for control of wilt causing pathogens is common in European countries, which should have to be practiced in Ethiopia. Studies on epidemiological element should have to be conducted to easily break the wilt epidemics.

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