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Review Article

Review on the Management of Fusarium Wilt (*Fusarium oxysporum)* Common Bean (*Phaseolus vulgaris* L.) through Integration of Cultural Practices, Host Plant Resistance and Fungicides

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Abstract

Common bean (Phaselous vulgaris L.) is one of the most important and stable legume crops worldwide. However, its production and productivity is limited by various factors, among these, diseases are largely devastating this crop over the world. From diseases, fusarium wilt caused by fusarium oxysporum, can have a severe economic impact on common bean fields. It is a widely distributed soil pathogen causing vascular wilt and overwinters as a saprophyte in soil or in plant debris that persists in the soil and remains viable for many years, or even in roots of some non-host plants. Successful disease management of susceptible cultivars is hardly achieved and there are few effective practices recommended for this disease, including host plant resistance. Chemical fungicides are not effective for vascular wilts since they do not prevent further root infection and phloem colonization by the pathogen and cultural practices help to prevent but not to eradicate the infestation. In this review article effort has been done to recap important scientific studies and its different disease management options including integrated disease management options. Because, there is no effective control measure solely against the target pathogen so far.

Keywords: *Control, Pathogens, Soil-borne, Species, Variability*

1. Introduction

Common bean (*Phaselous vulgaris* L.) is one of the most important legume crops worldwide, being the third most produced legume after soybean and peanut (Porteous-Alvarez *et al*., 2020). The harvested area of beans has steadily increased in the last few decades, from 23 million hectares in 1999 to 36 million hectares in 2017 (Neupane *et al*., 2022). It is considered a rich source of essential nutrients and proteins and in Africa and Latin America, more than 200 million people depend on this crop as a staple food (Batista *et al*., 2017). As a legume crop it is very treasured as it is capable, due to its association with some bacterial species of the genus *Rhizobium*, of fixing nitrogen to the soil (Porteous-Alvarez *et al*., 2020). However, it is affected by a variety of pests and diseases caused by bacteria, fungi, and viruses, some of them resulting in important economic losses (Porteous-Alvarez *et al*., 2020). One of the fungi affecting this and many other crops is *Fusarium* spp. (Porteous-Alvarez *et al*., 2020), a filamentous fungus that belongs to the phylum Ascomycota. *Fusarium* is a genus of ascomycete fungi that includes important plant pathogens and mycotoxin-producing contaminants of human and animal food (Sampaio *et al*., 2020). Wilts, blights, root rots and cankers are among the plant diseases symptoms caused by this genus and its distribution covers soils and organic substrates all over the world (Sampaio *et al*., 2020).

The species *Fusarium oxysporum* is well represented among the communities of soil-borne fungi, in every type of soil all over the world (Burgess, 1981). It was first identified on common bean in the USA in 1929 and has been classified as *F. oxysporum* f. sp. phaseoli (abbreviated *Fop*) (Xue *et al*., 2015). It has been detected in most of the bean-growing regions in Africa, East Asia, Europe, Latin America, and the western United States (Buruchara and Camacho, 2000). Fusarium wilt can have a severe economic impact on common bean fields from seedling up to pre-harvest stages (Toussoun and Marasas, 1983).

The disease is favored by mild temperatures and high soil moisture and can lead to yield reductions of 80% in susceptible common bean cultivars (Carvalho *et al*., 2015). It is also a problem in many other intensively cropped areas of the world, especially as high moisture (high rainfall and heavy rains, excessive irrigation or poorly drained fields) become more frequent early in the season with climate change and weather variability (Carvalho *et al*., 2015; Xue *et al*., 2015). Infested seeds and agricultural machinery are the main means of dissemination of the pathogen (Xue *et al*., 2015). In infested soils, diseased plants first appear in small patches, which tend to increase in the following cropping seasons. The infested area gets larger and may expand throughout the entire field in properly uncontrolled (Carvalho *et al*., 2015). Under favorable conditions, pathogen spores can be observed in the stem of the dead plant. In the field, the disease results in shortening of the life cycle, seed size and yield and ultimately leads to plant death (Buruchara and Camacho, 2000). The pathogen survives as a saprophyte in soil or in plant debris in the form of chlamydospores (dark, thick-walled resistant structures) that persist (long-term survival) in the soil and remain viable for many years, or even in roots of some non-host plants (Toledo-Souza *et al*., 2012; Carvalho *et al*., 2015).

After the pathogen is disseminated into a new area, disease control is restricted to crop rotation (Dhingra and Coelho-Neto, 2001). An important preventive management tool for reducing the spread of pathogens into new regions is accurate seed health testing (Mbofung and Pryor, 2010). Successful disease management of susceptible cultivars is hardly achieved and there are few effective practices recommended for this disease including host plant resistance (Carvalho *et al*., 2015). Current management of these diseases in the field relies on chemical seed treatment, other localized treatments, or cultural practices (Toussoun and Marasas, 1983). These strategies have not completely solved the problem, as the use of chemicals is rarely cost-effective and cultural practices help to prevent but not to eradicate the infestation. Thus, combining the compatible two or more methods to control fusarium wilt on common bean as an integrated disease management (IDM) is a paramount method against the disease. The current research work was a review of the efforts made in different aspects related to the IDM practices through cultural practices, host resistance and fungicides applications against fusarium wilt of common bean.

2. Literature review

2.1. Occurrence and importance of fusarium wilt

The importance of *fusarium* species is mostly estimated through damages that they cause either by destroying crops, grain, nursery plants, stored fruits, finished products, processed products, or by causing the decrease in the live-stock production or death of animals, human diseases, etc. (Levic *et al*., 2009). The majority species of the genus *fusarium* are capable of causing diseases (mycoses) in plants, animals and humans or mycotoxicoses in animals and humans (Levic *et al*., 2009). Among the wide range of plant species infected by *F. oxysporum* are tomato, banana, melon, cotton and legumes crops (Michielse *et al*., 2009). Grain and forage legumes account for 27% of the world's primary crop production behind cereals and oilseeds crops (Vance *et al*., 2000). Their cultivation is over 12 to 15% of Earth's arable land, highly impacting agronomy, the environment and human and animal nutrition and health (Azooz and Ahmad, 2015). However, the yield of most legume crops is still limited and unstable due to environment adaptability challenges and susceptibility to pests and diseases (Rubiales *et al*., 2015). One of these diseases is fusarium wilt, which promotes devastating damages in several legume species worldwide (Williams *et al*., 2016). As an example, *F. oxysporum* f. sp. pisi is considered a destructive pathogen of field pea, and is reported in every country where field pea is grown (Sampaio *et al*., 2020). In the most consumed food grain legume, common bean, *Fop* is among the most important diseases affecting its production worldwide (Sampaio *et al*., 2020).

2.2 Biology and epidemiology of the fusarium wilt

Because telomorphic stages of most *Fusaria* are unknown, *Fusarium* taxonomy has been based on morphological characteristics of the anamorph, including the size and shape of macroconidia, the presence or absence of microconidia and chlamydospores, colony colour, and conidiophore structure (Singleton *et al*., 1992). The difficulty in delineating species based on these features is evidenced by the many different systems that have been proposed, recognizing anywhere from 30 to 101 species (Nelson *et al*., 1983). Many of these taxonomic schemes group the species into sections. *Fusarium oxysporum* is an anamorphic species identified by morphological criteria shared by both pathogenic and nonpathogenic strains (Bao *et al*., 2002). In the simplest form, 2 hyphae can fuse in anastomose and form a stable heterokaryon. This strain can be vegetatively compatible and in the same vegetative compatibility group.

Fusarium oxysporum, a ubiquitous soil-borne pathogen that promotes vascular wilt in a wide range of plant species, is one of the most common species (Agrios, 2005). It represents one of the most important diseases of common beans worldwide and impacts the bean-producing areas of several countries (Toledo-Souza *et al*., 2012; Xue *et al*., 2015). The pathogen has asexual reproduction, which leads to little potential for gene flow and a low mutation rate, being considered a pathogen with low genotypic diversity (McDonald *et al*., 2002). In the absence of a host, *F. oxysporum* can survive extended periods in the soil as chlamydospores (Agrios, 2005). In the presence of a host, the infection cycle starts and fungal spore's germination and elongation happen towards host plant roots in response to specific plant signals (Turra *et al*., 2015). Root penetration occurs without the formation of specialized structures through the natural openings at the intercellular junctions of cortical cells or through wounds (Perez-Nadales and Di Pitro, 2011). Once inside the root, hyphae invade the root cortex, penetrate the endodermis, reaching the xylem vessels. Then, the fungus progresses vertically through the xylem, where it moves and multiplies, colonizing the host until a complete plant wilt (Agrios, 2005; Sampaio *et al*., 2020). Upon plant death, the fungus starts a profuse sporulation on the plant surface, dispersing micro- and macroconidia on the soil for the next cycle of infection (Agrios, 2005). Infected seeds are considered the main inoculum source and mean of dispersal of *F. oxysporum* (Carvalho *et al*., 2015). Following its introduction into an area, fusarium wilt may appear in small, isolated foci and, after several seasons, spread throughout the entire area (Abawi and Pastor-Corrales, 1990). The disease is difficult to control and there are a few effective management strategies (Carvalho *et al*., 2015). The inadequate rotation of cultures, especially in areas irrigated with central pivot, the lack of preventive measures of control of the pathogen dissemination and the increase of soil compaction made the Fusarium wilt one of the most important bean diseases in Brazil (Periera *et al*., 2013).

2.3 Management options for the management of fusarium wilt on common bean

2.3.1 Cultural practices

Proper cultural practices can reduce *F. oxysporum* incidence and damage (Sampaio *et al*., 2020). Proper selection of the planting site optimizes the use of *F. oxysporum* ff. spp.-free planting material in non-infested soils. For that purpose, accurate information on the disease history of the field with regard to production of susceptible crops is of utmost importance (Jimenez-Diaz *et al*., 2015). Soils infested with *F. oxysporum* ff. spp. can be recovered for agricultural production by reducing the amount of initial inoculum and/or its potential for disease to levels below the threshold for severe disease (Jimenez-Diaz *et al*., 2011). Pathogen dissemination can happen through contaminated and infected seeds. The uses of certified pathogen-free seeds or their effective quarantine are important measures for fusarium wilt control (Pande *et al*., 2007). To optimize the use of *F. oxysporum* -free seeds, it is important that they are planted in non-infested soils. When land is not limiting, avoiding infested soils can significantly reduce disease incidence but most of the time this is not possible (Haware, 1998). In these cases, the establishment of cultural practices as soil solarization and crop rotation is important to minimize *F. oxysporum* inoculum incidence.

Tillage systems and the use of cover and rotational crops are known to affect soil-borne pathogen populations and soil-borne diseases (Toledo-Souza *et al*., 2012). In soil-borne pathogens, like *F. oxysporum,* crop rotation may reduce the inoculum in the soil (Jimenez-Diaz *et al*., 2015) but be less effective due to the ability of *F. oxysporum* chlamydospores to survive in the soil for a long time (Agrios, 2005) and also to the inoculum multiplication in roots of symptomless carriers (Jimenez-Diaz *et al*., 2015). When designing rotations, alternative hosts, even asymptomatic ones, should be avoided. Further, weed management might be important; since *F. oxysporum* can colonize roots of asymptomatic common dicotyledonous weeds in common bean fields, serving as a *Fop* reservoir (Sampaio *et al*., 2020). Unfortunately, the optimization of promising legume crop rotations is hampered by the lack of information existing on the host/non-host range of all the other legume-infecting *F. oxysporum* ff. spp., as well as on the plant species inducing *F. oxysporum* ff. spp. chlamydospores, rhizosphere germination (Sampaio *et al*., 2020).

Dhingra and Coelho-Neto (2001) worked with potted individual plants and verified that the legumes *Dolichos lablab*, *Phaseolus lunatus*, *Mucuna aterrima*, *Canavalia ensiforme* and *Vigna unguiculata* were all hosts of *F. oxysporum* and noted that they would aid in the persistence of the pathogen in soil and in the incidence of bean fusarium wilt (Toledo-Souza *et al*., 2012). Millet, *Panicum maximum*, *Urochloa brizantha* and a consortium of maize with *U. brizantha* are the best rotations for Fusarium wilt management on common bean crops in Brazil (Toledo-Souza *et al*., 2012). Fusarium wilt in common beans was more favoured in the no-tillage than in the conventional cropping system, whether previous summer crops were grasses or legumes in Brazil (Toledo-Souza *et al*., 2012). One of the problems associated with the no-tillage system is soil compaction, which may aggravate *Fusarium* diseases (Toledo-Souza *et al*., 2012).

Organic amendments have been used to promote crop growth and yields since ancient in agriculture (Vincelli and Tisserat, 2008), but their deliberate application for the purpose of plant disease management is a more recent approach. Organic amendments cover a range of inputs, including animal (cattle, poultry, and swine) and green manures, composts, high N-containing products (blood, bone, and meat meal, fish meal, soy meal), etc. (Jimenez-Diaz *et al*., 2015). The adoption of strategies to increase soil organic matter can have positive results on the management of soil-borne diseases as *F. oxysporum*. One of the most efficient strategies to improve soil quality, decrease soil-borne pathogens and simultaneously enhance soil microbial activity is bio fumigation (Larkin, 2013). Crops belonging to the Brassicaceae family, as, for example, broccoli, are excellent green manures by producing a sulfur compound, glucosinolate, toxic to several soil pathogens, being effective in their control (Panth *et al*., 2020).

2.3.2 Host/plant resistance

The use of resistant varieties is widely recognized as the safest, most economical and effective crop protection method to control soil-borne diseases (Rubiales *et al*., 2015; Panth *et al*., 2020). However, several factors that impinge upon resistance to disease can seriously limit its use and effectiveness, including genetic and pathogenic variability, and the evolutionary pattern of the pathogen, availability of resistance sources, co-infection of the plant by other pathogens, genetics and penetrance of resistance (i.e., reduced expression as a result of interaction between host genotype and inoculum load, temperature, seedling age), etc. (Jimenez-Diaz *et al*., 2011). Resistance to pathogenic races of *F. oxysporum* ff. spp. can be monogenic or oligogenic and polygenic, and of complete or partial (intermediate) phenotype (Jiménez-Díaz *et al*., 2015).

The development of legume *F. oxysporum*-resistant varieties through plant breeding is a long process with several steps, constantly integrating novel research developments to increase efficiency in releasing solutions to fight new *F. oxysporum* ff. spp. or races infecting legumes (Sampaio *et al*., 2020). Precision breeding for fusarium wilt resistance is only possible by knowing the genetic basic of resistance. Through linkage mapping and genome-wide association studies (GWAS), different types of resistance against *F. oxysporum*, qualitative and quantitative, depending respectively on a single or several genes, were characterized among legumes (Sampaio *et al*., 2020). The development of legume resistant cultivars against *F. oxysporum* infection with an interesting agronomic potential is the main goal of any breeding program for fusarium wilt resistance. Breeding programs do not aim to obtain only disease resistance and high yield in common bean, but also upright growth habit, a light colored seed coat, and sieve size greater than 12 for the carioca seed coat and above 11 for the black seed coat. In disease resistance breeding programs, parental selection constitutes a basic and fundamental step because it determines the success of subsequent steps (Panth *et al*., 2020). After the selection and recombination of susceptible genotypes with those containing resistance, the method used to advance the segregating population is essential for obtaining resistant cultivars within shorter times and at lower costs. However, this decision depends on the breeder's knowledge of inheritance and the genetic parameters involved in the resistance.

Genetic control of fusarium wilt resistance in common bean has been shown to be race specific (Ribeiro and Hagedorn, 1979; Salgado *et al*., 1995). The *Fop*-1 gene confers resistance to the Brazilian race 2 of *Fop*, whereas *Fop*-2 confers resistance to the U.S. race 1 from S. Carolina (Ribeiro and Hagedorn, 1979). In addition to the single dominant resistance gene model, Salgado *et al*. (1995) reported on recessive and polygene resistance to race 4 from Colorado. The Colorado race was virulent on most bean cultivars grown in the U.S., but new sources of resistance were detected in Durango race beans from Mexico including Lef2RB and Sierra pinto (Velasquez-Valle et al., 1997). In Rwanda, the cultivars Vuninkingi (G685 originally from Guatemala) and Flor de Mayo (Mexico) were resistant to *Fop* (Buruchara and Camacho, 2000) which suggests that different races are present as Flor de Mayo is very susceptible to race 4 from Colorado and Spain (Velasquez-Valle *et al*., 1997).

The dominance of *Fop* resistance in common bean has also been reported in other studies (Ribeiro and Hagedorn, 1979; Pereira *et al*., 2009). The demand for common bean cultivars with disease resistance by farmers has encouraged breeders to engage in more accurate inheritance studies to estimate the parameters involved in the genetic control of pathogens (Batista *et al*., 2017). This is the first study on the inheritance of *Fop* resistance in common beans using the F2 generation from a partial diallel scheme to identify the genetic inheritance of resistance to *Fop* (Batista *et al*., 2017). According to Xue *et al*. (2015), the low percentage of resistance of common bean to this pathogen is related to the response of plant defense to *Fop*, which involves expression of a large number of gene fragments in different regions of the genome, complicating and intensifying the work of selecting resistant cultivars (Batista *et al*., 2017). Pereira *et al*. (2009) evaluated six crosses involving three resistant and four susceptible lines, and observed complete dominance in *Fop* resistance genetic control in common bean.

2.3.3 Biological control

Biological control with *Trichoderma* species has contributed to reduce fusarium wilt incidence mainly when applied on seeds (Carvalho *et al*., 2014). Seed treatment with *Trichoderma* spp. may protect seedlings against fusarium wilt in common bean (Carvalho *et al*., 2014). *Trichoderm*a antagonists combine different desired traits such as hyperparasitism, competition and antibiosis and survival on different soils, especially in the *rhizosphere* (John *et al*., 2010). Their identification requires a thorough selection and testing under disease-conducive weather. Successful management of fusarium wilt leading to yield loss reduction in commercial fields using competitive isolates of *Trichoderma* has been reported (Shali *et al*., 2010). Particularly in Brazil, the adoption of *Trichoderma*-based bio-fungicides has increased over the years due to their proven benefits in integrated management of white mold (*Sclerotinia sclerotiorum*) on different crops (de Aguiar *et al*., 2014). In recent years, bio-fungicides have been developed and commercialized worldwide (Shali *et al*., 2010).

The use of *Trichoderma* fungal species is among the most used in fusarium wilt biological control. *Trichoderma hamatum* (Bonord.) Bainier treatment in lentil seedlings reduced *F. oxysporum* f. sp. *lentis* colonization, while soil application of *T. harzianum* Rifai at common bean and chickpea growing areas reduced efficiently *Fop* and *F. oxysporum* f. sp. *ciceris* infection rates, respectively (Carvalho *et al*., 2015). The pod-filling is the growth stage when treatments aiming to reduced inoculum density and vascular wilt progress are evaluated (Toledo-Souza *et al*., 2012). Among the six *T. harzianum* isolates, CEN287 and CEN316 were the most effective isolates to reduce wilt incidence and severity and have shown hyperparasitic capacity against *F. oxysporum* (Carvalho *et al*., 2015).

2.3.4 Chemical control

Chemical control is one of the disease management practices for soil-borne diseases. However, this approach has numerous disadvantages at economical, environment and public health levels (Yadeta and Thomma, 2013). Until the implementation of a global agreement to protect the ozone layer, methyl bromide was widely used as fumigant due to its high efficiency against soil-borne diseases. Alternative fumigants to methyl bromide such as carbendazim, dazomet, chloropicrin and 1, 3-dichloropropene are among the presently most frequent used to combat fusarium wilt. In the past, chloropicrin and dazomet controlled pea wilt satisfactorily in severely infested soils (Sampaio *et al*., 2020). Lethal consequences on the *Rhizobium* Frank soil microbial communities were also revealed, namely by chloropicrin application (Sampaio *et al*., 2020). Nevertheless, it is important to reinforce that their frequent and indiscriminate use can not only alter soil microbial community composition but also may damage aquatic ecosystems, and even lead to the development of fungicide resistance (Panth *et al*., 2020). However, the efficiency of soil fumigation is curtailed by either survival of pathogens in soil layers below the depth of effective fumigation, or reintroduction of them through infected planting material or by conidia carried in the air or irrigation water (Jimenez-Diaz *et al.,* 2011).

2.3.5 Integrated disease management

Integrated management is the best strategy to control this disease and the use of resistant cultivars is decisive. They can be applied by biological, chemicals, cultural, physical, and regulatory methods, depending of the nature of the agents employed. For diseases caused by soil-borne pathogens, such as fusarium wilts, which are mainly monocyclic in nature, the control principles and methods should be targeted to excluding the pathogen, as well as reducing the amount and/or efficiency of the initial inoculum. The management of fusarium wilt disease is a difficult task, not only in legumes but in every plant species and relies on the integration of different disease management approaches. Measures for fusarium wilt control include genetic resistance and adoption of IDM actions, such as crop rotation and use of healthy seed (Toledo-Souza *et al*., 2012).

The integrated disease management of fusarium wilt is limited to crop rotation, seed treatment and use of resistant cultivars. The initial inoculum of *F. oxysporum* ff. spp. can be reduced by means of chemical, biological or physical disease control methods (Jimenez-Diaz *et al*., 2011). Achieving that aim by cultural practices such as crop rotation is of lesser efficacy because of the ability of chlamydospores of pathogens for long survival in soil. However, use of crop rotations in the integrated management of fusarium wilt diseases should not be disregarded to avoid recurrent increase of inoculum in soil (Jimenez-Diaz *et al*., 2015). A well-balanced use of biocontrol agents together with cultural control measures can result in a profitable *F. oxysporum* disease management improvement. Other practices could be integrated into a bio-control program (with effective *T. harzianum*) aiming to improve crop health and providing new standards of disease management where other techniques are inefficient which is suggested as a feasible alternative strategy for managing fusarium wilt (Carvalho *et al*., 2015).

3. Conclusions

Fusarium wilt caused by the soil-borne pathogen *F. oxysporum* promotes severe damages to common bean crop productivity. The ability to remain in the soil for many years in the absence of a host makes its eradication a difficult task. Effective management of fusarium wilt in common bean can only be achieved combining different disease management strategies. The IDM of fusarium wilt is limited to crop rotation, seed treatment and use of resistant cultivars. Crop rotation, another important agricultural practice in disease control, also requires more investigation. The use of resistant cultivars has been widely recognized as the most effective method for soil-borne diseases control. The different approaches addressed in this review revealed significant achievements and progresses in integrating different disease management practices in common bean crops. The IDM of fusarium wilt diseases is a difficult task because complexities of target pathosystems are overlaid on the inherent complexities of the management strategy itself. Much research is still needed on population biology and genetic diversity in fusarium wilt pathogens, as well as on disease risk prediction, disease-incidence-yield losses relationships, biological control, biotechnological breeding for disease resistance, etc., which should be carried out under a system approach. Thus, further research work should be done on different disease management strategies for this disease as to make appropriate IDM for the management of fusarium wilt of common bean.

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