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Endophytes: As Potential Biocontrol Agent —*Review and Future Prospects*

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Abstract

Endophytes are the microbes residing internally in the host tissues without causing visible disease symptoms. They have found involved in a balanced interaction with the plants and providing benefits such as, growth enhancement and disease resistance. In this review we hypothesize that endophytes can be employed as a potential biocontrol agent, as biocontrol is becoming most suitable disease management strategy due to its health and environment conservational benefits. This aspect of endophytes should be consider, there are several investigations that have revealed and proved the role of endophytes as best biocontrol agent. Mutualistic interaction of endophytes involve different mechanisms, as it may trigger certain genes involved in induced systemic resistance (ISR) that may initiate defense mechanism against attack of pathogens or by formulating secondary metabolites and other chemical compounds that are directly toxic to the pathogens. There is a need to explore the endophytic interaction and its mechanism of causing disease resistance more precisely.

Keywords: endophytes, biocontrol, induced systemic resistance (ISR), secondary metabolites, symbionts, arbuscular mycorrhiza fungi (AMF), endophytic diversity

1. Introduction

1.1 Endophytes

Endophyte was defined as "endophytes colonize internal tissues of host without causing symptoms, but chances are there that endophytes may cause disease after completing latency period" (Petrini, 1991). The word endophytes literally means "within plants" (In Greek; *endon*-within and *phyton*-plants). Endophytes is a vast term with respect to its literal meaning, host plants and inhabitants, such as fungi (Stone, Bacon and White, 2000), bacteria (Kobayashi & Palumbo, 2000), insects (Feller, 1995) and algae (Peters, 1991). Endophyte colonizes plant tissues internally (Carroll, 1986), without causing visible disease symptoms. They live in symbiotic interaction with plants. And they also show variation in symbiotic interaction, which ranges from facultative saprobe, to parasite, to mutualistic. However, like all endophytic interactions provides nutritional benefits and protection against environmental and microbial stresses (Schulz & Boyle, 2005).

Endophytes can be extracted from the external plant tissues cleaned with disinfectant or can be isolated from internal parts of the plants (Hallmann et al., 1997) without damaging them. Both commensal microbes, which do not affect their host plants, and mutualistic symbionts that are useful for biological control are part of endophytes (Araújo et al., 2000). The relationship between endophytes and plants is a matter of great interest and has been discussed alot before (Sturz et al., 2000).

Endophytes show great diversity with respect to their living, they are extensively found in association with the temperate grasses (Clay, 1989) and higher trees of forest. Endophytes are found present in plants belonging to different regions such as temperate, tropical regions and in boreal forests (Zhang et al., 2006). Arbuscular mycorrhiza fungi are present extensively throughout the terrestrial ecosystem, and fossil records and molecular analyses shows their association with plants from their origin millions of years ago (Redecker, Kodner, & Graham, 2000). Mutualistic bacteria has been identified in both monocots and dicots, that ranges from higher plants such as oak and pear, to lower plants like sugar beet and maize (Ryan et al., 2007).

Endophytic bacteria found within the plant system are dynamic, varied, and diverse (Sturz et al., 1997). For such plant-endophyte relationship to be stable and successful, some form of synchronization must be present. Bacterial endophytes lives, adapts and survives within the suitable environment provided by the host plants. And the host plants also get benefits from this partnership, such as growth promotion and protection (Shishido et al., 1995).

1.1.1 Endophytic Diversity

Endophytes show more diversity and abundance than plant pathogens within the plant systems (Ganley et al., 2004). These symbionts are very diverse, only small number of them has been characterized (Rodriguez et al., 2009). Endophytes mostly belong to phylums *Basidiomycota* and *Ascomycota* and they may be from orders *Hypocreales* and *Xylariales* of class *Sordariomycetes* or *Loculoascomycetes* (Unterseher et al., 2011).

However, many genera of fungal endophytes commonly reported are: *Aureobasidium*, species of *Trichoderma, Fusarium* and two yeast genera, *Pichia* and *Candida*. Endophytic fungi such as *Physoderma citri, Colletotrichum* spp., *Botryosphaeria* spp., *Lasiodiploidia theobromae*, *Phomopsis citri* (*Diaporthe citri*), *Alternaria*, *Cladosporium*, *Mycosphaerella*, and *Guignardia/Phyllostictina* were extracted from healthy citrus plants. *Colletotrichum* spp., and *Guignardia citricarpa* were the most prominent fungi species in different tangerine plants (Busby, Ridout, & Newcombe, 2016).

Grasses mostly involve endophytic fungi belonging to family *Clavicipitaceae*, tribe Balansiae. There are five genera and about 30 species in the tribe (Luttrell & Bacon, 1977). The genera *Atkinsonella* and *Myriogenospora* contain only one specie while the genera *Balansia*, *Balansiopsis* and *Epichloe'* contain more than one species. *Balansia* is the most diverse of all having 15 species (Diehl, 1950). These genera are classified on the basis of conidia formation (Clay, 1986). These fungi are termed endophytes, found in host meristem, young leaves and inflorescence (Leuchtmann & Clay, 1988). However, most species invade vegetatively running parallel to the long axis of host leaf and stem tissue cells (Clay, 1989).

Arbuscular mycorrhiza fungi is a part of mutualistic rhizosphere, these are micro symbionts that are involved in improvement of plant nutrient uptake and provides protection against different stresses (Smith & Read, 1997). AMF involves biotrophic *Glomeromycota* associated with different species of plants (Van der Heijden et al., 2015).

Review of previous studies on bacterial endophytes have characterized some of the bacterial types isolated from within the plant tissues after surface cleaning of plant tissues by using disinfectant such as sodium hypochlorite (Miche & Balandreau, 2001). The diversity of endophytes extracted from the poplar trees have been explained in a study (Porteous-Moore et al., 2006). Five taxa of endophytic bacteria were identified as *Microbacterium*, *Pseudomonas*, *Clavibacter*, *Curtobacterium*, *Cellulomonas* by molecular techniques such as gene sequencing and by fatty acid analyses (Zinniel et al., 2002).

Number of bacterial endophytes has been extracted from the vascular tissues of citrus varieties such as *E. aerogenes*, *Acinetobacter baumanii*, *Bacillus* spp., *Burkholderia cepacia*, *Citrobacter freundii*, *Corynebacterium* spp., *Arthrobacter* spp., *Enterobacter cloacae*, and *Pseudomonas aeruginosa*, *Acromobacter* spp., *Acinetobacter iwoffii*, *Alcaligenes-Moraxella*.

Some studies have concluded bacterial endophytes as polyphyletic belonging to vast range of taxa, such as *Actinobacteria*, *α-Proteobacteria*, *β-Proteobacteria*, *γ-Proteobacteria*, and *Fermicutes* (Miliute et al., 2015).

Rhizobacteria is also included in bacterial endophytes, playing vital role in host plants survival (Dobereiner, 1993).

1.1.2 Mode of Action

Number of studies has been done but how endophytes effect the plant disease severity is still unknown (Busby, Ridout, & Newcombe, 2016). Induction of host defense mechanism is consider to happen first, as Bacteria (Sequeira et al., 1977), nematodes (Kosaka et al., 2001), Viruses (Ross, 1961) and fungi (Pozo et al., 2002) induces plant defense mechanism, such as Systemic acquired resistance (SAR) and Induced systemic resistance

(ISR) (Van Wees et al., 2000). For example, a fungi *Colletotrichum tropicale* has stimulated hundreds of genes and their expression caused greater plant immunity in *Theobroma cocao* (Mejia et al., 2014).

Endophytes can also minimize the defense mechanism of plant allowing other pathogens to cause disease (Houterman et al., 2008). Many studies have been done and their results have shown suppressing effects of endophytes due to competition or endophytic metabolites (Martin et al., 2015). For example, *Ampelomyces* spp. Suppress the powdery mildew sporulation (Kiss, 2003).

Induced systemic resistance (ISR) is a unique way by which endophytes enhances the plant defenses against number of pathogens. Various root-inhabiting mutualists, such as *Trichoderma*, *Bacillus*, mycorrhiza species and *Pseudomonas* triggers the immune system of plant for enhanced defenses against pathogens (Pieterse et al., 2014).

"Induced resistance" is a term used for the resistance stimulated by chemical or biological agents, which helps the plants to fight against the pathogen attacks in the future (Kuc, 1982). ISR is only initiated when endophytes colonizes the root system of host plants (Lugtenberg & Kamilova, 2009). Biofilm formation is important for the root establishment of B. subtilis, polysaccharides of host cell wall stimulates the matrix production by triggering the bacterial genes (Beauregard et al., 2013).

The endophyte adapts new lifestyle for the sake of survival, in the dynamic medium of the host cells by host-specific metabolic cues (Lahrmann et al., 2013). *Trichoderma spp.* establishes around the plant roots, where it forms a structure like appressorium which is an important characteristic of pathogenic fungus (Mukherjee et al., 2013). *Pseudomonas, Bacillus, and Trichoderma* strains for establishing themselves around plant roots uses auxin as a triggering agent for the formation of large number of lateral roots, which helps in better nutrient uptake and defense against pathogens (Contreras-Cornejo et al., 2009).

Endophytes are found responsible of producing bioactive compounds that contributes to their biocontrol activity (Akinsanya et al., 2015). An endophytic fungus *Phomopsis spp*. is found responsible of producing number of secondary metabolites including antimicrobial and antifungal compounds (Erbert et al., 2012). The biologically active Xanthones were found in the fermentation products of *Phomopsis spp.* (Yang et al., 2013).

3-Methyl-2-aryl benzofurans obtained from the fermentation products of endophytic fungi *Phomopsis s*howed anti-TMV activity.

1.1.3 Dependency

Review of literature shows the dependency of endophytes on biotic and abiotic factors, host and pathogen (Busby et al., 2016). Environmental factors such as humidity, pH and temperature effects the endophytic interaction of fungi (Cook & Baker, 1983). For example, Trichoderma activity is influenced by soil moisture (Jones & Bienkowski, 2015), and *Candida* activity is effected atmospheric conditions add strength against apple pathogen (Usall et al., 2000). In a trial, variations were observed in the endophytic activity against Dutch elm disease, indicating that there may be some abiotic factors involved that influences endophytic activity (Martin et al., 2015).

Nonconductive or poor soil conditions are thought to affect the biological control activity of endophytes against plant pathogens (Handelsman & Stabb, 1996).

Disease triangle consists of three components, host, pathogen and the environment, each component should be present for the occurrence of the disease, besides environment the other two components also influences the activity of endophytes. In case of rust disease the influence of these components has been observed (Nischwitz et al., 2005; Kiss, 2003).

But in an experiment, it has been proved that pathogen matters most in disease occurring activity. *i.e.*, *Colletotrichum gloeosporioides* and *Pestalotia psidii* were tested against fifteen endophytic species. Fourteen of them showed defense against *C. gloeosporioides*, while nine were defensive against *P. psidi*i (Pandey et al., 1993). In another finding, nine endophytic species were tested against following wheat pathogens: *Drechslera tritici-repenti*, *Alternaria triticimaculans*, *Zymoseptoria tritici*, and *Bipolaris sorokiniana*. Nine of them showed full defense against *Zymoseptoria tritici* and *Drechslera tritici-repentis*, eight showed defense against *Bipolaris sorokiniana*, and four against *Alternaria triticimaculans* (Perello et al., 2002).

2. Claims

In this review we have claimed that "Endophytes are potential biocontrol agent" and our claim is based on the present research literature that has been reviewed in this regard.

Endophytes are believed to have biocontrol potential against plant pathogens (Sapak et al., 2008). Presence of endophytes in plant systems provides beneficial effects (Ting et al., 2010). Many studies have concluded the role of endophytes as potential biocontrol agent mainly against pathogens of vegetable and fruit crops, as in case of Chinese cabbage (Narisawa et al., 1998). Endophytes shows biocontrol agent properties against pathogens of tomato (Hallman & Sikora, 1995), banana (Ting et al., 2008), barley (Boyle et al., 2001). Biocontrol properties are also shown by endophytes by controlling *Ganoderma boninense* in oil palm (Sapak et al., 2008).

Number of investigations has revealed that endophytic fungi can be used as a biocontrol tool (Sikora et al., 2008). The endophytic fungi play antagonistic role and minimizes the threat of nematode attack (Sikora, 1992). Endophytic *Fusarium oxysporum* decreased the number of nematodes on banana (Sikora et al., 2008).

Many studies have also concluded that some bacteria, along with endophytic bacteria (EB), enhances the symbiotic activity of AMF in the host, and can be used as biocontrol agent against plant pathogens (AzcÓnAguilar et al., 1998). So, it has been recommended to use AMF and EB together as biocontrol partners and it has been proved (Gianinazzi et al., 2010).

Endophytes consist of mutualistic symbionts that can be used as potential biocontrol agent of plant pathogens. The potential of endophytes during symbiont/host interaction has been revealed in number of studies (Sturz et al., 2000).

Endophytic bacteria live in the same environmental conditions as the plant pathogens, such as vascular wilt pathogens. This is a positive aspect for endophytes to serve as biocontrol agents. Excessive research on biocontrol properties of microbes has revealed that endophytic symbionts extracted from plant tissues shows potential as biocontrol agent against pathogens (Duijff et al., 1997), nematodes (Hallmann et al., 1998) and insects (Azevedo et al., 2000).

Biological control of plant pathogens has been observed and proved on grasses having symbiotic association with endophytes. In vitro and field demonstration has been performed and suppression of diseases have noted in case of grasses associated with endophytes (Siegel & Latch, 1991). In past, potential use of endophytes as biocontrol agent has been revealed by many investigators (Schardl, 2001; Sturz et al., 2000).

2.1 Why Biocontrol?

Because, there are growing concerns with the detrimental environmental effects of chemicals used to control plant diseases. They cause soil, water and air pollution, and are often made from expensive and non-renewable petrochemicals that have many adverse effects on natural environment. Moreover, repeated chemical treatments are required for efficient control with increases the initial economic cost (Clay, 1989). And also, use of chemicals to control diseases favors the addition of resistant mutants to pest population. As a result, biocontrol has become an important integrated management strategy (Waage & Greathead, 1988).

The chemical compounds used for the management of plant diseases are not safe for the healthy environment. Consequently, we need to devise integrated managemental strategies. So, biocontrol is employed as a reasonable strategy for disease management (Mejia et al., 2008).

As human pathogens are becoming resistant to antibiotics similarly the plant pathogens have become resistant to many chemicals used for their control. With the excessive use of chemicals pathogens have develop resistant strains. For example, *Ustilago*, *Pythium*, *Phytophthora*, *Penicillium*, *Mycosphaerella*, *Sphaerotheca*, *Verticillium*, *Botrytis*, *Cercospora*, *Colletotrichum*, *Fusarium*, *Aspergillus* and *Alternaria* are the fungal pathogens that have developed resistant strains against fungicides used against them (Agrios, 2005). Resistant strains of *Erwinia amylovora* to antibiotic streptomycin, causal agent of fire blight, had been known since the late 1950s (McManus & Jones, 1994).

3. Evidences

Endophytes are potential biocontrol agent is supported by number of evidences from the literature reviewed.

Some members of *Acremonium* sp. can colonize roots or shoots and can decrease nematodes population; including *Acremonium coenphialum* (Pedersen et al., 1988), *Acremonium lolii* (Stewart, 1993) and *Acremonium strictum* (Goswami et al., 2008). *Acremonium implicatum* is a fungus that negatively affect *Meloidogyne incognita* causing root galls. This fungus was isolated from these galls caused due to *Meloidogyne incognita* (Lin et al., 2013) also from eggs of *Meloidogyne hapla* (Figure 1).

Greenhouse demonstration has revealed the effective role of *F. oxysporum* isolates in controlling *R. similis* in Uganda (Niere et al., 1998). Studies have proved the effectiveness of biological control of *R. similis* using *Fusarium oxysporum* in banana cultivars (Figure 2) (Pocasangre et al., 2000). Evidences have proved that nematodes are also invaded by microbes that can be used as endophytes. For example, *Meloidogyne javanica* and *Pratylenchus* sp. nematodes are invaded by the bacterium *Pasteuria (Bacillus) penetrans* (Figures 3A-3D). Cysts of the soybean cyst nematode *Heterodera glycines* are invaded by the fungus *Verticillium lecanii* (Figure 3E) (Agrios, 2005).

The most important fungi used as biological control agents against soil borne pathogens includes, *Gliocladium virens* and *Trichoderma harzianum*, they have been used commercially as potential biocontrol agent (Figure 4). They are used mixed with the potting media. They are efficient against damping-off diseases of ornamentals and vegetables caused by the oomycetes such as *Pythium* and *Botrytis* (Hoitink et al., 1991). Endophytic bacteria belonging to genus *Pseudomonas*, *Enterobacter*, *Pantoea* and *Bacillus* parasitize and/or seize the pathogenic oomycetes *Phytophthora* spp., *Pythium* spp., and *Fusarium* spp. (Figure 5) (Johansson et al., 2003). Various post-harvest diseases of fruits have been controlled using endophytic microbes. For example, endophytic bacteria *Pseudomonas* controlled *Penicillium* green mold of lemons and post-harvest rots of pear (Figure 6). Two *Pseudomonas syringae* strains have been approved postharvest decay control in citrus, apples (Janisiewicz & Korsten, 2002) and pears under the trade name Bio-Save. When several kinds of fruits, namely nectarines, apricots, plums and peaches were treated by *Bacillus subtilis*, they remained free of brown rot, caused *Monilinia fructicola*, for at least nine days (Wilson & Wisniewski, 1989).

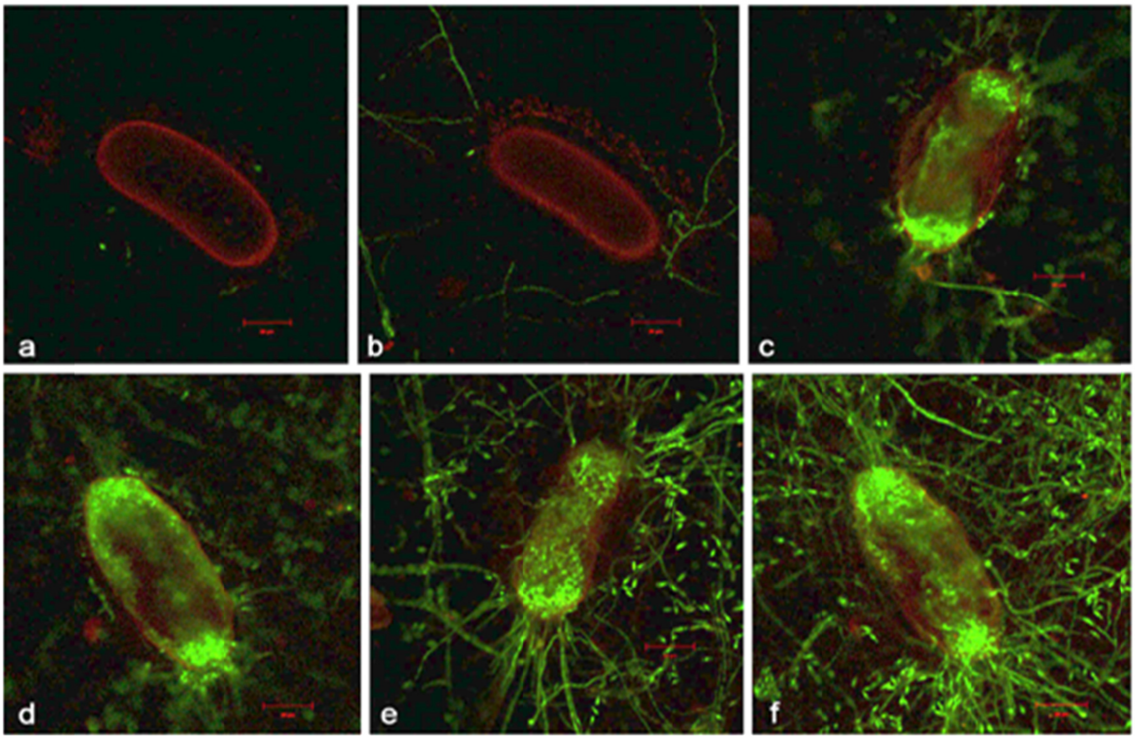

Figure 1. *Meloidogyne incognita* eggs are invaded by *Acremonium implicatum* (a, b) Eggs without fungus. (c, d, e, f) Eggs with fungus (Yao et al., 2015)

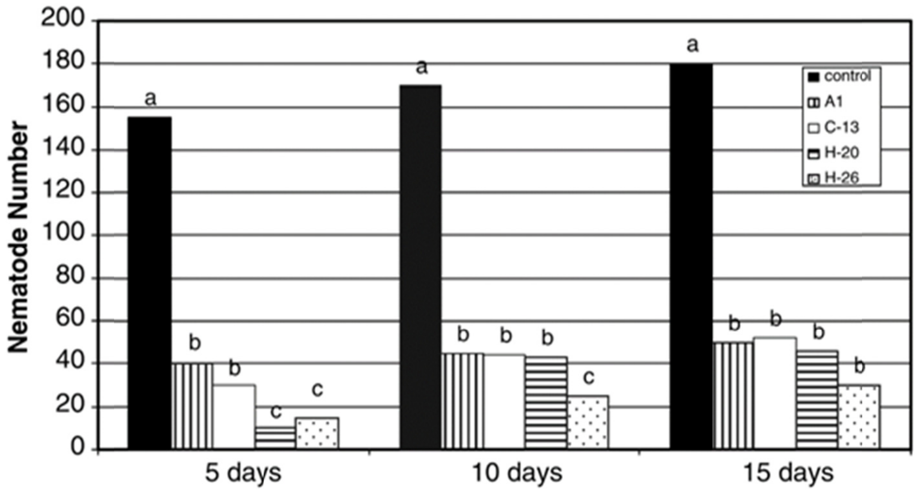

Figure 2. Enhancement of effectiveness of banana plants with four *F. oxysporum* isolates against *Radopholus similis* root infection. (Pocasangre et al., 2000)

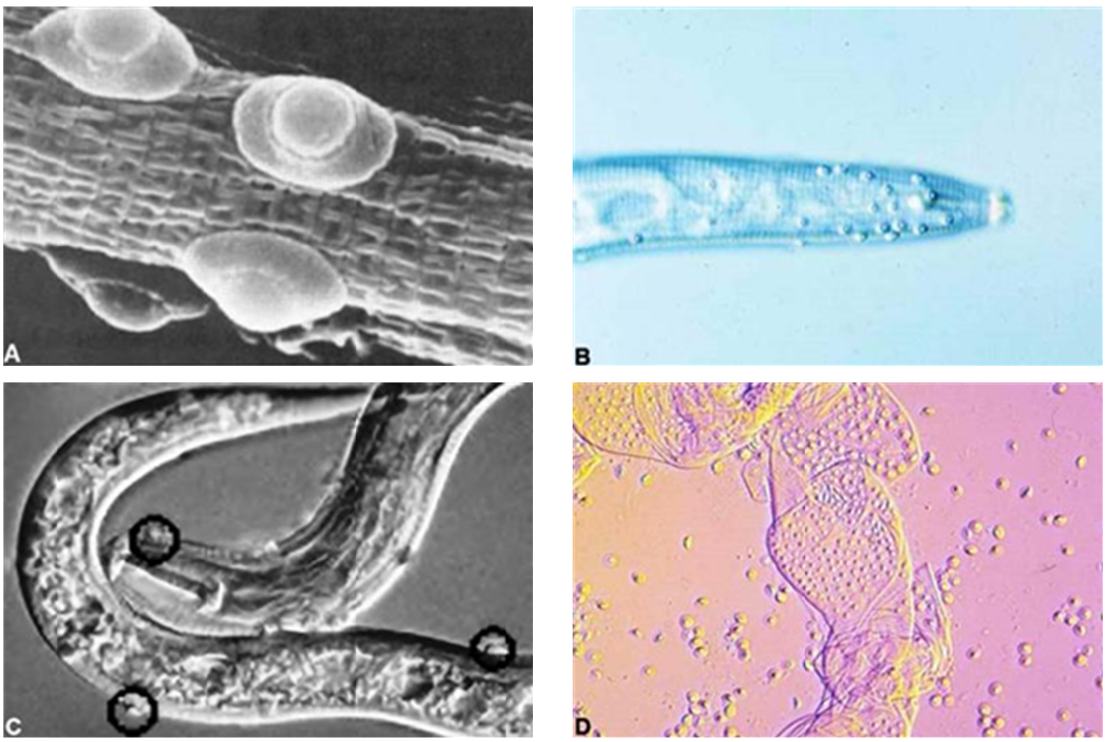

Figure 3. Biological control of nematodes, In (A, B, and C) *Meloidogyne juveniles* and (D) *Pratylenchus* sp. are invaded by the bacterium *Pasteuria penetrans* and in (E) a *Heterodera* cyst by the fungus *Verticillium lecanii* (Agrios, 2005)

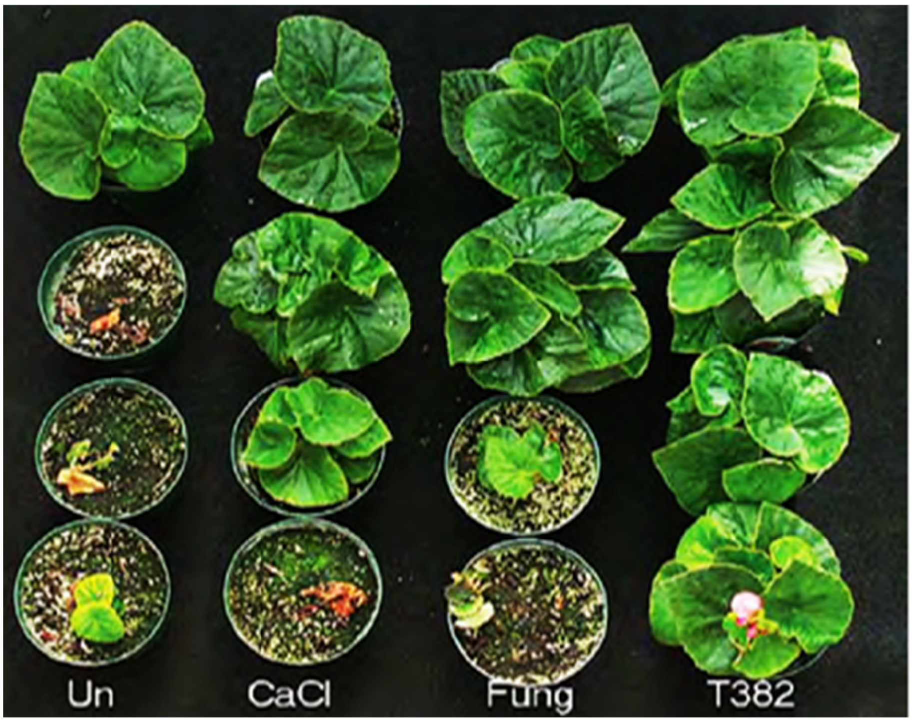

Figure 4. Comparative analyses of different disease control methods in Begonia plants inoculated with *Botrytis cinerea*. From left to right: Un, untreated control; CaCl, calcium chloride; Fung, fungicide (chlorothalonil) treatment; and T382, treatment with the biocontrol agent *Trichoderma hamatum* strain T382 inoculated into the potting mix (Hoitink, Inbat, & Boehm, 1991)

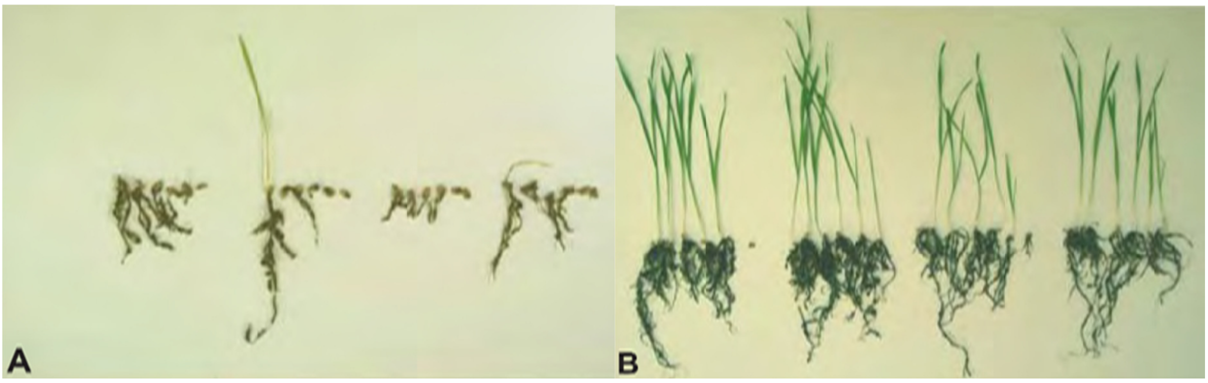

Figure 5. Biocontrol of wheat seedling blight caused by *Fusarium culmorum* by treating seeds with bacteria of the Pantoea sp. isolate MF626. (A) Untreated seeds (B) Treated seeds (Johansson et al., 2003)

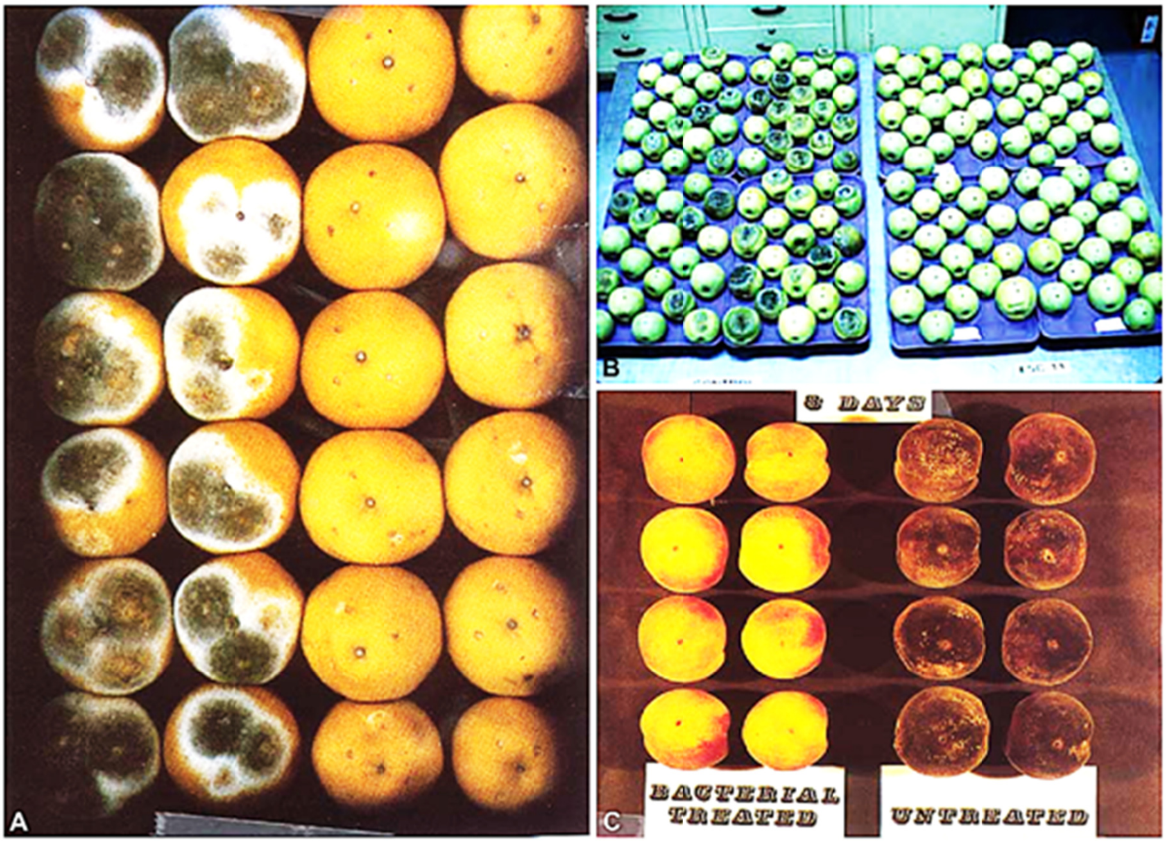

Figure 6. Biocontrol of post-harvest diseases. (A) Oranges treated with yeasts and inoculated with *Penicillium*. (B) Apples after 3 months, as they were inoculated with fungi *Penicillium* and *Botrytis* with (right) or without (left) treatment with the biocontrol bacterium *Pseudomonas syringae* (BioSave 110). (C) Peaches at left were protected from infection by the brown rot fungus (*Monilinia fructicola*) by prior treatment with the nonpathogenic bacterium *Bacillus subtilis*. Untreated peaches (right) became severely rotten within 8 days from inoculation with *M. fructicola* (A and C: Wilson & Wisniewski, 1989; B: Janisiewicz & Korsten, 2002)

4. Conclusion and Future Prospects

Considering endophyte-plant interaction and its significant role as potential biocontrol agent it can be employed as a better and reasonable integrated disease management strategy and can play a vital role in the promotion of low cost sustainable agriculture applications. With the availability of complete genome sequences of key endophytes that have proved their potential before, the genes contributing in the establishment of endophytes in plants and biocontrol properties can be identified. Those genes can be exploited to devise better biocontrol strategies. The information gathered can lay the foundation for molecular analysis that has shown promises in understanding other plant–microbe interactions.

The most important challenge is to understand the endophyte-host interaction and an important question rises here which require investigation is that, whether the endophytes are directly interacting with the plants or with the pathogens? Fortunately, with the help of modern genetic tools such as genomics and transcriptomics to identifying the altered gene expression, the answer to this question can be known.

In addition, studies should also be carried out in the direction to know about the effect of chemicals used for the control of plant pathogens on beneficial microbes, because it is believed that chemicals are affecting the efficiency the endophytes. Synthetic chemicals are observed to disturb the formation of nodules made by N-fixing bacteria (Fox et al., 2007). These nodules are believed to be beneficial to plants in number of ways.

The importance of the metabolites produced by the endophytes should be considered as they can be used to form biochemical commercially, as they have shown anti-microbial properties in number of studies. Metabolites produced by the endophytes have shown anti-fungal properties that can be used for the control of *B. cinerea* and other fungal pathogens (Lilja et al., 2010).

Despite of all the progress briefly described here, endophytes still need attention of researchers. As it can become an ultimate tool to handle plant diseases more effectively. Especially, the complex decline diseases that are major threat to the perennial plants and difficult to manage, *e.g.*, destructive mango wilt disease.

At the end, by considering the great potential of endophytes the road map for the future research can be designed. The understanding of the plant-microbe interaction should be given primary importance because by knowing this interaction better, it could one day leads to develop crop plants that can interact with endophytes/beneficial microbes more efficiently. Eventually, we can move towards gaining our goals of sustainable agriculture.

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