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Pseudomonas fluorescens: Biological Control Aid for Managing Various Plant Diseases: A Review

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ABSTRACT: Promiscuous usage of chemicals such as fertilizers and pesticides in agriculture sector has affected the environment and the ecosystem severely. Replacement of those hazardous biochemicals is very crucial and the best alternative solution for it is biological control or 'biocontrol'. Biocontrol is nature's solution for it is the usage of microorganisms to restrict the pathogen's growth and reduction in the impact of disease. Plant diseases are a major cause of yield loss all over the globe. Usage of biocontrol agent *Pseudomonas fluorescens* has been substantial in the suppression of these phytopathogens along with the enhancement of plant growth. Fluorescent pseudomonads are the best choice since they are abundant in the soil rhizosphere and possess the ability to utilize various plant exudates as nutrient. They suppress the disease through various mechanisms such as production of volatile antibiotics and other auxiliary metabolites, siderophores, HCN while also competing with the phytopathogens for niche and nutrients and through Induction of Systemic Resistance (ISR) in plants against diseases. Such versatility makes *Pseudomonas fluorescens* a well-endowed biocontrol agent of choice. The performance of *Pseudomonas fluorescens* in biocontrol of phytopathogens has not been consistent, so it is essential to keep exploring its efficacy through more research works in the future.

Keywords: Biocontrol, *Pseudomonas fluorescens*, rhizosphere, mechanisms, versatility etc.

INTRODUCTION

The term 'Biological control' or 'biocontrol' refers to the involvement of an organism directly or indirectly to reduce the pathogen's growth and lessen the impact of disease (Shurtleff and Averre, 1997). Plant diseases are a major cause of loss in yield all over the world (Alzandi and Naguib, 2019). Usage of biocontrol agents help to increase the possibility of disease resistance along with minimizing the usage of chemicals. Bacterial strains utilized as biocontrol agents mostly belong to the genera *Agrobacterium, Bacillus* and *Pseudomonas.* These bacterial biocontrol agents enhance plant growth by the suppression of either minor or major phytopathogens in addition to the production of plant growth promoting metabolites such as gibberellins, auxins etc. (Salt, 1979; Fravel, 2005).

Pseudomonas genus is the most multitudinous amongst the reported genera of Gram-negative bacteria (Gomila *et al*., 2015). *Pseudomonas* spp. are widespread aerobic, gram-negative bacteria, and have a huge tendency to adapt to various situations in the rhizosphere. They possess various qualities that make them excellent candidates for biocontrol and growth promoting agents (Weller, 1988). The *Pseudomonas* (Order: *Pseudomonadales*, Family: *Pseudomonadaceae*) are motile (containing one or several polar flagella), non-sporulating rods with Gram-negative reaction (Palleroni, 2008). They are chemo-organotrophic and catalase positive with a stringent respiratory metabolism.

Fluorescent pseudomonads act as an excellent plant-growth promoting rhizobacteria (PGPR) that is used in the biocontrol of various phytopathogens and pests. Besides its immense usage in agricultural sectors, it is notorious for its utilities in other fields also such as medicinal, industrial, bioremediation, environment and commercial sectors around the globe which is clearly depicted in Fig. 1 (Panpatte *et al*., 2016; Ramírez-García *et al*., 2019). Fluorescent *Pseudomonas* is amply studied and researched upon amongst other microbes of the rhizosphere. They have a certain distinctive feature that makes them distinguished easily from another *Pseudomonas* spp. It's their unique ability through which they produce water-soluble yellow-green pigment called fluorescein. They include of *P. aeruginosa,* the type species of the genus, *P. chlororaphis, P. putida, P. fluorescens, P. Aureofaciens* and the plant pathogenic species *P. cichorii* and *P. syringae* (Landa *et al*., 2003; De La-Funte *et al*., 2006). Among various *Pseudomonas* spp., *Pseudomonas fluorescens* has been widely used as a biocontrol agent. Some members of *Pseudomonas fluorescens* have shown potential to be a biocontrol agent as they have been shown to suppress plant diseases through protection of root and seeds from diverse fungal infections. *Pseudomonas* imposes its biocontrol activity in phytopathogens through direct antagonism and there is also induction of disease resistance in the host plant (Cartieaux *et al.*, 2003). They have been shown to reduce the effects of many fungal diseases and amplify plant growth (Hoffland *et al.*, 1996; Wei *et al.*, 1996). Several studies were conducted for finding out the favourable effects of *Pseudomonas fluorescens* as a plant growth promoter as well as a biocontrol agent in the management of diverse phytopathogens. (Couillerot *et al.*, 2009). The favourable effects on plants by Fluorescent pseudomonads comprises of the inhibition of soil pathogenic fungi through production ofseveral secondary metabolites including siderophore (Lemanceau *et al.*, 1992), antibiotics such as phenazines, pyoluteorin, pyrrolnitrin, 2,4-diacetylphloroglucinol (DAPG) and hydrogen cyanide (O'Sullivan and O'Gara, 1992). It has been also shown to compete against the phytopathogens for niche and nutrition along with playing a major role in the induction of systemic resistance (ISR) against diseases. The usage of *Pseudomonas fluorescens* as a plant growth promoter and biocontrol agent requires a great deal of understanding between its interaction with other bacteria and their performance in rhizosphere (Kloepper *et al.*, 1989; Gotz *et al.*, 2006; Panpatte *et al.*, 2016). This review discusses the diseases controlled by the bacterial antagonist in diverse agricultural as well as horticultural crops.

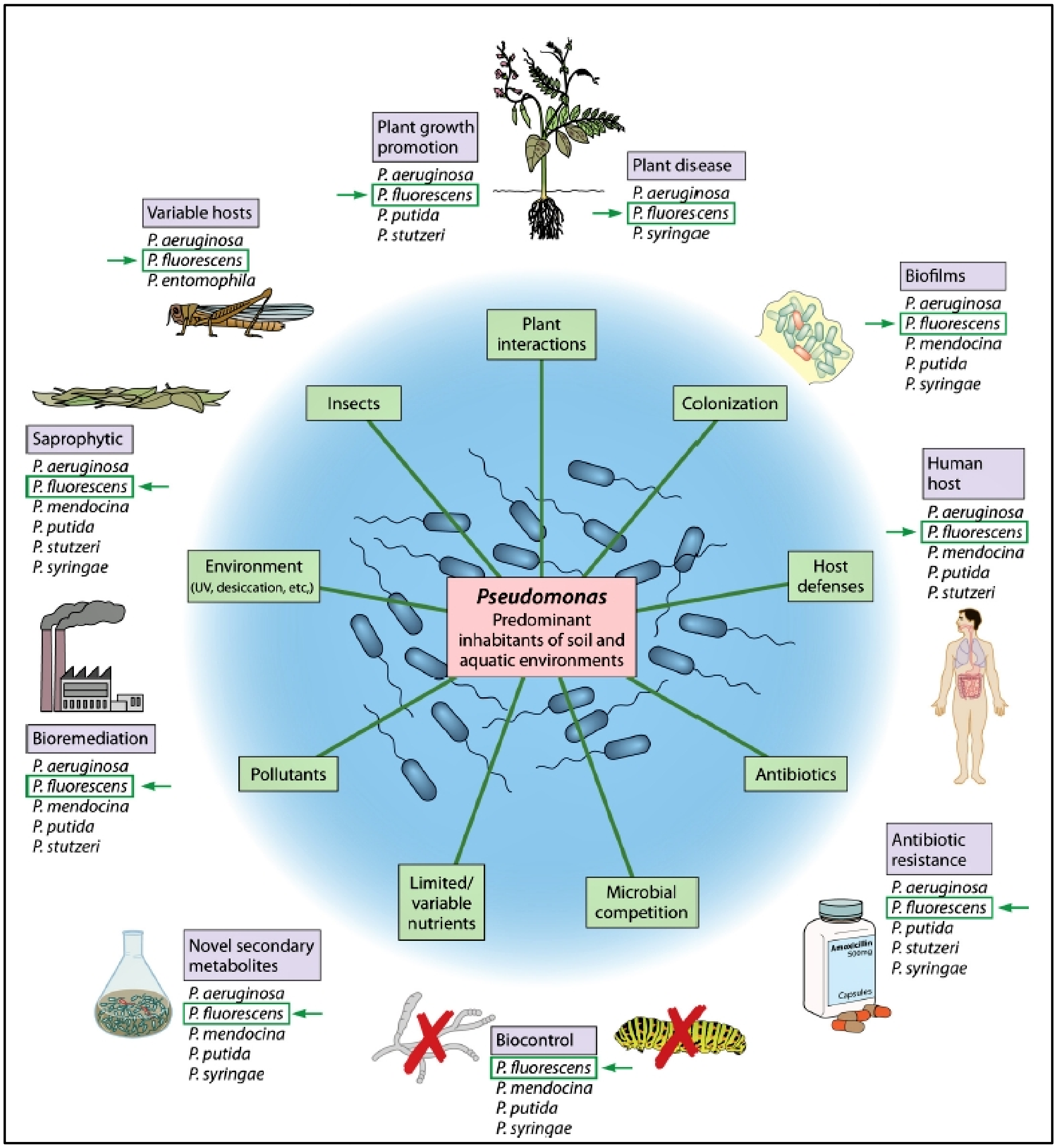
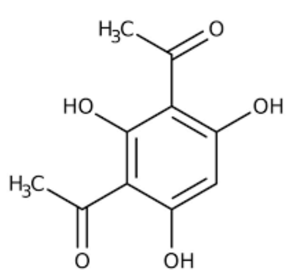


Fig. 1. Multidimensional use of *Pseudomonas* spp. in various sectors highlighting its versatility as a successful colonizer due to its various functional abilities. (Source: Silby *et al.*, 2011; Scales *et al.*, 2014).

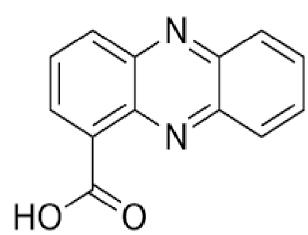
Table 1: Volatile antibiotics released by *Pseudomonas fluorescens* that are effective against diseases.

***Pseudomonas fluorescens* strain**	**Component**	**Pathogen/Disease controlled**	**References**
P. fluorescens 2-79	Phenazine-1 carboxylic acid (PCA)	*Gaeumamomyces graminis var. tritici* Take all of wheat	Thomashow *et al.*,(1990)
P. fluorescens LBUM636	Phenazine-1 carboxylic acid	Late blight of potato *Phytophthora infestans*	Morrison *et al.*, (2016)
P. fluorescens Pf1	HCN, siderophore, pyocyanin, fluorescin	Coleus root rot *M. phaseolina*	Vanitha *et al.*, (2014)
P. fluorescens Q2-87	DAPG	*P. syringaepv. tomato* in *Arabidopsis*	Vincent *et al.*, (1991)
		Take all of wheat	Harrison *et al.*, (1993)
	DAPG	*Gaeumamomyces graminis var. tritici*	Weller *et al.*, (2004)
P. fluorescens CHA0	DAPG	Take all of wheat	Stutz *et al.*, (1986)
		Gaeumamomyces graminis var. tritici	Voisard *et al.*, (1989)
		Black root rot of tobacco	
	DAPG, HCN	Damping off of cress and cucumber	Haas *et al.*, (1991)
	Pyoluteorin	Tomato crown and root rot disease	Keel *et al.*, (1992)
		F. oxysporum f. sp. radicis-lycopersici	Maurhofer *et al.*, (2004)
	HCN		Duffy and Defago, (2007)
P.fluorescens Pf-5	Pyoluteorin, pyrrolnitrin DAPG	*R. solani*and *Pythium ultimum* damping off of cotton	Howell *et al.*, (1979) Howell *et al.*, (1980)

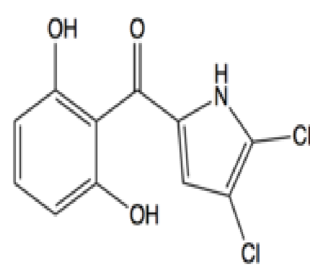
*DAPG-2,4-diacetylphloroglucinol, HCN- Hydrogen Cyanide



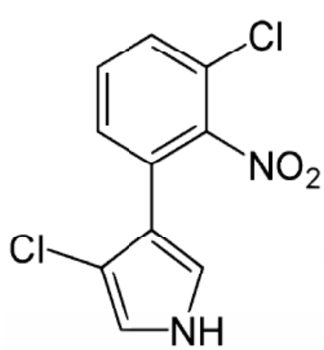
DAPG



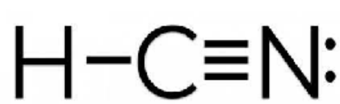
Phenazine-1-carboxylic acid



Pyoluteorin



Pyrrolnitrin



Hydrogen Cyanide (HCN)

Fig. 2. Structure of important volatile antibiotics released by *Pseudomonas fluorescens.*

A. Biocontrol Mechanism of Pseudomonas fluorescens

In recent years, a major diversity of rhizosphere microorganisms has been reported, characterized, examined and researched upon for their role as biocontrol agents against soil-borne phytopathogens. Microorganisms can produce various metabolic substances that can limit or reduce the damage caused by phytopathogens by producing antibiotics, variety of enzymes, side rophores and sometimes through induction of systemic resistance that incite general defence in the host plants. The microorganisms have also been found to function as competitors of pathogens for essential nutrients and ecological niche (Panpatte *et al*., 2016). The mechanisms through which the fluorescent *Pseudomonas* exerts its bio-control effects are:

Antibiosis through production of Antibiotics and secondary metabolites. Bacterial bio-control agents have been found producing antibiotics and are essential in management of various plant diseases as they are easy to isolate from the soil. The production of antibiotics can be affected by several factors such as pH, temperature and the levels of different metal ions, mainly of Zinc Zn^{2+}(Duffy and Defago, 1997). Amongst others, certain strains of the fluorescent pseudomonads have been focused upon due to their potential ability to control seed and soil-borne pathogenic fungi and Oomycetes (Keel *et al.,* 1992, Keel *et al.*, 1996). Effective biocontrol strains of *Pseudomonas* spp. with fewer exceptions, produce diffusible or/and volatile antibiotics that can inhibit pathogens *in vitro* (Haas *et al*., 2002). Fluorescent pseudomonads is peculiarly capable of synthesizing many antibiotics that help in the maintenance of plant pathogens as well as increase its own vigour (Mazzola *et al*., 1992; Gaur *et al*., 2004). Several of these antibiotics have a broad-spectrum activity however, strain-strain variations are also seen to exist (Raaijmakers *et al*., 2002). Moderate development pace of bacteria in the rhizosphere immensely favours the development of secondary metabolites (Haas and Defago, 2005).

Pseudomonas fluorescens can producemany secondary metabolites (Table 1) that allows it to successfully contend with other competing microorganisms. These include phenazine-1-carboxylic acid (PCA) (Laursen and Nielsen 2004; Mavrodi *et al.*, 2006; Weller *et al*., 2007), 2,4-diacetylphloroglucinol(DAPG) (Keel *et al*., 1996; Moynihan *et al*., 2009), rhizoxin (Tsuruo *et al*., 1986; Takahashi *et al*., 1990; Gross and Loper, 2009), pyoluteorin (Schinder *et al.,* 1995; Sarniguet *et al*., 1995) and hydrogen cyanide (HCN) (Ramette *et al*., 2003). Recently discovered novel antifungal metabolites such as tensin (Nielsen *et al*., 2000) and viscosinamide (Nielsen *et al.,* 1999) play a major role in protection against phytopathogens. *P. fluorescens* 2-79 (Table 1) synthesizes an antibiotic phenazine-1-carboxylic acid which was found to supress a disease pathogen *Gaeumanomyces graminis var. tritici* which is the causal organism of take all of wheat. The roots of wheat colonized by 2-79 strain were found to be having the antibiotic. The isolation of the strain 2-79 had been done in field studies as well as in growth chamber in USA (Thomashow *et al*., 1990). In another study, *P. fluorescens* strain LBUM636 was found to produce PCA which helped in the significant inhibition of late blight pathogen while its mutant that was not able to produce PCA only slightly altered the pathogen's growth (Morrison *et al*., 2016). Further proof for the part played by phenazines can be determined by the analysis of transposon insertion mutants that are unable to produce phenazine-1-carboxylate and are lessened in disease suppressiveness (Thomashow and Weller, 1988; Pierson and Thomashow, 1992). DAPG or 2,4- diacetyl phloroglucinol is an anti-fungal metabolite that is responsible for biocontrol abilities of *P. fluorescens* (Delany *et al*., 2000). DAPG is a phenolic metabolite possessing antifungal, phytotoxic and anthelminthic properties (Abbas *et al*., 2002). Haas *et al.,* (1991) and Keel *et al.,* (1992) stipulated the importance of DAPG that was produced by *P. fluorescens* strain CHA0 which helped in the suppression of wheat take all pathogen. DAPG along with HCN was proved efficient in the suppression of black root rot of tobacco produced by the *P. fluorescens* strain CHA0 (Stutz *et al*., 1986; Voisard *et al*., 1989). Pyrrolnitrin is seemed to be active against many fungi such as Deuteromycetes, Basidiomycetes and Ascomycetes. Karunanithi *et al*., (2000) had perceived that pyrrolnitrin an antibiotic compound produced by *P. fluorescens* was beneficial in inhibition of growth of *M. Phaseolina* which had produced an inhibition zone of 12 mm. Howell *et al*., (1980) indicated that pyoluteorinan antibiotic released by Pf-5 strain of *P. fluorescens* suppressed the growth of *Pythium ultimum,* causal agent of damping off in cotton. Also, pyoluteorin was responsible in suppression of damping-off of cress and cucumber which is released by the *P. Fluorescens* (Maurhofer *et al*., 2004). *P. fluorescens* strain Pf-5 which was isolated from the rhizosphere of cotton contained pyrrolnitrin and pyoluteorin which helped in the suppression of damping-off of cotton caused by *Pythium ultimum*and *Rhizoctonia solani* (Howell *et al*., 1979; Howell *et al*., 1980). Also, volatile organic compounds produced by *Pseudomonas fluorescens* strain ZX was helpful in the disease suppression of blue mould decay on postharvest citrus fruits (Wang *et al.*, 2021).

Risk is involved in using antibiotic-producing biocontrol agents, since plant pathogens are widely known to build resistance against antibiotics (Zhang *et al*., 2003).

Competition for space and nutrients. The soil microbes derive their nutrients from the plants mainly and are hugely dependent upon it. Rhizosphere's surface is remarkable carbon sink and amasses a huge number of diverse nutrients such as water, hydrogen ion, iron, oxygen, enzymes, vitamins, and other important secondary metabolites. The root harbours a lot of nutrients which creates competition for space and nutrients for the diverse number of microorganisms it attracts. Fungal pathogens can be eradicated from the soil by augmenting competition for nutrients such as carbon, nitrogen, oxygen, iron or water which hinders the ability of the fungal pathogens to disperse in the soil rhizosphere (Leong, 1986; Loper and Buyer, 1991). *Pseudomonas fluorescens* can adapt to such conditions and create competition for the pathogens which decreases the pathogen's chances of survival (Rovira, 1969). So, it is necessary to assess the ability of the bacterium in colonization of roots which in turn provides some protection against soil-borne pathogens. Weller *et al.*, (2002) defined root colonization as the phenomenon in which rhizobacteria introduced into the seeds, vegetative plant parts or soil get dispersed among roots growing in raw soil, multiply and survive for aninterval of time in the presence of indigenous soil macroflora. Most of the *P. fluorescens* strains have been found to have a short generation time which makes them great biocontrol agents. *P. fluorescens* strain WCS365 was seen to appear on the tomato root within 1 day of seed inoculation with the strain WCS365 (Chin-A-Woeng *et al*., 1997; Bloemberg *et al.,* 2000). O- antigen chain, a bacterial lipopolysaccharide can aid in root colonization. O-antigen side chain of PCL1205 strain of *P. fluorescens* is associated with root colonization in tomato plants (Dekkers *et al*., 1998). An example of competition for nutrients is limitation of iron as iron constitutes as a growth factor in all organisms. There is iron limitation in neutral and alkaline soils. *P. fluorescens* can utilize the ferrous ion through the production of siderophores. It gives an edge over other phytopathogens which do not possess efficient iron binding and uptake systems. Siderophore deficient mutants were found to be less effective against phytopathogens in comparison with their wild type of parental strains that had the ability to produce siderophores (Bakker *et al.*, 1986).

Table 2: Induced systemic resistance determinants by various *Pseudomonas fluorescens* strain in different plants.

***Pseudomonas fluorescens* strain**	**Host plant**	**Pathogen/Disease controlled**	**Bacterial determinant**	**References**
P. putida WCS358	*Arabidopsis thaliana*	*P. syringaepv. tomato*	Flagella	Meziane *et al.,* (2005)
P. putida WCS358	Bean Tomato Eucalyptus	Bacterial wilt *Ralstoniasolanacearum*	LPS Pseudobactinsiderophore	Ran *et al.,* (2005)
P. fluorescens WCS374	Radish	Fusarium wilt *Fusarium oxysporum*f. sp.*raphani*	LPS Pseudobactin siderophore	Leeman *et al.,* (1995) Leeman *et al.,* (1996)
P. fluorescens P3	Tobacco	Tobacco necrosis virus (TNV)	Salicylic acid	Maurhofer *et al.,* (1998)
P. putida BTP1	Bean	*Botrytis cineria*	*N*-alkylated benzylamine derivative	Ongena *et al.,* (2005)
P. aeruginosa 7NSK2	Tomato	*Botrytis cineria*	Pyocyanin Pyochelin	Audenaert *et al.,* (2002)
P. aeruginosa PM12	Tomato	Fusarium wilt *Fusarium oxysporum* Schlecht. f. sp. *lycopersici*	3-hydroxy-5methoxy benzene methanol (HMB)	Fatima and Anjum (2017)

*LPS-Lipopolysaccharides

Induced Systemic Resistance. Biocontrol agents generate chemical stimuli that activates the host defence mechanism of the host plants through biochemical changes which in turn imparts resistance against pathogen infections (Nega, 2014; Upadhyay *et al*., 2021). The stimulus generated by the plants are called as pathogen associated molecular pattern (PAMP's) and for those generated by microorganisms for the induction of resistance are called as microbe associated molecular pattern(MAMP's) (Kohl *et al*,. 2019; Upadhyay *et al*., 2021). Induced resistance can be defined as a state of improved defensive ability developed by plant reacting to a certain biotic or chemical stimulus (Van *et al*., 1998). Simply, Induced Systemic Resistance or ISR is a broad-spectrum plant immune response initiated by salutary plant bacteria that live in association with the plant roots. *Pseudomonas* spp. has been reported to induce ISR against diverse pathogens in several plant species through the process of priming (Nguyen *et al*., 2020). There are very few fluorescent pseudomonads (Table 2) that can trigger ISR response in the plants to fight against diverse phytopathogen infections(Van Wees *et al*., 1997; Kamilova *et al*., 2005). Immunized plants after such response show defence responses quicker and stronger when pathogen attacks resulting in upgraded level of protection. In 1991, Van Peer and his research group in the Netherlands discovered independently that ISR is a mode of action of plant growth promoting rhizobacteria (PGPR) mainly of the fluorescent pseudomonads group that helps in the suppression of diseases by eliciting ISR response in the plants (Van Peer *et al*., 1991). Flagellin a protein component of bacterial flagella may induce defence reactions in plants. In *Arabidopsis thaliana,* flagella's involvement in ISR was studied for *P. putida* strain WCS358 and it was observed that it triggered ISR response against *P. Syringae* pv. *tomato*. However, the mutant of WCS358 that was devoid of flagella was equally responsible for triggering ISR which suggests that, it also had other determinants that can elicit ISR response in the *Arabidopsis thaliana* plant(Gómez-Gómezand Boller, 2000; Zipfel *et al*., 2004; Meziane *et al*., 2005). In radish, *P. fluorescens* WCS374 strain's LPS played an important role in ISR against fusarium wilt caused by the pathogen *F. oxysporum* f. sp. *raphani.* Strain WCS374 was applied as a seed treatment to radish seeds which were able to reduce *Fusarium* wilt by average 42% and increase in the yield by average of 45%. Further evidence in the involvement of LPS in ISR, was provided by a study in which application of isolated LPS was carried along with the use of mutant strains that lacked O-antigenic side chain of their LPS. The mutants lacking O-antigen were not able to elicit ISR response in radish for reduction of disease incidence whereas; application of LPS was helpful in triggering ISR in the radish plant which helped in the significant reduction of fusarium wilt of radish (Leeman *et al*., 1995). In another study in bean and tomato, WCS358 strain mutant devoid of the O-antigen was unsuccessful in activation of ISR in bean and tomato plants while application of LPS was able in triggering the ISR response in bean and tomato plants (Meziane *et al*., 2005). *P. putida* WCS358 strain's *pseudobactin siderophore* was responsible for ISR in the control of bacterial wilt in eucalyptus. Penetration of leaves with the bacterium WCS358 or purified pseudobactin was salutary in reduction of bacterial wilt by triggering ISR response in eucalyptus whereas the mutant devoid of the pseudobactin siderophore was ineffective in doing so (Ran *et al*., 2005). Also, in another study, purified pseudobactin of WCS374 induced ISR in radish against fusarium wilt pathogen whereas, pseudobact in isolated from other strains were found ineffective in triggering ISR response in radish (Leeman *et al*., 1996). *P. putida* BTP1 is seen to induce ISR in bean to combat *Botrytis cineria* when grown in limited iron conditions in the field. The compound responsible for the triggering of ISR response in bean against *Botrytis cineria* was characterized as *N*-alkylated benzylamine derivative however, its mode of action seems to be the involvement in stimulation of lipoxygenase pathway (Ongena *et al*., 2002, Ongena *et al*., 2004, Ongena *et al*., 2005). *P. aeruginosa* 7NSK2 triggered ISR in tomato against *Botrytis cineria* with the combined action of pyochelin and pyocyanin. Mutants of 7NSK2 lacking any of the compounds pyochelin or pyocyanin did not induce resistance indicating that both compounds are necessary in induction of ISR as their combination significantly suppressed *B. cineria* (Audenaert *et al*., 2002). In a study, salicylic acid synthesis genes were taken from PAO1 strain of *P. aeruginosa* and were expressed in *P. Fluorescens* strain P3 which does not produce salicylic acid but was able to enhance ISR in tobacco against TNV (tobacco necrosis virus) indicating that salicylic acid can also induce the ISR response in tobacco against TNV (Maurhofer*et al.,* 1998). 3-hydroxy-5-methoxy benzene methanol (HMB) was found as the potential elicitor produced by *P. aeruginosa* strain PM12that helped in the induction of ISR in tomato plants against fusarium wilt pathogen (Fatima and Anjum, 2017). So, bacterial metabolites such as siderophores, lipopolysaccharides, salicylic acid, pyochelin, pyocyanin and other cell envelope components such as flagella are the potential bacterial determinants in the induction of ISR response in plants (Audenaert *et al*., 2002).

Production of Hydrogen Cyanide. There are different mechanisms involving the biocontrol of diseases by the bacterium *P. fluorescens.* HCN production by the fluorescent pseudomonads is salutary in effective biocontrol of phytopathogens (Voisard *et al*., 1989; Laville *et al*., 1998). HCN is renowned for its activities in disease management through the suppression of phytopathogens (Keel *et al*., 1989). Biocontrol agent *P. fluorescens* is involved in the suppression of diseases through the production of HCN in fungal phytopathogens such as *Septoria tritici* and *Puccinia recondite* f. sp. *tritici* in wheat plants (Flaishman *et al*., 1996), and *Thielaviopsis basicola* in tobacco (Voisard *et al*., 1989). HCN is thought to be involved directly in the inhibition of fungi which makes the bacterium effect equivalent to HCN mediated defence mechanism in plants(Luckner, 1990; Blumer and Haas,2000). HCN restrains the terminal cytochrome c oxidase in the respiratory chain and ties itself to metalloenzymes (Knowles,1976; Blumer and Haas, 2000). Siddiqui *et al.,* (2006) reviewed the important action played by HCN in disease suppression of root knot disease of tomato. HCN production appears to be confined to Proteobacterias, in which it has been proven in a few *Pseudomonas spp*. and to certain species of cyanobacteria (Blumer and Haas, 2000). Apart from its role in plant protection HCN has proved to be calamitous in its deleterious effects on several plants such as potato, lettuce etc. (Bakker and Schippers, 1987; Alstrom and Burns, 1989; Kremer and Souissi, 2001). These deleterious HCN producing strains have been researched upon for biocontrol of weeds and might be a possible biocontrol agent for weeds such as barnyard grass, green foxtail etc. (Kremer and Souissi, 2001).

Production of siderophores. Biocontrol may implicate suppression of pathogens by stripping it off of nutrients. Iron is mostly available on the earth's crust but most of it is found in its insoluble form that is ferric hydroxide. Iron is not readily available at neutral and alkaline pH. Bacteria need iron at micromolar concentrations for growth, so they have evolved high-affinity iron uptake systems to provide iron into the plant cell (Neilands and Nakamura, 1991). Siderophores are low molecular weight Fe^{3+} specific chelators which are produced by many aerobic and facultative anaerobic microorganisms including fluorescent *Pseudomonads* spp. under very low iron concentration circumstances. The siderophores are involved in the sequestration of ferric ions in the environment and such ferrated siderophores are taken up by the microbial cells via specific recognition by membrane proteins (Höfte, 1993). The mode of action of these siderophores is competition between plant pathogens and *P. Fluorescens* (Loper and Buyer, 1991). Siderophore's different affinity towards ferric ion depends on their structure which is hydroxymate and phenolate type structures, classified as pyoverdins and pseudobactins respectively (O'sullivan and O'Gara, 1992). In case of pathogens, siderophores are either unproduced or if produced are of lower affinity in comparison to salutary microorganisms, therefore, phytopathogens have a lesser chance in accumulation of iron for their growth (Lemanceau *et al*., 1992). Kloepper *et al.*, (1980) isolated fluorescent siderophore from the strain B10 that proved to have disease suppression actions. A mutant of *Pseudomonas spp.* strain WCS358 that is deficient in siderophore, lost its ability in enhancing the growth of potatoplants whereas the wild strain of WCS358 was fully capable in enhancing the growth of the potato plants (Bakker *et al*., 1986). In a nutshell, the growth of pernicious microorganisms is confined by the restriction of iron accessibility in the soil rhizosphere due to iron competition between them and *Pseudomonas* spp. (Loper and Buyer, 1991).

CONCLUSION

Huge progress has been made over the past few years in understanding the root colonization phenomenon by the fluorescent pseudomonads along with the several mechanisms through which it helps in suppressing soil borne phytopathogens. Remarkable advances have been made in the 21st century regarding the biotechnology of *P. fluorescens* biocontrol agents for the protection of crops. Biocontrol agents require assistance even after their application for proper establishment in the soil rhizosphere whereas chemical pesticides do not require it. So, to ensure biocontrol we must give emphasis to the quality of the biocontrol agent as well as keep an eye on how it performs in the niche while competing with other pathogens. *P. fluorescens* has a huge prospect in the future as a biocontrol agent and as a plant growth promoter in sustainable management practices. The major limitations of *P. fluorescens* in biocontrol are its shelf life and its incongruous performance in the field which can be improved upon by further research works in the days to come.

FUTURE PROSPECTS

In present scenario, it is mandatory to use eco-friendly methods in the management of agricultural practices. Anthropogenic activities have poseda threat to soil health and productivity. Indiscriminate use of chemicals such as pesticides, insecticides and fertilizers has deteriorated the environment and the ecological balance. We have become too much reliant on the use of chemicals for farming. Agrochemicals might pose as a swift solution to everything in the present but might create severe problems for the future generations. We must adapt to sustainable farming methods for the conservation of soil health and ecological balance. For practicing sustainable agriculture, we must consider the use of biocontrol agents for disease management and plant growth. *Pseudomonas fluorescens* is a PGPR that can help in both plant growths as well as in the management of diverse plant diseases. It has been used as a bio-fertilizer as well as a biocontrol agent since decades in the field of agriculture. It has colossal potential in the fulfilment of plant nutrients, suppression of several phytopathogens, bioremediation etc. Therefore, it has immense potential as an alternative to agrochemicals, since it is cheaper, efficient, eco-friendly and an effective PGPR in the augmentation of crop yield. Apart from this, it reduces input costs and environmental pollution. The future prospects might include easy *in situ* multiplication methods, longer shelf life, identification of potential biocontrol strains and further insight into its genetic, proteomic and transcriptional up and down regulation that are playing a major role in plant defence against many biotic and abiotic stresses.

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