Soil Biology & Biochemistry xxx (2014) 1–9

Contents lists available at ScienceDirect

Soil Biology & Biochemistry

journal homepage: www.elsevier.com/locate/soilbio

Review

Scoping the potential uses of beneficial microorganisms for increasing productivity in cotton cropping systems

Q2 Lily Pereg*, Mary McMillan

School of Science and Technology, University of New England, Armidale, NSW 2351, Australia

ARTICLE INFO

Article history:
Received 10 July 2014
Received in revised form
30 September 2014
Accepted 22 October 2014
Available online xxx

Keywords:
Biofertilization
Biocontrol
Phytostimulation
PGP
Cotton

ABSTRACT

There is a growing body of evidence that demonstrates the potential of various microbes to enhance plant productivity and yield in cropping systems. Realizing the potential of beneficial microbes requires an understanding of the role of microbes in growth promotion, particularly in terms of fertilization and disease control, the underlying mechanisms and the challenges in application and commercialization of plant growth-promoting (PGP) microbes. This review focuses specifically on the use of PGP microbes in the cotton industry and summarizes the commercial bioinoculant products currently available for cotton; highlighting factors that must be considered for future development of PGP microbial products for the cotton industry. Given the paucity of information on beneficial microbes for cotton production systems in comparison to those for other cropping systems (e.g. legumes and grains), a snapshot of the current research is critical in light of the increased interest in cotton inoculants, mainly in developing countries such as India, and the overall increased interest in PGP applications as part of promoting sustainable agriculture.

1. Introduction

Agricultural industries such as the cotton industry rely heavily on the use of chemical fertilizers, herbicides and pesticides. One of the aims of agricultural biotechnology is to develop microbial inoculants to enhance plant growth and suppress plant disease, with a key goal of reducing reliance on chemical fertilizers and pesticides (Adesemoye et al., 2009). Many factors need to be taken into consideration during the development of such inoculants commercially (Berg, 2009) including selection of appropriate plant growth-promoting (PGP) microbes based on target host plant, soil type, indigenous microbial communities, environmental conditions, inoculant density, suitability of carriers and compatibility with integrated crop management.

Plant growth and productivity is heavily influenced by the interactions between plant-roots and the surrounding soil, including the microbial populations within the soil. The plant rhizosphere harbours microorganisms that may have positive, negative or no visible effect on plant growth. Although most rhizospheric microbes appear to be benign, deleterious microorganisms include pathogens and microbes producing toxins that inhibit root growth or those that remove essential substances from the soil. By contrast the main mechanisms for plant growth promotion include suppression of disease (biocontrol); enhancement of nutrient availability (biofertilization); and production of plant hormones (phytostimulation) (reviewed by Martinez-Viveros et al., 2010; Bhattacharyya and Jha, 2012). Studies of PGP microbes indicate that multifunctionality is a hallmark of the most beneficial (Vassilev et al., 2006; Avis et al., 2008).

The indigenous rhizospheric microbial population of agricultural soils is greatly influenced by agricultural practices (e.g. soil cultivation, season, stubble retention, burning etc.), crop plant species, cultivar and genotype, as well as soil type (Berg and Smalla, 2009; Reeve et al., 2010). Plant exudates may cause changes to soil characteristics such as pH and carbon availability, impacting the diversity and activity of microbial populations (Haichar et al., 2008). Bioaugmentation, the addition of microbes to agricultural soils, thus becomes a valuable influence on soil microbial processes.

In light of this, the question under consideration is the potential for successful application of biofertilization, biocontrol and phytostimulation in cotton production systems. This review summarizes the types of PGP microbes and the mechanisms by which they enhance plant growth, with particular attention to those tested on cotton, and discusses the factors essential to the practical application and commercialization of microbial inoculants for cotton. In addition, currently available commercial PGP and biocontrol products for cotton production systems are evaluated.

* Corresponding author. Tel.: +61 2 6773 2708; fax: +61 2 6773 3267.
E-mail address: lily.pereg@une.edu.au (L. Pereg).

http://dx.doi.org/10.1016/j.soilbio.2014.10.020
0038-0717/© 2014 Published by Elsevier Ltd.

2. Plant growth promotion in cotton: biocontrol, biofertilization and phytostimulation

2.1. Mechanisms of disease suppression

Globally, crop growth protection and health is continuously challenged by emerging, re-emerging and endemic plant pathogens (Miller et al., 2009). Chemical pesticide and fungicide use has led to environmental concerns and pathogen resistance, forcing constant development of new agents (Fernando et al., 2006). Rhizospheric microbes that suppress plant pathogens could be used as biocontrol agents, and may be considered as alternative to chemical pesticides. There are a number of mechanisms for plant pathogen suppression including direct inhibition of pathogen growth through production of antibiotics, toxins, hydrogen cyanide (HCN) and hydrolytic enzymes (chitinases, proteases, lipases) that degrade virulence factors or pathogen cell-wall components (reviewed in Whipps, 2001; Compant et al., 2005).

Antibiotics are a normal part of the self-protective arsenals of bacteria, such as *Pseudomonas* species (e.g. *Pseudomonas fluorescens* strains) (Haas and Defago, 2005) and *Bacillus* species (e.g. *Bacillus subtilis*) (Kim et al., 2003), as well as fungal species such as *Trichoderma*, *Gliocladium, Ampelomyces* and *Chaetomium* (Kaewchai et al., 2009) and therefore these organisms have great potential for soil conditioning. Multifunctional organisms such as *Trichoderma harzianum* Rifai 1295-22 appear to enhance plant growth by solubilising phosphate (P) and micronutrients required by plants, such as iron and manganese, and also suppresses plant pathogens (Altomare et al., 1999). HCN production suppresses microbial growth and may inhibit pathogens such as root-knot, bacterial canker and black rot in tomato and tobacco (Voisard et al., 1989; Siddiqui et al., 2006; Lanteigne et al., 2012). However HCN might be harmful to plants by inhibiting energy metabolism and reducing root growth (Siddiqui et al., 2006). Many different bacterial genera produce HCN, including *Alcaligenes*, *Aeromonas*, *Bacillus*, *Rhizobium* and *Pseudomonas* spp. (Ahmad et al., 2008).

Pathogen suppression can also occur competitively through indirect inhibition. Selected bacteria and fungi produce siderophores as iron chelating agents especially during iron deficiency (Sharma and Johri, 2003), including *Bradyrhizobium*, *Pseudomonas*, *Rhizobium*, *Streptomyces*, *Serratia*, and *Azospirillum* (Martinez-Viveros et al., 2010). Their ability to deplete iron from their surroundings makes it unavailable to pathogenic fungi, creating a competitive advantage (O'Sullivan and O'Gara, 1992; Loper and Henkels, 1999). Inoculation with siderophore-producing bacteria grown under iron limiting conditions has a positive effect on plant growth (Carrillo-Castaneda et al., 2002); however the potential role for a combination of several PGP mechanisms and not siderophore production alone cannot be discounted.

Other mechanisms involved in disease suppression include activation of the plant's own defence system, known as induced systemic resistance (ISR). Volatile compounds released by PGP bacteria and fungi can trigger ISR, resulting in enhanced expression of defence-related genes in the host (Ryu et al., 2005; Hossain et al., 2007; Naznin et al., 2014).

2.2. Microbes that suppress disease in cotton

Cotton pathogens present a high economic burden to growers (Pereg, 2013). Seedling disease complexes are caused by several fungal and bacterial pathogens including *Pythium ultimum, Rhizoctonia solani, Fusarium* spp., *Verticillium* spp., *Thielaviopsis basicola* and *Xanthomonas campestris* pv. *malvacerum* (*Xcm*). Management strategies to prevent disease include selection of suitable varieties and planting times, crop rotation with non-host species, optimised seed bed preparation and irrigation schedules, agrochemicals and improved farm-hygiene practices. Unfortunately, quite often fungicides are not effective against soil-borne pathogens and management strategies that control disease caused by one pathogen not only may not be effective in controlling others but might actually increase damage by other pathogens (Pereg, 2013). Disease-resistant cotton varieties with increased resistance to *Fusarium* and *Verticillium* spp. have been selected (Kappelman, 1980; Gore et al., 2009). While pathogen-specific resistance can be incredibly valuable, this is too restrictive in the face of the number of cotton pathogens, and commercial transgenic varieties with resistance to multiple soil-borne diseases are currently unavailable. Despite attempts to develop such resistant variants, cotton seedling disease remains an ongoing issue for producers. Consequently the studies that have identified PGP microbes with potential as biocontrol agents against common cotton pathogens (see Table 1) provide an important alternative.

Table 1
Biocontrol agents identified to control common cotton pathogens.

Biocontrol agent	Pathogen/s controlled (geographic region)	References
Trichoderma virens	*Pythium ultimum (USA)*	Howell, 1982; Howell and Stipanovic, 1983; Howell, 2002
	Rhizoctonia solani (USA)	Howell et al., 2000
	Fusarium oxysporum	Zhang et al., 1996a
	Verticillium dahliae	Hanson, 2000
Pseudomonas fluoroscens	*Pythium ultimum*	Howell and Stipanovic, 1980; Loper, 1988; Hagedorn and Nelson, 1990; Howie and Suslow, 1991; Loper, 1988
	Rhizoctonia solani	Howell and Stipanovic, 1979
	verticillium dahlia	Mansoori et al., 2013; Erdogan and Benlioglu, 2010
	Xanthomonas campestris (Xcm) (India)	Habish, 1968; Mondel et al., 2000, 2001
Streptomyces lydicus	*Pythium ultimum (USA)*	Yuan and Crawford, 1995
Burkholderia cepacia	*Rhizoctonia solani (USA)*	Zaki et al., 1998
Trichoderma harzianum	*Rhizoctonia solani (Israel)*	Elad et al., 1980
	Fusarium oxysporum	Sivan and Chet, 1986
Cladorrhium foecundissimum	*Rhizoctonia solani (Argentina)*	Gasoni and Stegman de Gurfinkel, 2009
Bacillus subtilis	*Fusarium oxysporum*	Zhang et al., 1996a
	Verticillium dahliae	Mansoori et al., 2013

A number of organisms can cause damping-off in cotton, resulting in substantial losses to growers. *P. ultimum* soil infestation is one such organism, but research has demonstrated that several rhizospheric microbes have an antagonistic effect against *P. ultimum* infection in cotton, such as *Entobacter cloacae* and *Erwinia herbicola* (Nelson, 1988). The fungus *Trichoderma (Gliocladium) virens* improves the survival of cotton seedlings, possibly due to the production of the antibiotic compound gliovirin (Howell, 1982; Howell and Stipanovic, 1983). Several *Trichoderma* spp. control the disease by competing for metabolites released from the germinating seeds (Howell, 2002). *P. fluorescens* increases seedling survival and cotton stand in *P. ultimum* infested soil, possibly through antibiosis and antagonistic siderophore production (Howell and Stipanovic, 1980; Loper, 1988; Hagedorn and Nelson, 1990; Howie and Suslow, 1991). *Streptomyces lydicus* can destroy germinating oospores and damage the cell walls of fungal hyphae, making it a potential biocontrol agent against *Pythium* seed and root rot in cotton and other crops (Yuan and Crawford, 1995).

Similarly *R. solani* also plays a critical role in the pronounced losses due to cotton damping-off. Seed treatment with a *P. fluorescens* strain from the rhizosphere of cotton seedlings, or pyrrolnitrin, an antibiotic produced by *P. fluorescens*, greatly increased seedling survival in *R. solani* infested soils. Pyrrolnitrin