Integrating Biological Control Agents for Sustainable Management of Soybean Diseases in India

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ABSTRACT:
Despite hefty production and application of new technologies for soybean production in India, the crop suffers from various diseases that induces heavy losses. This in turn place a heavy burden on the output and the quality through high-cost treatment, making it really a problem for the farmers. However, injudicious use of pesticides causes problems with secondary pest emergence, potential threat to the environment, pathogen invulnerability, and crop residues. The promise of biological control for the freeway to control major soybean diseases infecting, such as soybean rust, charcoal rot, bacterial pustule, or downy mildew. *Trichoderma spp., Pseudomonas fluorescens,* and *Bacillus spp*. are widely used as biological control agents (BCA) owing to their mechanism, which consists of antibiotics, competition, parasitism, and ISR, both suppressing pathogens and promoting plant well-being. Specific biological control strategies, such as seed treatment, soil and foliar application, as well as the compatibility of biological control with cultural practices for disease management, are discussed. The review also shows the issues involved with implementing BCA in these different agroecological regions of India. Aspects of environmental heterogeneity, lack of storage infrastructure, and farmer education are also discussed.

1. Introduction

1.1 Overview of Soybean Cultivation in India

Soybean (*Glycine max*) is among the world's most valued crops Suffice, it is grown in India primarily for food and industrial use, partly due to its rich protein and oil content. Soybean is produced in large quantities in India; it is usually grown in the states that include Madhya Pradesh, Maharashtra, as well as Rajasthan (Tiwari, 2017). Soybean is not just an income generation crop for millions of farmers but also a strategic food security crop for India. Soybean can therefore be grown for cooking oil, feed for animals and a variety of protein foods. In the same way, soybean improves soil fertility and its resistance to various diseases and pests without the use of chemical inputs which lead to low soil health (Kumar et al., 2017).
However, several constraints affect production of soybean in India most of which include increasing diseases infections which affects not only the quantity but also quality of produce. India has experienced a number of ups and downs in the soybean yields over the last decade due to numerous biotic stresses among them diseases from pathogens like fungi, bacteria, and virus (Singh, & Sharma, 2021). Sustainable and profitable farming of soybean in the region therefore requires appropriate disease management.

1.2 Challenges in Soybean Cultivation

Soybean diseases which include rust, charcoal rot, bacterial pustule and root rot diseases were noticed to greatly affect the yield in India. Ward et al. (2012) established that 60 percent yields loss could be occasioned by rust alone provided it was not controlled. Pesticides have been the dominant form of disease management in the soybean crop; however, the extensive use and continuous application of chemicals have resulted in the following drawbacks;(Sethi, & Saesaeb, 2018). However, chemical pesticides are expensive and any addition to the cost of production is unbearable to many small holder farmers. This economic loss goes hand in hand with growing post-harvest consumer expectation of products free from chemical residues in their agricultural produce, elevating the pressure for other effective disease management methods (Devi et al., 2015).

1.3 Need for Biological Control

Biological control seems to be a viable solution to chemical treatment especially for many resources poor farmers in India in search of affordable methods of controlling diseases. Biological control methods involve use of natural enemies like antagonists that are bacteria and fungi that check the growth of pathogenic organisms and so minimizes on the use of synthetic pesticide. However, chemical control has several limitations because it affects both target and non-target organisms, while BCA, as an environmentally friendly method, has little or no effect of the environment. Moreover, BCAs can simply be incorporated into the working of modern agriculture since they complement disease control, without necessarily complicating or altering conventional farming techniques (Pawar et al., 2015).

Latest investigations show that Trichoderma spp. and Pseudomonas fluorescens are effective antifungal bio control agents due to mechanisms such as competition and antibiosis and induced systemic resistance (Kavitha & Rajendran, 2023). The beneficial microbes not only suppress the pathogens by their direct adverse action but also help in enhancing the soil health thus following integrated management of crops diseases (Meena et al., 2017). The past few years of research and mentioned successful case histories of biological control suggest that it can be a key component of sustainable soybean disease management in India.

Hereby the proceedings of the review are made to compile the existing information regarding the biology control of soybean diseases especially in Indian context. The following are the objectives of the study; A major purpose of this study is to analysis the major soybean diseases or pests in India and their economic analysis. The nature and kinds of bio control measures and their method of operations that are applicable in soybean diseases are also described here. The effectiveness of the field application strategies for biological control as well as some subjects are also discussed in this research paper.

2. Principal Diseases Incidentally Affecting Soybean in Indian Context

Soybean (Glycine max) production in India is hampered by several diseases' resultant of fungal, bacterial as well as viral origin. These diseases cause significant yields reductions and Soybean crop quality thus disease control remains core business in production. The following section describes the most common soybean diseases in India, their pathogen, signs, and effects on soybean production.

2.1 Soybean Rust

Soybean rust disease or Soybean stem rust which is primarily caused by the fungus *Phakopsora pachyrhizi* is one of the most destructive diseases of soybean crops of India. This is a disease that is indicated by small, reddish-brown to dark-brown discoloration on the underside of the leaves. During the advance stage of the disease, leaves develop chlorosis and drop early, thus minimizing the leaf surface area and have a direct impact on yield (Rani & Kumar, 2018). Well, under favorable environment (high humidity and moderate temperature) it can spread quickly to lead to yield loss ranging between 40-60% if not controlled (Borah & Deb, 2019). Because it is common, rust has become one of the key focuses of soybean diseases control measures in India.

2.2 Charcoal Rot

Charcoal rot is another disease that affects soybean production in India and stretches from Punjab down to the south; it is caused by the soil-borne fungus *Macrophomina phaseolina* more so, in dry areas with high temperatures. The disease impairs the plant's water transport system leading to rotting of root and stem portion of the plant. Such include wilting, early defoliation and the formation of black micro sclerotia on the root and stem initials making them appear like charcoal (Borkar, 2020). The pathogen is more prevalent in regions that experience the drought condition and is very persistent to control in the soil. Yield loss due to charcoal rot can be up to 30 per cent and depends on the environmental factors and management practices (Nataraj et al., 2019).

2.3 Bacterial Pustule

A non-host disease, bacterial pustule, is caused by *Xanthomonas axonopodis pv glycines* and occurs in the mid and the South India particularly in the humid zones. Initial signs and apparent features by the pathogen are small water soaked spots that later form pustules on the epidermal layer of the leaves; these pustules are surrounded by a narrow yellow zone (Sharma & Thakur, 2018). Bacterial pustule on its own does not reduce yields dramatically, however what it does is that the plants become more vulnerable to other diseases especially under conditions of high humidity and high temperatures. Some of the methods used (Procedures of controlling this disease include crop rotation and using resistant varieties) though such measures cannot be adopted by small (Sharma et al., 2022).

2.4 Rhizoctonia Root Rot

Rhizoctonia root rot from *Rhizoctonia solani* is another common fungal soil borne disease, which can infect soybean plants at different stages of development including seedlings as well as at maturity. Affected plants display signs of root rot, stem fungal infections, and yellowing and browning of the lower leaves and resulted in poor plant growth and development (Khodke et al., 2010; Upadhyay et al., 2022). Rhizoctonia root rot is more serious in heavy soil and seems to be favored by cool, wet conditions. Losses from this disease may be partly in terms of yield as it relates with the root system and its ability to pull nutrients from the soil affecting crop yields (Kaur & Sidhu, 2023).

2.5 Downy Mildew

Other fungal disease that affects soybean fields in India include Downy mildew – *Peronospora manshurica*. It normally develops on the leaves and causes greenish yellow to pale yellow circular or irregular patches on the upper surface of the leaves with grayish white fungal mycelium on the lower surface. Downy mildew disease prefers high humidity and moderate temperatures therefore offered seasonally in certain regions of India (Das & Chattopadhyay, 2019). Yield reductions by downy mildew are usually less severe compared to other diseases, but if not well controlled, it will greatly influence seed quality and weak plant growth. Control measures involve crop rotation, resistant varieties, but the disease is normally combated by chemical control in affected areas.

2.6 Yellow Mosaic Virus

Mungbean Yellow Mosaic Virus (MYMV) & Whitefly (*Bemisia tabaci*) of Soybean: Yellow mosaic virus (YMV) is the most devastating viral disease affecting soybean crops in India. In this disease, symptoms appear on the plant leaves as yellow mosaic patterns, that affect the amount of photosynthesis and thus poor plant growth and yield. YMV occurrence has elevated because of increased whitefly populations, especially where there are warm and dry conditions (Swati et al., 2023). Yield losses because of YMV may vary between 20 and 80 per cent depending on the potency and impact of the disease as well as the variety of the crop (Gupta & Lal, 2022). The management of YMV is difficult partly because there are few resistant varieties and whiteflies are mobile insects.

2.7 Impact on Yield and Quality

These diseases account for major quantitative loss in India with soybean production being prone to such diseases. Yield losses from major diseases are estimated to be between 10 and over 50 % depending on disease type, environment and control measures. For instance, rust alone decreases yield between 40-60%, charcoal rot and yellow mosaic virus causes yield loss between 20-50% (Ward et al., 2012). Besides yield loss, diseases of germinating seeds impair seed quality, including germination capability and oil contents that, in turn, decrease the market value of the crop (Tiwari, 2014). These diseases collectively dictate the necessity of aggressive, composite disease management models using efficient and 'green' techniques like biocontrol.

3. Biological Control Agents in Soybean Disease Management

In managing diseases of soybean crops, BCA's has been used in controlling major diseases that affect the crop. Biological control agents (BCAs) are environmental friendly and reduce the use of chemical control to minimal levels which makes it a sustainable method of soybean diseases control by exploiting the natural existing antagonistic relationship between useful organisms and pathogenic microorganisms. Soybean pathogens are suppressed by BCAs including beneficial fungi, bacteria, and viruses through mechanisms such as competition, antibiosis and parasitism as well as the activation of systemic resistance mechanisms. The kind of biological control agents in use especially with regards to soybean disease, their functioning and roles of such control in overall control of soybean diseases in India are also highlighted here.

3.1 Microorganisms That Enhance Successful Defense of Soybean Diseases

There are some good microbes that can work as BCAs against soybean diseases, *Aspergillus flavus, Cochliobolus sterili, Diplodia maydis, Macrophomina phaseolina, Mycosphaerella tomatophila, Penicillium spp* and more. Key examples include:

Trichoderma spp.: Soybean diseases managed by Trichoderma fungi have ranked the fungi as some of the most researched and applied biocontrol agents. It is noteworthy that they show antagonistic effects with a wide range of pathogens such as *R. solani, M. phaseolina, and P. pachyrhizi*. For illustration, *Trichoderma harzianum* demonstrated effectiveness in counts regarding root rot and rust by outcompeting, toxin release and actual parasitism of pathogenic fungi (Goswami et al., 2019). Studies conducted on field tests in India have revealed that Trichoderma biocontrol agents provided in formulations enhanced the value-added impact through minimizing the disease effects and maximizing plant growth and root growth (Kumar et al., 2014).

Pseudomonas fluorescens: This beneficial bacterium is yet another high-value BCA that controls bacterial pustule and downy mildew of soybean through antibiosis, competition and ISR in soybean plants (Rajput & Yadav, 2020). Research has also found that foliar sprays of Pseudomonas fluorescens decrease disease intensity and increase yield besides making the soybean plant more resistant to subsequent attacks (Sharma et al., 2022).

Bacillus spp.: Different types of *Bacillus* for example *Bacillus subtilis* and *Bacillus amyloliquefaciens* has mechanisms of inhibiting the pathogens through release of lipopeptides, enzymes and Antibiotics. Work done by Zhang et al. (2009) has demonstrated that Bacillus subtilis has the potential to combat *Phytophthora sojae* – the pathogen responsible for soybean root rot – through the release of antifungal secondary metabolites and exclusive biofilm formation which hinders pathogen adhesion and colonization. Also, these bacteria improve plant nutrient uptake and thus have potential use in an integrated pest management systems (Zeng et al., 2012).

3.2 Mechanisms of Biological Control

Biological control agents have devised several strategies with which they can effectively control pathogens and prevent plant diseases. Some of the primary mechanisms include:
Antibiosis: In this mechanism, BCAs generate toxic factors including antibiotics, lytic enzymes and secondary metabolites that deter or suppress the growth of pathogens. For instance, chitinases and glucanases which are enzymes produced by Trichoderma spp. its used to break the cell walls of pathogenic fungi (Sarkar, & Singh 2019). Like this implication, *Pseudomonas fluorescens* produces ant-bacterial antibiotics like phenazine and pyocyanin against bacterial and fungal pathogenic outputs in soybean (Prabhukarthikeyan et al., 2018).
Competition: BCAs limit the opportunities for a pathogen to find nutrients and space to grow and spread on the plant, to filter out. For instance, Bacillus subtilis forms biofilm on the root hair of soybean and competes with the soil pathogens for niche and resource to minimize chances of pathogenic invasion (Thakur et al., 2022). This competitive exclusion is most useful on diseases such as Rhizoctonia root rot, which is all about pathogens colonizing the root zone.
Parasitism: Some biocontrol agents have a positive pathogenicity; on infesting the pathogen it causes death of the latter. Trichoderma spp. forms biofilms on the hyphae of the attacking fungal pathogens and invades their cell walls and absorbs nutrients from the host cells which kills the fungus (Martanto et al., 2020). In soybean rust and root rot diseases for example this mode of action has been quite effective.
Induced Systemic Resistance (ISR): Some BCAs elicit the plant's own defense mechanisms and make the plant more resistant to a few pathogens. It has been demonstrated that Pseudomonas fluorescens and Bacillus spp. cause ISR in soybean plants via the liberation of chemical signals to the plant defense requisite genes, thereby increasing the plant's resistance to infective organisms (Meena & Kalyan, 2018). This "priming" effect of course facilitates rapid and effective reaction from the plant on attacks from pathogens in a bid to cut incidences of disease.

3.3 Particular Uses of Biocontrol Agents in Soybean Diseases

There has been successful use of biocontrol agents in different methods, for the control of soybean diseases. These applications include:
Seed Treatment: So, when application of *Trichoderma harzianum* or *Pseudomonas fluorescens* is done on the soybean seeds it has been proved effective in controlling diseases like root rot and charcoal rot. Seed treatment guarantees that the beneficial microbes take an early root in the root zone to protect against pathogen attacks from the seedling stage (Yu et al., 2022). According to the literature, the treatment of seeds with BCAs resulted in enhanced stand, vigor, growth and yield, and decline in the use of chemical fungicides (Bailey, & Lazarovits, 2003).
Soil and Foliar Applications: The effect of bacterial inoculation through local application of Bacillus subtilis has been found successful in lessening the severity of RR by forming a barrier of antagonistic microbes over the roots of soybean. Foliar sprays containing Pseudomonas fluorescens successfully control foliar diseases such as the bacterial pustule and downy mildew diseases as the applied strain of biocontrol agent must come into direct contact with the pathogen on the leaves (Pathak & Sharma, 2022). The results have also revealed that foliar application is beneficial in areas of high humidity due to foliar diseases.
Integration with Cultural Practices: The use of biocontrol agents supplemented with standards methods like crop rotation, residue management and soil treatment can greatly improve disease modulation. For instance, growers might choose to rotate soybean with non-host crops, and

apply Trichoderma in soil amendments, which have been found to reduce the pathogen load in the ground and lower the occurrence of diseases such as charcoal rot (Khan et al., 2019). They make it possible to adopt a sustainable disease control in soybeans besides minimizing one's reliance on chemical pesticides.

3.4 Strength and Weaknesses of Biocontrol Agents

The advantages of BCAs include the use of these natural and biological agents is ecological friendly, there is little chance of developing resistance to the pests, and lastly the soil is generally benefited in terms of health. However, some of the limitations encountered during field application are; inconsistency in its effectiveness influenced by conditions in the field, competition with native microorganisms and some formulations of BCA have a short shelf life (Ward et al., 2012). Therefore, to obtain the optimum outcome from the biocontrol agents it is important to develop the formulation improvements, quality of BCAs and widespread integration of BCAs into the disease management strategies.

4. Biological Control Strategies for Soybean Diseases in India

Diseases have always been a crucial challenge for soybean production in India and as such understanding more about them would be beneficial to farmers and participants in the industry. Effective use of BCAs therefore depends on selected strategies that involve the use of these agents at various stages of soybean crop management. India has successfully used seed treatment, soil and foliar application techniques as an effective alternative for soybean bio-control diseases in conjunction with cultural practices. This section describes the primary biological control measures adopted in India and reveals the problems faced in their practice.

4.1 Seed Treatment

Application of BCAs during seed treatment is a common practice adopted in soybean disease management. Applying BCAs to seeds effectively creates an early shield in the root zone in an attempt to lock out the soil borne pathogens. Microorganisms that could be applied are *Trichoderma harzianum*, Pseudomonas fluorescens, Bacillus subtilis and so on (Nakkeeran et al., 2016). Seed treatments are useful against root rot, charcoal rot and damping-off diseases since the pathogen is in the soil and the plant is first attacked when it is very young.

In India, studies have indicated that the use of *Trichoderma harzianum* on seeds minimized disease occurrence by thirty percent or more with untreated seeds. Moreover, this practice has been found to have an effect of increasing the seed germination, stimulating root development as well as increasing vigour of the plant (Zeng et al., 2012). Seed treatment is especially beneficial for small holders farmers because it uses a little amount of BCAs and is therefore cheap to apply. But the effectiveness of seed treatment aspects depends on the prevailing environmental conditions; high soil moisture and temperature fluctuations are known to influence the effectiveness of the BCAs (Patel & Gupta, 2021).

4.2 Soil Application

Soil application of BCAs is another successful measure of controlling soil-borne pathogens especially in the affected regions. This method involves incorporating BCAs into the soil or standardizing application around the root region to build a good microbial population that inhibits pathogenic microorganisms. Trichoderma spp. and B. subtilis are used directly on seeds before planting or as drench around the plant base while P. fluorescens is applied on seeds prior to planting (Sarma et al., 2011).

Soil treatments with *Trichoderma harzianum* have been found to control pathogens like *Macrophomina phaseolina*, the causal pathogen of charcoal rot, and *Rhizoctonia solani*, the root rot pathogen, because of *T. harzianum* inhibitory effect on pathogen colonization of the rhizosphere. Studies conducted on field also have also demonstrated soil application of *Trichoderma* reduced diseases by about 40% and promoted plant growth and yield (Massart et al., 2015). These practices are especially applicable for farmers who use conservation tillage since this approach affects the soil least while encouraging microbial activity in the root profile. However, factors like uniformity of the substrate in relation to soil, and the indigenous microbial load influences the outcomes of the applications on soil (Pandey & Ranjan, 2020).

4.3 Foliar Application

These include applying the BCAs directly to the foliage in order to prevent or control foliar diseases such as rust, bacterial pustule and downy mildew. This strategy is effective because it directly attacks pathogens onto the exterior of the leaf in which the infection starts. During foliar application; both *Pseudomonas fluorescens* and *Bacillus subtilis* are more frequent as they counter both bacteria and fungi (Ward et al., 2012).

In India foliar spray with Pseudomonas fluorescens have proved effective in reducing the incidence of bacterial pustule as *Xanthomonas axonopodis* is the causative agent (Kumar & Srivastava, 2022). Likewise, the control of rust and downy mildew by foliar application of Bacillus subtilis was also successful. Antimicrobial compounds on the outer face of leaves of these BCAs inhibit the likelihood of pathogens gaining a foothold. Foliar applications also prompt the establishment of systemic resistance in plants to future infections by pathogens (Sheoran et al., 2024).

Foliar application can be effective, if restricted to a significant extent by factors of the environment. For example, BCA becomes less effective when it is washed away by excessive rain that also affects the plants on which it is sprayed. Furthermore, it was also found that foliar application might require to be done repeatedly and this could be time consuming affair for the farmer.

4.4 Biocontrol in Combination with Biological Practices

Application of bio control agents together with other agronomic practices like crop rotation, residue management and soil amendments is a noble approach of improving the effectiveness of BCAs and also minimizing the incumbent pressures of pathogens in soybean fields. Crop rotation for instance can help avoid buildup of soil pests such as certain disease-causing organisms which do not infect soybean by growing other crops such as maize or wheat for some seasons. It is most useful for the control of charcoal rot and root rot diseases which develop when there are successive soybean crops in the region (Gupta & Bhardwaj, 2019).

The ecological practices include residue management through pulling out or burying infected plant residues to remove the pathogen inoculum from the field. Applying Trichoderma alongside residue management decreases disease incidence beyond that of residue management alone because the BCA establishes itself on the residues and breaks them down, thus reducing pathogen survival (Bailey, & Lazarovits, 2003). Soil organic matter using organic compost or biofertilizers also improves the BCAs and reduces the fitness of the soil for harbouring pathogenic microbes (Zian et al 2024).

That way, such cultural practices can be embraced as an additional means of disease management as well as encourage sustainable farming through decreased use of chemicals and better nutrient status in the soil. However, the effectiveness of this approach solely hinges on the success of consistent application and local adjustments of these practices by the individual farmer – a relative luxury in the context of limited resources especially in developing countries.

4.5 difficulties in field application

Hypotheses derived from these studies include biological control approaches for soybean diseases could be effective if applied practically in India. Key challenges include:

Environmental Variability: Anderson (2002) notes that the effectiveness of BCAs may be affected for instance by temperature and humidity prevailing within specific geographical location as well as the pH of the soil in that area, which may be quite different from another region.
Competition with Native Microorganisms: BCAs introduced either into the soil or directly on the leaf surface have to overcome competition by indigenous microorganisms that may reduce its colonization and efficacy (Kaur & Singh, 2021).
Limited Shelf Life and Storage: Some BCAs have a very short lifespan, and they have to be stored under certain conditions for them to remain effective. This can be a challenge to the small holder famers as they may not afford to put on proper means of storage (Prabhukarthikeyan et al., 2018).
Awareness and Training: First, the target consumers, these farmers in India many may have no clue about biocontrol products and how they are used. Awareness creation, training, and extension services are required to address adoption rates for and appropriate utilization of BCAs. However, field research conducted in Indian scenario show that combination of BCAs with cultural management practices and correct application techniques can significantly minimize the disease frequency in soybean, increase yield and promote sustainable agriculture. Further research and education to soybean farmers will enhance the application and effectiveness of biocontrol programs in soybean production.

5. Conclusion

Soybean diseases pose unique management challenges in India that have primary implications on yield, quality, and the soybean growers' income. No pathogen is known to develop resistance to chemicals, plant or insect pathogens are controlled through chemicals that have drawbacks, environmental friends, and residues. In this regard, biological control can be a more effective, environment friendly, and sustainable method of controlling soybean diseases using favorable microorganisms against the diseases-causing microorganisms.
This review also brings to light the possibility of biocontrol agents (BCAs) such as Trichoderma spp., Pseudomonas fluorescens and Bacillus spp. against major soybean diseases like rust, charcoal rot, bacterial pustule and downy mildew. All these BCAs operate in differently and in diverse ways; antibiosis, competition, parasitism and ISR (induced systemic resistance). Literature review have depicted that, the implementation of the BCAs in controlling the diseases of soybean has yield a substantial reduce in the disease incidence and enhanced vigor of the crop thus, increasing the yield of the crop alike, other studies conducted in different parts of India (Massart et al., 2015; Sheoran et al., 2024).
BCAs like Trichogramma, Pseudomonas spp., and Colletotrichum spp. provide the seed treatment, while soil and foliar application of the same bacterium is effectively used in the MVM disease infested region of India. seed treatment method is useful when it comes to the control of soil borne diseases during the germination and initial growth of plant while the foliar application has effect on the diseases on the leaves. A systems-orientated approach of soil application and practices such as crop rotation, as well as residue management can provide an effective disease management solution that is also ecologically sensitive (Ward et al., 2012; Patel & Gupta, 2021). However, field research conducted in Indian scenario show that combination of BCAs with cultural management practices and correct application techniques can significantly minimize the disease frequency in soybean, increase yield and promote sustainable agriculture. Further research and education to soybean farmers will enhance the application and effectiveness of biocontrol programs in soybean production.

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