

Bio-Control Agents in Sustainable Pest Management and Mechanisms of Action, Selection, Formulation and Challenges in Agriculture

V.S. Chatage

Department of Botany, Kai. Rasika Mahavidyalaya, Deoni Dist. Latur, Pin- 413519

Email-vaishalichatage3@gmail.com

Abstract

Bio-control can be control of the type of living organisms with the application of another. The use of Bio-control agents are also called biological control and are mainly used for the reduction of pest population and produce yields that are free of any pests. The bio-control methods are a long-term method and most importantly, a self-sustaining one that helps in the control of invasive species of plants. To meet this challenge and prevent crop diseases, chemical pesticides have been widely used. However, their negative effects on human health and the environment have driven the search for sustainable alternatives. In this context, microbial-based bio-pesticides, particularly *Trichoderma* and *Bacillus*, have emerged as key biocontrol agents in agroecosystems. This review provides a comprehensive overview of their agricultural significance, focusing on their mechanisms of action, efficacy, and biotechnological advancements aimed at optimizing their performance. *Trichoderma* spp. act primarily through mycoparasitism, nutrient competition, and antibiosis, while *Bacillus* spp. Unlike traditional reviews that primarily describe their biological functions, this work offers a structured framework for their application, addressing key factors such as selection criteria for effective bio-control agents, formulation strategies, product stability, viability, and regulatory challenges in commercial agriculture. By integrating biological, technological, and practical perspectives, this review aims to bridge the gap between scientific advancements and real-world agricultural applications, contributing to the development of scalable and sustainable disease management strategies.

Keywords: Bio-control , sustainable pest management, Challenges in Agriculture

Introduction

Agriculture has been a fundamental pillar in the social and economic transformation of countries, particularly in developing nations, where it plays a crucial role in ensuring food security and contributing significantly to the economy. However, the prolonged use of agrochemicals has led to serious consequences for the environment, soil health, and human well-being, making the need for more sustainable alternatives ever more pressing (Zhao et al., 2020). According to the World Health Organization (WHO, 2022), over 1,000 pesticides are used worldwide, many of which accumulate in the adipose tissue of organisms, posing risks to both health and the environment (Souza, 2016; Zhang et al., 2019). Although pesticides are necessary for crop protection and food security, their inappropriate or excessive use can lead to serious consequences (Beyuo et al., 2024). These include the negative impact on non-target organisms, such as pollinators and beneficial species that naturally control pests (Elhamalawy et al., 2024), as well as the promotion of pest resistance, which complicates pest control and increases production cost (Kumar Chaube and Pandey, 2022).

Bio-control agents employ diverse mechanisms to protect plants against pathogenic invasion. Using one or a combination of processes, they may interact with the pathogen directly or indirectly to reduce plant disease (Farzand et al., 2019 and Ayaz et al., 2021). BCA in the rhizosphere region competes for space and resources, and interferes with pathogens' pathogenicity through different substances such as lipopeptides, biosurfactants, bacteriocins, volatiles, and enzymes that have antimicrobial effects by slowing the development or metabolic activity of pathogens. This article provides a comprehensive review of the potential of *Trichoderma* spp. and *Bacillus* spp. as BCAs, analyzing their mechanisms of action, selection processes, and the challenges associated with their formulation and large-scale implementation. The effectiveness of these microorganisms is influenced by various factors, including environmental conditions, proper formulation, and the selection of specific strains with desirable characteristics (Naamala and Smith, 2020). By reviewing the latest scientific literature, this paper aims to provide a holistic view of how these microorganism function in modern agriculture, highlighting their successes and the challenges that must still be

overcome to ensure their widespread adoption in sustainable agricultural systems. Moreover, this review compiles a list of biological products currently available on the Ecuadorian market (Supplementary Materials), offering valuable insights into the practical application of BCAs in different agricultural contexts. This information can help guide future efforts in integrating these biocontrol solutions more broadly into farming practices, contributing to a shift toward more environmentally sustainable agriculture.

***Trichoderma* and *Bacillus* in agriculture.**

Trichoderma is a filamentous fungi genus that includes 260 species, of which 35 have economic importance as BCAs in agriculture, or as producers of enzymes and antibiotics in industry (Sharma et al., 2019). Fungi within the *Trichoderma* genus are characterized by being present in the vast majority of ecosystems due to their rapid growth and tolerance to different abiotic stresses (Khan & Mohiddin, 2018). In its interaction with plants, *Trichoderma* can live as a rhizospheric, epiphytic, or endophytic microorganism, without ever colonizing the vascular bundles (Poveda et al., 2020a). By colonizing the roots, *Trichoderma* induces local and systemic expression of abiotic stress tolerance-related genes (abscisic acid and ethylene-related genes), which causes better plant responses under stress situations (Poveda, 2020a). These plant responses include better photosynthetic performance, higher pigment concentration, higher proline content, induction of lateral root development, oxidative inhibition reduction, heat-shock protein production, lipid peroxidation rate reduction and electrolyte leakage, increased antioxidant enzymes, and increase of plant tolerance to drought, salinity, extreme temperatures, or anthropogenic pollution conditions (Zaidi et al., 2014, Hidangmayum and Dwivedi, 2018).

Biological control of plant diseases has become a research hotspot, and biofertilizer *Bacillus subtilis* in agriculture is one of the most representative biocontrol species. Plant diseases are usually caused by pathogenic fungi or bacteria, and often show symptoms such as yellowing, wilt, and ulcers on the leaves. The common plant disease control method is chemical control, like spraying pesticides. However, chemical control has various disadvantages. The antibacterial substances secreted by *B. subtilis* in agriculture mainly include lipopeptides, protein antibacterial substances, phenolic substances, and polyenes.

As Microbial Fertilizer

1. Promoting Plant Growth.

Bacillus subtilis can secrete active substances that can promote plant growth, flowering and fruiting, which helps increase yield and income.

2. Improve Soil Structure.

Bacillus subtilis in agriculture can significantly increase soil alkaline nitrogen, phosphorus content, available potassium, and total potassium content. It can also improve and regulate nutrients in the plow layer, thereby regulating soil nutrients, changing soil microbial flora structure and decomposition of pesticide residues in soil.

3. Improve Crop Quality.

After *Bacillus subtilis* colonizes in the soil, it will produce a large number of plant hormones and organic acids, forming a benign plant-soil-microbial ecosystem, thereby effectively improving crop quality. *Bacillus subtilis* uses in agriculture, main on seeds for vegetables, soybeans, cotton and peanuts, as well as flowers and ornamental seeds. It can be used as a Guard to plant and protect the root system of the plant. Besides *Bacillus subtilis* also can be used as organic material preservatives.

Also, endophytic microorganisms, which live inside plants without causing harm, are also part of the plant growthpromoting (PGP) group. Among endophytic fungi, species like *Penicillium* sp., *Guignardia mangiferae*, *Hypocrea* sp., *Neurospora* sp., *Eupenicillium javanicum*, *Lasiodiplodia theobromae*, and *Trichoderma* sp. have proven effective in inhibiting *Fusarium oxysporum* f.sp. *cucumerinum*, the principal causal agent of stem rot in cucumber under greenhouse conditions (Abro et al., 2019). Among these agents, fungi such as *Trichoderma* spp. and bacteria such as *Bacillus* spp. enhancing soil health, promoting plant growth, and controlling plant pathogens (Alizadeh et al., 2020). *Trichoderma* is a filamentous fungus present in the rhizosphere and roots (Ghorbanpour et al., 2018; Jaroszuk-Ścisiel et al., 2019). According to the Myco Bank classification, the *Hypocrea/ Trichoderma* includes more than 300 species characterized both molecularly and morphologically (Tamandegani et al., 2020).

These fungi colonize plant roots and produce metabolites with antimicrobial properties, contributing to plant health (Tyśkiewicz et al., 2022).

Pest Management Challenges in Agriculture

Pest management is a critical aspect of agriculture, ensuring crop health and productivity. However, it is fraught with challenges that threaten the sustainability of agricultural practices. This article provides a comprehensive guide to the challenges faced in pest management in agriculture and explores potential solutions, including integrated pest management strategies and the role of technology.

The Impact of Agricultural Pests

Agricultural pests, including insects, weeds, and diseases, impact crop production and farming economies. These organisms can cause economic losses by reducing crop yields and degrading the quality of harvested produce. The Food and Agriculture Organization (FAO) estimates that pests can lead to as much as 40% global crop loss annually, translating to billions of dollars in economic damage. Pests can also cause environmental harm, such as transmitting diseases to other plants, which can spread rapidly through agricultural ecosystems. Certain insect pests can act as vectors for plant viruses. The presence of pests can also lead to food contamination, either directly or indirectly through toxins they might produce, posing risks to human health.

At the same time that the agrochemical industry invested heavily in the creation of new and better insecticides, scientists in academia, government, and small private companies started developing a wide range of alternative tools and strategies to protect crops or otherwise mitigate pests, e.g., through population suppression techniques. Some of these alternative tools have enjoyed success, sometimes spectacularly so, albeit in limited application or contexts. The present-day exception to this is the widespread introduction of genetically-modified crops (maize, soybean, canola, cotton) that constitutively produce insecticidal proteins from *Bacillus thuringiensis* (Bt). These crops are extensively grown, especially in the Americas, and a recent meta-analysis on their impacts report average crop yield increases of 22% with reductions in chemical pesticide use of 37% (Klumper and Qaim, 2014). Organic food production, which essentially eschews the use of synthetic pesticides, provides one interesting glimpse into the future of pest management. Limited 30 years ago to small-scale, local production near urban centers, it has been successfully adapted to an industrial scale, as demonstrated in California for example. Production of organic food in the USA and EU in the decade beginning in 2008 grew by 77%, but in 2017 that still only represented 5.5% of the total food supply in those jurisdictions (Marrone, 2019). In affluent countries, and those experiencing rapidly increasing standards of living, food safety concerns amongst the public are driving demand for organic food to the extent that demand exceeds supply.

A key question is whether those bodies that provide certification for organic production, or the increasingly adopted standards for “sustainably” produced food, will come to embrace genetically modified (GM) food crops. Pickett (2016) makes a compelling case for the need for GM food crops, if we are to have any hope of producing the volumes of food needed by 2050 for the fast-growing human population. A major hurdle to the successful development and implementation of GM crops is public acceptability: public trust in pest management tools is low, and the government agencies tasked with regulating their use respond to public pressure. While scientists are in broad agreement that the risks from GM food production are extremely low, the perceived hazard remains high (Pickett et al., 2019). He further argues that this incongruity is a consequence of regulatory agencies focusing on the technology, rather than the safety of the products obtained using such technologies.

Conclusion

The agri-food industry bears a significant responsibility to meet global food demand with products that are not only nutritious and of high quality but also safe. As highlighted throughout this review, BCAs such as *Trichoderma* and *Bacillus* offer a viable and sustainable alternative to conventional chemical pesticides. These beneficial microorganisms have demonstrated their ability to enhance crop productivity, promote soil health, and improve resilience against various diseases, thereby contributing to eco-friendly agricultural systems. Understanding the mechanisms of action, selection criteria, formulation processes, and challenges.

Altogether, there appear many emerging technologies and opportunities to achieve the goal of reducing pre-harvest crop losses. As I stated previously, none of these alone are likely to be a panacea for pest management except in very specific contexts. Production of GM crops has grown steadily over the past three decades, but even for those crops this technology has not entirely displaced the use of chemical pesticides. The extent to which we can lessen our dependence on pesticides in the foreseeable future—modifying the goal from reducing pre-harvest

crop losses to achieving acceptable or optimal yields with fewer chemical inputs—will rely not only on advances in the science of pest management, but also on society's willingness to accept newer technologies along with their inherent, and presumably lesser, risks. As one expert explained, we may need a crisis in food production or prices to deviate from current pest management practices, as in the industrialized world, “the alternatives all come down to economics.” Going forward, risk and regulation will be key determinants of pest management practice. We should hope, at the least, that government regulatory decisions are informed by good science in the future.

Acknowledgments

The author wishes to thank my principal and also thank to my colleagues for sharing their insights, Stevenson for their critical reading of the manuscript. Thank to my guide Dr. U.N. Bhale time to time guides to my research work.

REFERENCE

- Abro, M. A., Sun, X., Li, X., Jatoi, G. H., and Guo, L. D. (2019). Biocontrol potential of fungal endophytes against *Fusarium oxysporum* f. Sp. *cucumerinum* causing wilt in cucumber. *Plant Pathol. J.* 35, 598–608. doi: 10.5423/PPJ.OA.05.2019.0129
- Alizadeh, M., Vasebi, Y., and Safaie, N. (2020). Microbial antagonists against plant pathogens in Iran: A review. *Open Agric.* 5, 404–440. doi: 10.1515/opag-2020-0031
- Ayaz M., Ali Q., Farzand A., Khan A.R., Ling H., Gao X. (2021). Nematicidal Volatiles from *Bacillus atrophaeus* GBSC56 Promote Growth and Stimulate Induced Systemic Resistance in Tomato against *Meloidogyne incognita*. *Int. J. Mol. Sci.* 2021;22:5049. doi: 10.3390/ijms22095049.
- Beyuo, J., Sackey, L. N. A., Yeboah, C., Kayoung, P. Y., and Koudadje, D. (2024). The implications of pesticide residue in food crops on human health: a critical review. *Discov. Agric.* 2, 123. doi: 10.1007/s44279-024-00141-z
- Elhamalawy, O., Bakr, A., and Eissa, F. (2024). Impact of pesticides on non-target invertebrates in agricultural ecosystems. *Pesticide Biochem. Physiol.* 202,105974.doi:10.1016/j.pestbp.2024.105974.
- Farzand A., Moosa A., Zubair M., Khan A.R., Massawe V.C., Tahir H.A.S., Sheikh T.M.M., Ayaz M., Gao X. (2019). Suppression of *Sclerotinia sclerotiorum* by the Induction of Systemic Resistance and Regulation of Antioxidant Pathways in Tomato Using Fengycin Produced by *Bacillus amyloliquefaciens* FZB42. *Biomolecules.* 2019;9:613. doi: 10.3390/biom9100613.
- Ghorbanpour, M., Omidvari, M., Abbaszadeh-Dahaji, P., Omidvar, R., and Kariman, K. (2018). Mechanisms underlying the protective effects of beneficial fungi against plant diseases. *Biol. Control* 117, 147–157. doi: 10.1016/j.biocontrol.2017.11.006
- Hidangmayum, A., Dwivedi, P. (2018). Plant responses to *Trichoderma* spp. and their tolerance to abiotic stresses: a review *J. Pharmacogn. Phytochem.* 7 pp. 758-766
- Jaroszuk-ścisł, J., Tyskiewicz, R., Nowak, A., Ozimek, E., Majewska, M., Hanaka, A., et al. (2019). Phytohormones (Auxin, gibberellin) and ACC deaminase in vitro synthesized by the mycoparasitic trichoderma DEMTKZ3A0 strain and changes in the level of auxin and plant resistance markers in wheat seedlings inoculated with this strain conidia. *Int. J. Mol. Sci.* 20 (19), 4923. doi: 10.3390/ijms20194923
- Khan, M. R., and Mohiddin, F. A. (2018). *Trichoderma*: its multifarious utility in crop improvement. In: *Crop Improvement through Microbial Biotechnology*. Elsevier. pp. 263–291. doi: 10.1016/B978-0-444-63987-5.00013-X.
- Klumper W. Qaim M. (2014). A meta-analysis of the impacts of genetically modified crops. *PLoS ONE* 9:e111629. 10.1371/journal.pone.0111629
- Kumar chaube, S. , and Pandey, S. (2022). TRICHODERMA: A valuable multipurpose fungus for sustainable agriculture. *Malaysian J. Sustain. Agric.* 6, 97–100. Available at: www.myjsustainagri.com (Accessed April 22, 2025).
- Marrone P. G. (2019). Pesticidal natural products – status and future potential. *Pest Manag. Sci.* 75, 2325–2340. 10.1002/ps.5433

- Naamala, J., and Smith, D. L. (2020). Relevance of plant growth promoting microorganisms and their derived compounds, in the face of climate change. *Agronomy* 10, 1179. doi: 10.3390/agronomy10081179
- Pickett J. A., Midega C. A. O., Pittchar J. Khan Z. ,R. (2019). Removing constraints to sustainable food production: new ways to exploit secondary metabolism from companion planting and G. M. *Pest Manag. Sci.* 75, 2346–2352. 10.1002/ps.5508
- Pickett J. A. (2016). The essential need for GM crops. *Nat. Plants* 2:16078. 10.1038/nplants.2016.7
- Poveda, J., Eugui, D., Abril-Urias, P., (2020a.). Could *Trichoderma* be a plant pathogen? Successful root colonization. In: *Trichoderma*. Springer, Singapore. pp. 35–59. doi: 10.1007/978-981-15-3321-1_3.
- Sharma S. , Kour, D. , Rana, K. L. , Dhiman, A. , Thakur, S. , Thakur, P., and Singh K. (2019). *Trichoderma*: biodiversity, ecological significances, and industrial applications, Recent Advancement in White Biotechnology Through Fungi, Springer, Cham. pp. 85-120, 10.1007/978-3-030-10480-1_3
- Souza, E. (2016). The effects of sublethal doses of essential oils and their constituents on antimicrobial susceptibility and antibiotic resistance among food-related bacteria: A review. *Trends Food Sci. Technol.* 56, 1–12. doi: 10.1016/j.tifs.2016.07.012.
- Tamandegani, P. R., Marik, T., Zafari, D., Balázs, D., Vágvyölgyi, C., Szekeres, A., et al. (2020). Changes in peptaibol production of *Trichoderma* species during in vitro antagonistic interactions with fungal plant pathogens. *Biomolecules* 10, 730. doi: 10.3390/biom10050730
- Tyśkiewicz, R., Nowak, A., Ozimek, E., and Jaroszuć-Ścisł, J. (2022). *Trichoderma*: the current status of its application in agriculture for the biocontrol of fungal phytopathogens and stimulation of plant growth. *Int. J. Mol. Sci.* 23, 2329. doi: 10.3390/ijms 23042329
- WHO (2022). Pesticide residues in food. Available online at: <https://www.who.int/news-room/fact-sheets/detail/pesticide-residues-in-food> (Accessed February 11, 2025).
- Zaidi, N.W., Dar, M.H., Singh, S., Singh, U.S. (2014). *Trichoderma* species as abiotic stress relievers in plants. In: Gupta, V.K., Schmoll, M., Herrera-Estrella, A., Upadhyay, R.S., Druzhinina, I., Tuohy, M.G. (Eds.), *Biotechnology and Biology of Trichoderma*. Elsevier. pp. 515–525. doi: 10.1016/B978-0-444-59576-8.00038-2.
- Zhang, S., Zhang, S., Zhang, C., Wang, X., and Shi, Y. (2019). Cucumber leaf disease identification with global pooling dilated convolutional neural network. *Comput. Electron. Agric.* 162, 422–430. doi: 10.1016/j.compag.2019.03.012.
- Zhao, Lyu, N., Wang, D., Wu, X., Zhao, Y., Zhang, L., et al. (2020). PhlG mediates the conversion of DAPG to MAPG in *Pseudomonas fluorescens* 2P24. *Sci. Rep.* 10, 4296. doi: 10.1038/s41598-020-60555-9.