Ag4Dev

Tropical Agriculture Association International

Agriculture for Development



No. 51 | Summer 2026

Special issue on the development and use of biological agents and extracts in tropical agricultural systems

- Biologicals and their current status
- Biopesticides, biofertilisers and biostimulants
- Bioprospecting
- Development of biological products
- Registration of biologicals
- Farmer experiences with biologicals
- Biologicals: A reality check
- Biologicals within a broader environment

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Agriculture for Development

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- Sources of funding should be listed in the acknowledgements.

References

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Journal (article): Aguilar-Støen M, Moe SR, Camargo-Ricalde SL, 2009. Home gardens sustain crop diversity and improve farm resilience in Candelaria Loxicha, Oaxaca, Mexico. *Human Ecology*, **37**(1), 55–77.

Journal (online): Osbourne K, Dolman AM, Burgess S, Johns KA, 2011. Disturbance and the dynamics of coral cover on the Great Barrier Reef (1995–2009). *PLoS ONE*. https://doi.org/10.1371/journal.pone.0017516

Book: Brammer H, 2012. *The physical geography of Bangladesh*. Dhaka: University Press.

Book (edited): Fuglie KO, Sun Ling Wang, Ball E, eds, 2012. *Productivity growth in agriculture: an international perspective*. Wallingford, UK: CAB International.

Book (chapter): Warner K, 1997. Patterns of tree growing by farmers in eastern Africa. In: Arnold JEM, Dewees PA, eds. *Farms, trees & farmers: responses to agricultural intensification*. London: Earthscan Publications, 90–137.

Conference proceedings (published): McIntosh RA, 1992. Catalogues of gene symbols for wheat. In: Miller TE, Koebner RM, eds. *Proceedings of the Seventh International Wheat Genetics Symposium*, 1987. Cambridge, UK: Institute of Plant Science Research, 1225–1323.

Agency publication: Grace D, Jones B, eds, 2011. *Zoonoses (Project 1) Wildlife/domestic livestock interactions*. A final report to the Department for International Development, UK.

Dissertation or thesis: Lenné JM, 1978. *Studies of the biology and taxonomy* of Colletotrichum *species*. Melbourne, Australia: University of Melbourne, PhD thesis.

Online material: IPC, 2020. Malawi: Acute food insecurity update of projection November 2019 – March 2020. Integrated Food Security Phase Classification (IPC). https://www.ipcinfo.org/ipc-country-analysis/details-map/en/c/1152329/?iso3=MWI. Accessed 14 May 2021.

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- Self-explanatory with an appropriate title (caption) above the table, without abbreviations.
- Number with Arabic numerals, *eg* Table 2.
- Refer to tables in the sequence in which they are presented.

Figures

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Accepted figure file types: .tif, .eps, .jpg or .pdf. Indicate approximate location of each figure in the text, and be sure to provide a cross-reference within the body of the text.

All photographs should be submitted as separate JPG files with an indication in the text of where each photo should be placed.

No lecture notes or PowerPoint presentations, please. PowerPoint presentations can be submitted to the webmaster for possible use on the TAA International website news pages. However, please indicate when a figure has been created in PowerPoint, as the editors might ask for the file so we can make modifications.

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February 2025



Parasitoid Trissolcus sp. attacking Halyomorpha eggs (Photo: CABI)

Ag4Dev 51: Special Issue
The development and use of biological agents and extracts in tropical agricultural systems

Contents

IFC Guidelines for authors

2 Editorial
The development and use of biological agents and extracts in tropical agricultural systems | Andrew Ward

6 Article 1
David Grzywacz – Going viral with Dave G | Phil Stevenson, Andrew Ward, Jill Lenne, Debbie Rees and Keith Jones

8 Article 2
Biological pesticides – an overview | Rob Reeder

12 Article 3
Rhizobial inoculants to enhance legume N_2-fixation, grain yields and soil fertility in Africa | Ken Giller

20 Article 4
Biologicals – commercial reality – current and future potential market | Jonathan Shoham

25 Article 5
Endophytic fungi: cryptic biologicals with a high-vis future | Harry Evans

31 Article 6
Isolation and characterisation of plant growth-promoting bacteria in Guatemala | Mariafernanda Alarcón-Mendez, Lizbeth Coxaj-Alvarez, Adriana Maria Gil-Herrera and Martha Patricia Herrera-González

33 Article 7
The Aflasafe story: from aflatoxin challenge to safer food and trade | Alejandro Ortega-Beltran

37 Article 8
The Green Muscle experience: beyond biopesticide identification | Belinda Luke

41 Article 9
The *Metarhizium* story (or the *Metarhizium* safari in Africa) | Henry Wainwright

44 Article 10
Development and registration of bioprotectant Biophyt 1.0 for sustainable agriculture | Augustus Thomas, WendyAnn Isaac and Duraisamy Saravanakumar

47 Article 11
Streamlining regulatory frameworks for biopesticides in Africa and the Middle East | Stella Simiyu, Fasil Tadesse, Ibrahim Traore, Bakr Abdelmoneim and Margaux Rundstadler

49 Article 12
Brazil biological market | Jade Bortoletto

52 Article 13
Lessons learned from promotion of biologicals in Chiang Rai, Thailand | Dr Atthawit Watcharapongchai and Thanchanok Pongputhinan

56 Article 14
Effective use of biological inputs in regenerative agriculture in Brazil | Aline Vick

58 Article 15
Biologicals also need stewardship | Keith A. Jones

62 Article 16
Biofertilisers and biostimulants: is the bubble about to burst? | Ken Giller

67 Article 17
The Sri Lanka experience – why a phased transition to biologicals is vital | Alan Bullion

68 Article 18
Beyond the hype: an agroecological checklist for the biopesticides sector | Dr Mélanie Surchat, Dr Charlotte Pavageau, Dr John Garcia Ulloa and Moritz Fegert

70 Article 19
One Health, Plant Health and biologicals | Julian Smith and Elizabeth Warham

75 Tropical Agriculture journal: The Journal of the Faculty of Food and Agriculture (formerly, Imperial College of Tropical Agriculture), The University of The West Indies

The Tropical Agriculture Association International (TAA International) is a professional association of individuals and corporate bodies concerned with the role of agriculture for development throughout the world. TAA International brings together individuals and organisations from both developed and less-developed countries to enable them to contribute to international policies and actions aimed at reducing poverty and improving livelihoods. It grew out of the Imperial College of Tropical Agriculture (ICTA) Association, which was renamed the Tropical Agriculture Association (TAA) in 1979 and the Tropical Agriculture Association International (TAA International) in 2023. Its mission is to encourage the efficient and sustainable use of local resources and technologies, to arrest and reverse the degradation of the natural resources base on which agriculture depends and, by raising the productivity of both agriculture and related enterprises, to increase family incomes and commercial investment in the rural sector. Particular emphasis is given to rural areas in the tropics and subtropics and to countries with less-developed economies in temperate areas. TAA International recognises the interrelated roles of farmers and other stakeholders living in rural areas, scientists (agriculturists, economists, sociologists, *etc*), government and the private sector in achieving a convergent approach to rural development. This includes recognition of the importance of the role of women, the effect of AIDS and other social and cultural issues on the rural economy and livelihoods.

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Editorial

The development and use of biological agents and extracts in tropical agricultural systems

Andrew Ward



Supporting farmers so that they are empowered to implement best agricultural practices is the key theme throughout Andrew's 30-year career. This career has been spent in both the public and private sectors, with working to promote biologicals, particularly biopesticides, a recurring theme. He lived in Nigeria for 3 years working for an NGO and conducting research for a PhD supervised by UEA and Rothamsted. After university he joined the DFID-funded Crop Protection and Research into Use programmes. These focussed on developing agricultural research outputs and delivering them to small-scale farmers in low- and middle-income countries. In 2011 he joined the CGIAR and worked in its coordination offices in Montpellier (France) and then on a systems-based research programme based in Lusaka (Zambia). Linking with the private sector was a key element of research into use, and in 2017 he joined the trade association, CropLife International, where he is Stewardship Director.

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Tropical Agriculture Association International members represent a broad house, often demonstrating a healthy diversity of experiences, perspectives and opinions. This is an asset as diversity leads to informative and challenging discussions. Such diversity was present throughout our November 2025 conference on 'The development and use of biological agents and extracts in tropical agricultural systems' (shortened to the TAAI Biologicals Conference). The conference, held at Rothamsted, focussed on biopesticides, biofertilisers and biostimulants from bioprospecting to farm-level use.

Biologicals have been a significant focus throughout my career. In the mid-1990s I worked for an NGO, Diocesan Development Services, in Kogi State, Nigeria. With an excellent on-farm trial programme, we were an obvious choice for many researchers looking to bring biological, particularly botanical, innovations to farmers and to try them on farm. These products achieved success in managing pests and raising soil fertility without the need to buy farm inputs. However, the farm-level production of the biological inputs and their efficacy were factors that put the farmers off using them. When the projects finished, I did not see any farmers continue to produce these biologicals, although farmers might have adopted them if they had been able to work through challenges with the researchers. Later in the 1990s I worked on the Department for International Development's Crop Protection Programme. This programme funded scientists who identified biological pesticides and demonstrated their efficacy. But whilst the science was incredibly exciting, the situation on the ground for farmers did not seem to change. Simply identifying a product that worked was not the end of the science; there were formulation and production issues even before challenges of registration (in many countries biopesticides had to be registered using the same procedures as chemical pesticides).

TAAI brings together technical and downstream scientists. This edition of *Ag4Dev* reflects this, with papers that illustrate the journey from discovery all the way through to use by farmers. One researcher who had a deep understanding of the challenges facing the development and farmer adoption of biological products was David Grzywacz. His was an incredible intellect, grounded in the reality of what it takes to bring about change for the farmer. David mentored many, and, with his incredible passion for his work, inspired colleagues around the world to address the challenges in farmer access to biologicals. Unfortunately, he passed away in January 2025. In this edition there is an article from Stevenson *et al* that describes David and his work. TAAI decided to name the poster award in his honour. The competition resulted in joint winners, a tie between Biovision International and the University of Guatemala. The content of the posters is presented in the papers by Surchat and Alarcón-Mendez.

The journal starts with papers on the two main biological product lines that are explored – biological

products for managing pests (Reeder) and biological products for enhancing plant nutrition (Giller). Biological pesticides comprise a large part of the biologicals market. This group includes microbials and their extracts, macrobials, semiochemicals and botanicals. They can be used to enrich natural enemies already present, to manage co-evolved hosts that have become an invasive pest in a new location or for mass release for short-term population reduction. Biopesticides have become more attractive as a pest control option as pests have developed resistance to conventional pesticides and the range of pesticides registered for use has reduced. However, getting biopesticides to farmer use is a complex journey.

Biofertilisers contain living microorganisms which, when applied to seeds, plant surfaces or soil, colonise the rhizosphere or the interior of the plant and promote growth by increasing the supply or availability of primary nutrients to the host plant. A biostimulant is a product that stimulates plant nutrition processes independently of the product's nutrient content, *eg* nutrient use efficiency, tolerance to abiotic stress, quality traits or availability of confined nutrients in soil or rhizosphere.

Reeder and Giller provide an overview of how biologicals have the potential to revolutionise plant nutrition and manage pests. Some of these products can be produced at a farm level although, in general, commercial production brings advantages in terms of the quality of product and scale of use. It is also easier to track trends in the use of commercially produced biologicals. In this journal, Shoham presents significant growth in the sales (and presumed use) of biologicals, with higher market growth rates than chemical products. Use of biologicals has been increasing year on year for at least the last 10 years. This is a trend set to continue, and as biologicals are increasingly used by farmers in tropical agricultural systems, understanding biologicals is critical in planning for agricultural development. However, it should be noted that sales of biologicals are still dwarfed by the sale of chemical-based farm inputs.

This issue highlights issues linked to the identification of suitable biological products (bioprospecting). Evans is a world authority in bioprospecting and his paper explores the complexity of not just identifying biological control agents but also endophytes that could affect the host plant action of biological control agent. Evans advocates for bioprospecting to focus on the centre of origin of the pest species. However, with multiple similar species and sub-species present, the evaluation of best candidates is critical. It also needs to be understood whether the natural enemy can manage a pest by itself or if it requires the presence of other species (*eg* endophytes). The paper from Alarcón-Mendez describes the work presented in her award-winning poster, based on identification of candidate species in Guatemala.

The development of biological products and the fulfilment of their potential require time. This point is clearly made in the papers led by Luke and Ortega-Beltran presenting the LUBILOSA and Aflasafe initiatives. Aflasafe was developed to address the very real, but often little-acknowledged, health problems caused by aflatoxins. Aflatoxins are amongst nature's most carcinogenic chemicals. They are thought to be the cause of 30 percent of liver cancer in Africa. Importers do not want to procure contaminated food; as a result, over USD 100 million of groundnut and maize exports are rejected every year due to aflatoxin concentrations. Aflatoxin is produced through the action of a fungus, usually an *Aspergillus* species. However, IITA, working with others, has identified a more competitive species of *Aspergillus* which does not produce aflatoxin. This is the biological agent within Aflasafe, a biological which prevents the production of aflatoxin.

The impacts of locusts on crops and farm livelihoods are well known. Although there are chemical pesticides that are effective against locusts, there are risks with their use and in some environments it is not possible to apply them. The LUBILOSA project identified isolates of the fungus *Metarhizium acridum*, which was effective as a locust control biological product. This was developed into the product Green Muscle, and the private sector was identified as the delivery mechanism to the locust control authorities. However, with inconsistent locust outbreaks, long procurement times and the fact that Green Muscle contains a living organism, the challenges did not stop with the research. Systems needed to be developed so that Green Muscle could be available where and when it was needed and in sufficient quantities.

Both project teams have benefitted from donor support over several decades. This has enabled them to address the technical and downstream scientific challenges and provide stability through working in multiple countries. This is an important consideration when looking to develop a biological product through the public sector.

Wainwright details an alternative route to commercialisation, working with a research organisation which has already conducted a lot of the initial research. For many years the International Center for Insect Physiology and Ecology (ICIPE), based in Kenya, had been conducting bioprospecting of Metarhizium fungus species. This work was picked up by the Real IPM company, who were looking for a biological tool for managing red spider mite, a pest of

many horticultural crops. The product is effective and has been registered for use in eight African countries.

Thomas has been part of a team that has conducted research to develop a plant growth stimulator and biopesticide in the West Indies. They have developed a product named Biophyte. For the Biophyte team, it was the registration of biological products that was critical to their commercial promotion. Regulatory requirements for chemical-based inputs are different from those for biological inputs. Developing the registration documents has been a complex journey with extensive testing required at every step, from species identification to label design.

Simiyu further explores the issue of registration in Africa. Africa has had the slowest growth in the uptake of biopesticides, and part of the problem has been the slow and complex registration process, particularly in West, Central and Northern Africa. Registration could be accelerated by the acceptance of a standard definition, according to existing regulatory guidance *(eg* OECD), to implement reduced data requirements for biological pesticides (compared with chemical pesticides), agree low-risk status for biopesticides and harmonise requirements across the region.

The journal progresses to consider the field use of biologicals. This section starts with a focus on Brazil from Bortoletto. Brazil is the most dynamic biologicals market in the world. In 2024, in Latin America, 62 million hectares of farmland were treated with biopesticides (56 million in Brazil). The trend in use and farmers' income continues to rise and is a result of favourable public policies and increasing global demand for lower pesticide residues. However, bureaucracy and adoption issues remain as challenges to further accelerating uptake.

Watcharapongchai's paper details a more farmer-led initiative. In Thailand, GIZ is working with farmers to produce the fungus *Trichoderma*, which can be used by farmers to fight plant pathogens. However, the first step was to understand farmer perceptions (and misunderstandings) about biologicals. Raising awareness and addressing misperceptions of biologicals were essential before *Trichoderma* could be promoted through local production and use.

Ultimately, whether a biological is used or not is determined by the farmer. Aline Vick farms Fazenda Estância in Brazil. Like many Brazilian farmers, she is utilising biologicals, particularly soil inoculants. She receives technical support with biologicals, but even with trusted products, she tests them on a small scale before widespread adoption. Observation is critical, especially with factors such as high temperatures and dry periods.

These papers detail a positive journey from prospecting to farmer use. The landscape is more complicated than that, and some of the challenges and considerations to be borne in mind are presented in the final set of papers.

Farmers using biological products need to follow best management practices; they require stewardship. Jones provides some of the areas where such stewardship is required for different classes of biopesticides to ensure they fulfil their potential and deleterious impacts are avoided. He provides further consideration on how to incorporate biopesticides into integrated pest management (IPM) systems, an important consideration as biologicals need to be deployed as part of a system.

Giller's paper presents extensive experience of biofertilisers and biostimulants. Nitrogen-fixing bacteria, as inoculants, can significantly boost soil fertility, particularly when applied in conjunction with other nutrients that could be limiting factors. Such inoculants can be manufactured locally and meet regulatory requirements. This technology continues to develop, providing increasing benefits to farmers. However, increasingly there are claims about products that will enable non-legumes to fix nitrogen. As a reader, we must ask if the system needs strong regulation so that all claims about products are based on scientifically proven evidence. Is the situation different from that with biopesticides, where it has been argued that farmers will simply refuse to buy non-efficacious products?

Bullion focusses on how government intervention can affect availability of farm inputs in his paper. In Sri Lanka in 2021, an embargo was placed on the use of chemical fertilisers and pesticides. It was hoped that this would support the development of biological tools. However, the change was too sudden; without a transitional period, the biological sector could not respond, farm productivity declined and costs increased for all.

Biologicals could be a positive disruption to how agriculture is currently viewed. For example, One Health approaches seek to optimise the health of humans, animals, plants and ecosystems through a multi-sectoral approach. Therefore, biologicals should not just be seen as an agricultural tool, but the broader implication of their deployment needs to be considered.

Biovision argued that biological products should not simply be added to current farming systems – rather, they should be an opportunity to reconsider agriculture and environmental and human health, farmer-centred approaches, supporting the local economy and context-specific regulation.

In conclusion, the papers in this journal edition show justified excitement about biologicals fulfilling their potential. However, we do need to bear in mind that biologicals are not silver bullets. They are often specific in their action, and their compatibility with conventional farm inputs should be considered. Although we are seeing increases in the use of biologicals, there are still many challenges remaining to their fulfilling their potential. These are related to investments in research, the local environment for business, registration and legislative requirements, transportation and storage facilities, as well as technical and stewardship support. However, the journal shows that significant steps forward have been made. This volume provides valuable insights for all involved in agriculture, but particularly those interested in how to best bring biological products through to farmers in tropical agricultural systems.

David Grzywacz – Going viral with Dave G

Phil Stevenson, Andrew Ward, Jill Lenne, Debbie Rees and Keith Jones

Phil Stevenson is employed by the Natural Resources Institute (NRI) and works at the Royal Botanic Gardens at Kew. He leads both work on plant and fungal traits as well as the ecological function of plant chemicals, especially those that mediate interactions between plants and insects.

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Andrew Ward is the Director of Stewardship at CropLife International, having previously worked within CGIAR and for the Department for International Development (DFID)-funded Crop Protection and Research into Use Programmes.

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Jill Lenne has over 40 years' experience in agricultural research, management, governance and development, including 22 years with CGIAR institutes and 8 years with UK institutes. She worked with Dave G on projects whilst at NRI, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and NR International.

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Debbie Rees was Dave G's wife from 1998 until his death.

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Keith Jones has more than 45 years' experience in sustainable agriculture, integrated pest management and biological control in Africa, Asia and Latin America. Keith started his career at what is now NRI, where he focussed on the development of insect baculoviruses for pest management.

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Dave G was a pioneer of DNA technology to identify viral biopesticides. Here he was using Random Fragment Length Polymorphism (RFLP) to identify *Helicovperpa arimgera* NPV. (Source: Mark Parnell, NRI)

The poster competition at the TAAI conference on the 'Development and Use of Biological Agents and Extracts in Tropical Agricultural Systems' was named after David Grzywacz, more commonly known, maybe for obvious reasons, as Dave G. Dave passed away in January 2025 but had been an inspiration to the organisers of the conference earlier in their careers. He was always great fun, a committed family man and always looked to mentor and support people in the early days of their careers, but was very practical and no-nonsense when it came to the topic of biologicals. In this we felt that he was the right person for the award to be named after. The posters were judged by ex-colleagues and friends of Dave and two winners were chosen, which felt appropriate as Dave supported so many researchers in both Europe and in the tropics:

> Alarcón-Mendez M *et al* 'Isolation and characterisation of plant growth-promoting (PGP) bacteria from maize, beans, cacao, cardamom and Milpa system, in Guatemala.' Universidad del Valle de Guatemala, Guatemala; and
>
> Surchat M *et al* 'Biopesticides beyond the hype: a checklist to develop a locally led, agroecologically rooted biopesticide sector.' Biovision International.

During the conference, Dave's ex-colleague Phil Stevenson illustrated both Dave's amazing character and his inspiring research. He took participants on a tour of Dave's research across Thailand, India, Nepal and Tanzania as he worked to explore how biological control, particularly through the use of entomopathogenic virus, could be used to manage

major caterpillar (lepidopteran) pests, including cotton bollworm and African armyworm. Dave devoted his career to this area of research. In addition to identifying effective biotypes his research looked at environmental and formulation factors that would affect their efficacy – critical to their effective deployment in pest control.

Dave joined the Natural Resources Institute in 1990 as a senior scientist and insect pathologist after working at the Centre for Overseas Pest Control since 1979. He headed the Insect Pathology Research Group, the Sustainable Agriculture Group and the Agriculture, Health & Environment Department in 2005–2006.

Some of his major contributions were in the development of commercial biological pesticides based on insect viruses to control global and emergent pests. For example, Dave was instrumental in developing and evaluating a method for biological control of African armyworm, published in 2006. Additionally, he was a major contributor to the first-ever paper on the role of *Wolbachia* (a group of insect-infecting bacteria) in mediating virus infections, showing that *Wolbachia* made African armyworm more susceptible to viral infections rather than protecting them. A significant barrier to the broader adoption of biopesticides is their vulnerability to ultraviolet radiation from sunlight, which reduces their longevity and effectiveness. Dave and Ken Wilson from Lancaster University developed a formulation which was able to protect biopesticides from degradation by ultraviolet radiation.

He was a trusted advisor to emerging companies in Kenya, Ghana and Tanzania, guiding them in the production of biological pesticides. Dave was a fellow of the Royal Entomological Society and a member of the Society for Invertebrate Pathology. He was also a reviewer for several scientific journals, including *Biological Control*, *Journal of Pest Science*, *African Journal of Agricultural Research*, *Experimental Agriculture*, *Crop Protection*, *Pesticide Biochemistry and Physiology*, *Entomological Research* and *Journal of Insect Science*.

Dave was very sociable and would love to have beer with colleagues, often associated with both serious scientific discussions and amusing stories. Professor Phil Stevenson recalled one example: "Dave once drafted a seemingly serious concept note for managing rhinos in Nepal's Terai region, where they are a big problem for farmers living close to Chitwan game reserve. The 'sustainable' solution he submitted for approval involved having then NRI director John Perfect's jazz band to play the Spice Girls Songbook and frighten the rhinos back to the forest. I can still hear his infectious laugh now." Phil Stevenson referenced the following papers describing Dave G's work:

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Dave's life is celebrated on the NRI website: nri.org/latest/news/2025/celebrating-the-life-and-legacy-of-david-grzywacz-a-visionary-scientist-and-beloved-colleague

Biological pesticides – an overview

Rob Reeder



Rob Reeder is a plant pathologist and team leader at CABI's centre in Egham, UK. With a career spanning more than 30 years, he has worked in over 25 countries, focussing on sustainable and ecological approaches to pest and disease management. He has played a significant role in the detection and monitoring of major plant health outbreaks and in strengthening diagnostic capacity in lower-income countries. Rob has been closely involved in the development of plant health systems through the Plantwise and PlantwisePlus programmes and currently supports the global implementation of PlantwisePlus. In addition, he contributes to the design, development and implementation of a range of plant pathology projects, further strengthening CABI's applied research and capacity-building efforts.

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Introduction

Biologicals are products derived from natural organisms or naturally occurring substances. They can be used as an alternative to, or alongside, chemical inputs. By working through natural biological interactions, they often reduce reliance on conventional synthetic pesticides and fertilisers. There are three main types:

- Biocontrols – which help manage pests and diseases directly.
- Biostimulants – which enhance plant health, improve stress tolerance or induce systemic resistance.
- Biofertilisers – which enhance nutrient availability and improve soil fertility through microbial activity or biological nutrient cycling.

Biocontrol agents

This review will focus on biocontrol agents, also referred to as biopesticides. There is no universally accepted definition, and the market contains a diverse range of products. Definitions vary by regulatory authority and geographic region, reflecting differences in legal frameworks, scientific standards and local agricultural practices. Typically, these products include active substances derived from microbials, macrobials, semiochemicals or botanicals.

Microbials are pest control products that contain living microorganisms, such as bacteria, fungi, viruses, protozoa or their naturally occurring metabolites. They are used to control pests through biological mechanisms (*eg* infection, competition or toxin production) and are typically applied using formulations and application methods similar to conventional pesticides.

Macrobials are invertebrate natural enemies (*eg* predatory insects, predatory mites or parasitoids) used in pest management. They are typically released in an inundative or augmentative manner, and they aim to predate or parasitise the target pests.

Both microbials and macrobials are often applied as living organisms; as such, the speed of kill and shelf life differ compared to their chemical counterparts, and they require different mass production methodologies.

Semiochemicals are natural substances produced by plants, animals or other organisms that trigger a behavioural or physiological response in the target organism, either within the same species (pheromones) or between species (allelochemicals). These chemically active, signalling compounds are used to alter pest behaviour, typically to disrupt mating, attract or repel pests from specific areas or otherwise influence pest activity. They are widely applied in crop protection for functions such as pest monitoring, mating disruption, mass trapping and lure-and-kill interventions.

Biopesticides provide multiple modes of action, ranging from repellence and antifeedant effects to antimicrobial or insecticidal activity, and they play an increasingly important role in sustainable pest management. In addition to these traditional natural products, an emerging class of biopesticides is RNA-based pesticides, which utilise RNA interference (RNAi). These products contain externally applied double-stranded RNA (dsRNA) molecules designed to trigger RNAi in target organisms, silencing specific genes to suppress pests or pathogens and, in some cases, modulate plant physiological traits.

A related regulatory subcategory recognised in some jurisdictions is Plant-Incorporated Protectants (PIPs), which the United States Environmental Protection Agency classifies as a distinct type of biopesticide. PIPs encompass both the pesticidal substances produced within a plant and the genetic material enabling

the plant to produce those substances. As a result, genetically engineered crops expressing *Bacillus thuringiensis* toxin genes are designated as PIPs, since the pesticidal protein is synthesised inside the plant itself rather than being applied externally.

Benefits of biologicals

The biopesticides market is growing rapidly, driven by increasing demand for sustainable agriculture and concerns about the environmental and health impacts of chemical pesticide use. The global biopesticides market is projected to reach approximately USD 22 billion by 2032, growing at a compound annual growth rate of around 8.2 percent between 2023 and 2032.

Regulatory pressures have also played a significant role in driving the development and adoption of biopesticides. For example, their development and commercialisation in Kenya in the early twenty-first century was partly accelerated by stringent European Union Maximum Residue Level regulations, which prompted exporters to seek crop protection solutions that could reliably meet residue compliance requirements.

As this market expands, biopesticides are increasingly recognised as an important component of sustainable crop protection strategies. Compared with conventional synthetic chemical pesticides, they are often characterised by lower toxicity, greater specificity toward target pests and faster environmental degradation, which can reduce overall environmental exposure and pesticide residue levels in food.

These characteristics often result in favourable environmental profiles. However, risk assessments are still required before the introduction of a biopesticide into a non-indigenous environment to ensure ecological safety. For this reason, scientists generally prefer to use locally occurring species or isolates when developing biopesticide products. Nevertheless, biopesticides can contribute to reducing the overall ecological impact of crop protection, supporting sustainability and aligning with agroecological and regenerative agriculture approaches.

Because biopesticides are typically more selective and less harmful to non-target organisms, they are particularly compatible with Integrated Pest Management (IPM) approaches, as described by Jones in this edition of *Ag4Dev*. This selectivity helps conserve beneficial organisms such as natural enemies and pollinators, thereby supporting biological control within crop protection programmes.

Biopesticides can also serve as alternative crop protection tools that help reduce the selection pressure on pests to develop resistance to conventional chemical pesticides. Pest resistance to macrobials and pheromone-based semiochemicals is considered unlikely. Some microbial biopesticides have been assigned mode of action classifications, allowing resistance risks to be monitored and managed through systems such as those developed by the Insecticide Resistance Action Committee.

Challenges in current crop protection systems

Currently, the crop protection market is dominated by synthetic chemical pesticides. The Food and Agriculture Organization of the United Nations (FAO) estimates that over 2 million tonnes of chemical pesticides are used globally each year (FAOSTAT 2023). Unregistered and counterfeit pesticides of unknown toxicity are estimated to comprise up to 25 percent of the pesticide market.

Indiscriminate use of highly toxic plant protection products is affecting product efficacy as well as human and livestock health. This, in turn, decreases the resilience of agricultural and other land use systems to new pest invasions. In addition, pesticide use has been linked to negative impacts on biodiversity.

There is also growing evidence of the risks that pesticides can pose to human health. According to the University of Edinburgh's Centre for Pesticide Suicide Prevention, it is estimated that pesticide ingestion results in the hospitalisation of more than 2 million people worldwide each year. Gunnell *et al* (2007) estimate that pesticide self-poisoning causes over 258 000 deaths globally each year, accounting for approximately 30 percent (range 27–37 percent) of suicides worldwide. Accurate estimates of pesticide poisoning and mortality remain difficult to obtain, particularly in tropical agricultural regions, because health surveillance, toxicological reporting and environmental monitoring systems are often incomplete or inconsistent.

In addition to these health and environmental concerns, the continued reliance on chemical pesticides is increasingly undermined by the rapid development of pest resistance. Repeated applications of pesticides with the same mode of action (MoA) exert strong selection pressure, enabling resistant pest biotypes to emerge and spread more quickly. While integrated resistance-management strategies can help slow this process, they depend on access to a sufficiently diverse set of pest-control tools with different MoAs, an option that is not always available to farmers. When resistance reduces pesticide efficacy, farmers may respond by increasing application rates or spraying more frequently to maintain control,

inadvertently escalating both economic costs and environmental risks. For example, Varah *et al* (2020) estimate that herbicide resistance in black-grass (*Alopecurus myosuroides*) in the UK could impose economic losses approaching GBP 1 billion per year.

Challenges and limitations with biopesticides

While sustainable solutions like biologicals offer many benefits, it is important to recognise some of their limitations.

Slower speed of action: Compared with conventional chemical pesticides, many biopesticides act more slowly, as their activity often relies on biological processes such as infection, parasitism or disruption of pest development rather than immediate toxic effects. This slower action may reduce farmer confidence in their ability to provide effective pest control, particularly in situations where rapid suppression of pest populations is required to prevent economic damage. As a result, farmers may revert to chemical pesticides or apply additional biopesticide treatments, potentially increasing costs.

Narrow host range: Many biopesticides are highly specific to particular pests. While this specificity helps minimise impacts on non-target organisms, it also limits their usefulness in cropping systems where multiple pest species occur simultaneously. Because crops are often attacked by several pests that might otherwise be managed with a single broad-spectrum chemical pesticide, multiple biological products may be needed (where available), increasing costs and adding complexity to pest management programmes.

Storage and shelf life constraints: Stored biopesticides, particularly those containing living microorganisms, often require specific storage conditions to maintain viability and efficacy. Many microbial products have relatively short shelf lives compared with conventional chemical pesticides, and their performance can be significantly affected by temperature, moisture and storage duration. Exposure to high temperatures during storage or transport may reduce the viability of microbial agents, thereby reducing product effectiveness.

Regulatory complexity: Regulatory frameworks for biopesticides vary considerably between countries. In some jurisdictions, biopesticides follow separate approval pathways from conventional chemical pesticides, while in others they are regulated under the same system. Where regulatory systems were originally designed for chemical pesticides, the data requirements and risk-assessment procedures may not always be well adapted to biological products. Lengthy or complex regulatory processes can therefore present barriers to commercialisation, particularly as profit margins for biopesticides are often lower than for conventional pesticides.

Variable field performance: The efficacy of biopesticides can vary depending on environmental conditions, pest pressure and application practices. Environmental factors such as temperature, humidity and ultraviolet radiation can influence product performance, particularly for microbial agents that must survive and establish in the field to exert their effects. In addition, factors such as timing of application, formulation quality and compatibility with other crop protection practices can influence field efficacy, meaning that successful use often requires more careful management than conventional pesticides.

Production and formulation challenges: The large-scale production and formulation of biological control agents can present additional technical challenges compared with conventional chemical pesticides. Many microbial biopesticides require specialised fermentation processes, quality control procedures and formulation technologies to maintain the viability and stability of the active organism. Ensuring consistent product performance can therefore be more complex, particularly where living organisms are involved. In addition, formulation technologies must protect the biological agent from environmental stresses such as ultraviolet radiation and desiccation while maintaining shelf stability and ease of application. These factors can increase manufacturing costs and create barriers to large-scale commercial production. Despite these challenges, when used correctly and as part of an integrated approach, these solutions still provide significant benefits for sustainable crop protection.

PlantwisePlus: strengthening the enabling environment for biological control

CABI's PlantwisePlus programme strengthens plant health systems in low- and middle-income countries by supporting smallholder farmers to adopt safer and more sustainable crop production practices that enhance food security and rural livelihoods. Operating from policy to field level, the programme works with governments to predict, prevent and manage plant health threats, while equipping public and private advisory services with gender-responsive tools and training that promote lower-risk pest management. Its prevention-focussed approach prioritises IPM and pesticide risk reduction, encouraging biological control and other agroecological practices that protect crops while safeguarding people, animals and ecosystems.

Through collaboration with more than 300 public and private sector partners, PlantwisePlus strengthens national and local capacity to address emerging pest challenges and aims to reach 75 million smallholder farmers with the knowledge and resources needed to improve production, reduce biodiversity loss and build resilience to climate change.

Complementing these system-level efforts, PlantwisePlus also improves access to practical tools that support the uptake of biological pest management solutions. A key innovation is the CABI BioProtection Portal, a free, user-friendly platform that helps growers and agricultural advisers identify and source registered bioprotection products. Users can search for products available in their country and access guidance and training materials on biological control and IPM. The portal is currently available in more than 50 countries and over 15 languages, covering more than 950 crops, over 2000 pests and more than 4000 registered products. Alongside product listings, it provides learning resources designed to build knowledge and confidence in the use of biological control and other sustainable pest management approaches.

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Rhizobial inoculants to enhance legume N_2-fixation, grain yields and soil fertility in Africa

Ken Giller



Ken Giller was recognised as the TAAI 'Development Agriculturalist of the Year' in 2024. He has conducted research on nitrogen fixation in the tropics for over 40 years and is author of the book Nitrogen Fixation in Tropical Cropping Systems *published by CABI in second edition in 2001. He has led a number of initiatives such as the Bill & Melinda Gates Foundation-funded 'N2Africa – Putting Nitrogen Fixation to Work for Smallholder Farmers in Africa, (n2africa.org), which worked in 11 countries over 10 years from 2009 to 2019. Ken has over 500 peer-reviewed papers and has been on the Web of Science list of Highly Cited Researchers (top 1 percent) since 2016. He has supervised over 100 PhDs successfully – more than half from African countries. Ken joined Wageningen University as Chair of Plant Production Systems in 2001 after holding professorships at Wye College, University of London, and the University of Zimbabwe.*

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Abstract

Rhizobial inoculants are the most widely used biological agent in agriculture. Robust evidence accumulated over the past decades demonstrates that rhizobial inoculation is advantageous for grain legume production in Africa. High-quality inoculants are key to ensuring consistent legume yield responses. Other limiting factors, particularly the lack of plant-available phosphorus in African soils, must be addressed to ensure an effective legume-rhizobium symbiosis.

Introduction

The N_2-fixing symbiosis between legumes and the root-nodulating bacteria, rhizobia, is the foundation of sustainable agriculture. Rhizobial inoculants can lay claim to being one of the first, if not *the* first, biological products to be deployed at scale in agriculture. The first records of inoculation using pure cultures of rhizobium to ensure effective nodulation date back to 1896 (Williams, 1984). Brazil is the world leader in production and deployment of rhizobial inoculants, due to the importance of soybean production and the long history of research on nitrogen fixation (Santos *et al*, 2019).

In this paper I summarise research that makes a case for future investment in making rhizobial inoculants available to smallholder farmers in Africa. The article proceeds as follows: After giving some background to the legume-rhizobium symbiosis and rhizobial inoculants, I provide a brief history of research and production of rhizobial inoculants in Africa. I then summarise the findings of a large 'development to research' project that focussed on enhancing the inputs from N_2-fixation for smallholder farmers in Africa, which evaluated the use of inoculants for different legumes in 11 countries. I conclude with some thoughts on future directions for use of rhizobial inoculants in Africa, and how barriers that prevent smallholder farmers from accessing inoculants might be overcome.

The legume-rhizobium symbiosis and the use of inoculants

Types of rhizobia

Initially, only two types of rhizobia were recognised: fast-growing bacteria, *Rhizobium*, that formed colonies within 3–4 days and produced an acid reaction when grown in the laboratory, and slow-growing bacteria, *Bradyrhizobium* (brady = slow), that formed colonies after around 8 days and produced an alkaline reaction. Rhizobia were found in temperate legumes, the peas (*Pisum sativum* L.), and beans – common bean (*Phaseolus vulgaris* L.) and faba bean (*Vicia faba* L.), whereas bradyrhizobia were found in nodules of soybean (*Glycine max* (L.) Merrill) and tropical legumes such as cowpea (*Vigna unguiculata* (L.) Walp.), groundnut (*Arachis hypogaea* L.) and mung bean (*Vigna radiata* (L.) R. Wilczek). Life was simple!

As research progressed, and bacteria were isolated from the nodules of a wider range of legumes and characterised using molecular taxonomy, it became clear that there are many types of root-nodulating bacteria, with a wide range of growth rates on artificial media. The bacterial genes required for nodulation (*nod* genes) and N_2-fixation (*nif* and *fix* genes) are closely linked on plasmids or 'symbiotic islands' that can be transferred horizontally among bacteria. This means that molecular (evolutionary) phylogeny is not a useful guide to the host range of rhizobia. This led

Martinez-Romero *et al* (2024) to propose guidelines for classifying rhizobia based on 'symbiovars', which directly highlight symbiotic specificity. They describe more than 60 symbiovars of rhizobia across at least 10 bacterial genera, and the number will undoubtedly continue to increase as symbioses of additional legumes are investigated in future.

When is rhizobial inoculation required?

First, we need to understand why some legumes respond more frequently to rhizobial inoculation than others. Legumes differ widely in the diversity of bacteria with which they nodulate and form an effective symbiosis. Soybean and chickpea (*Cicer arietinum* L.) form nodules with a narrow range of rhizobia and are said to be highly specific. When introduced into a new environment, specifically nodulating legumes require inoculation with compatible rhizobia. By contrast, at the other end of the spectrum, cowpea is a much more permissive or 'promiscuous' host, which can form nodules and fix N_2 with a wide variety of both fast- and slow-growing rhizobia (Pueppke & Broughton, 1999). This means that cowpea very often encounters effective rhizobia in the soil and fixes nitrogen without the need for inoculation, as do other tropical grain legumes such as groundnut and mung bean. Common bean (*Phaseolus vulgaris* L.) is a special case: it forms nodules with a wide range of rhizobia, but the nodules formed are often not particularly effective in N_2-fixation (Moura *et al*, 2022). Although common bean is widely regarded as a poor N_2-fixer, in favourable environments when nodulated with effective rhizobia it can fix at rates similar to other grain legumes (Giller, 1990).

Soybean dominates the global market for rhizobial inoculants for two reasons: the strong likelihood that grain yields will be increased when the crop is inoculated due to its specific rhizobial requirement, and its economic importance. Although Africa is currently a minor global player, soybean production is increasing exponentially, driven largely by the market for protein-rich feed for poultry and aquaculture. South Africa, Nigeria and Zambia produce the most Soybean. Many other countries rely on import of soya meal as livestock feed, although it could easily be produced locally, which offers an opportunity for smallholder farmers.

Assessing the need for inoculation

Simple 'need-to-inoculate' trials reveal whether or not rhizobial inoculation is required (Giller *et al*, 2016). Ideally such trials have three treatments: (i) an uninoculated control (-I, -N); (ii) an uninoculated control treatment with N fertiliser added (-I, +N); and (iii) a treatment inoculated with the best-quality inoculant, without fertiliser N (+I, -N). The treatment with added N fertiliser is needed to determine whether legume growth is N-limited. The inoculated treatment assesses whether N limitation can be overcome by establishing effective N_2-fixation through rhizobial inoculation. It is important to ensure that other nutrients are not limiting, in particular phosphorus. Possible outcomes of such need-to-inoculate trials are shown in Table 1.

Table 1. Possible outcomes of need-to-inoculate trials and explanations of the underlying causes (after Sessitsch *et al*, 2002; Giller *et al*, 2016)

	Plant growth	Nodulation	Explanation
Uninoculated control	Poor growth, plants yellow	No nodules	No native rhizobia capable of infecting the test legume
	Good growth, plants dark green	No nodules	Soils rich in mineral N, no native rhizobia capable of nodulating the test legume
	Poor growth, plants yellow	Many small ineffective nodules	Native rhizobia ineffective in N_2-fixation with the test legume
	Good growth, plants dark green	Many small ineffective nodules	Soils rich in mineral N, native rhizobia may be effective or ineffective
	Good growth, plants dark green	Many large nodules, red inside	Large soil population of effective compatible rhizobia
Inoculated plants	Poor growth, plants yellow	No nodules	Inoculum does not contain a compatible strain or inoculum dead
	Poor growth or growth not as vigorous as N-fed plants, plants pale green or yellow	Few nodules, or many small ineffective nodules	Poor quality inoculant not delivering enough cells, or rhizobial strain not highly effective or competitive
	Good growth, plants dark green	Many large nodules, red inside	Highly effective inoculant
Nitrogen-fed plants	Poor growth, plants yellow	No nodules or few nodules	Other factor limiting plant growth
	Good growth, plants dark green	No nodules or few nodules	Availability of mineral N inhibits nodule formation

A lack of response to inoculation in N-deficient soils is usually either due to the inoculant being of poor quality, or the presence of a large soil population of bacteria equally effective as the inoculant strain. Likelihood of a response to rhizobium inoculation can also be predicted based on counting the population of compatible rhizobia in the soil: response is likely when there are fewer than 50 cells g soil^{-1} (Thies *et al*, 1991). Soil rhizobia populations above this threshold do not preclude response, but raise the bar in terms of the effectiveness and competitiveness of the inoculant strain. A strong response to rhizobial inoculation requires a large number of bacteria to be delivered on the seed (Brockwell *et al*, 1989). This leads to early nodulation on the crown of the root system, which assists plant establishment and ensures vigorous growth.

Substantial research is devoted to isolating and screening rhizobial strains for use in inoculants. This involves isolating the bacteria from nodules, authenticating them as rhizobia, screening for nodulation and effectiveness in the glasshouse before comparing the best-performing strains in field trials. Particularly for promiscuous legumes such as cowpea and common bean, the introduced strain should be sufficiently competitive to displace the native rhizobial population in the soil. Readers interested in isolating and conducting research on rhizobia are referred to the excellent, open-source manual edited by Howieson and Dilworth (2016).

Types of rhizobial inoculants

Rhizobial inoculants can be produced in any basic laboratory equipped for isolation and cultivation of bacteria (Williams, 1984). Most commonly, a solid carrier is used to coat the bacteria onto the legume seed before sowing. Peat is often the preferred carrier due to its excellent moisture retention characteristics. The peat needs to be finely ground, the acidity corrected and nutrients added before being filled into polyethene packets, which are then sterilised to reduce the number of contaminating bacteria. The bacteria are grown in broth, which is then diluted before being injected into the inoculant packets.

The sterilisation step is key to ensuring inoculant quality; too many contaminants will gradually overgrow the rhizobial strain, reducing the effectiveness of the inoculant and its shelf life. Pasteurisation by autoclaving is not fully effective, resulting in inoculants with an effective shelf life of only three to six months; sterilisation by irradiation can give a completely sterile carrier and a shelf life of two years. Rhizobial inoculants can be stored at ambient temperatures of around 20°C. Contrary to popular belief, this means that cold storage chains are not needed for delivery of inoculants, although care should be taken to prevent exposure to direct sunlight or excessive temperatures during transport. Liquid inoculants have become more popular in Brazil due to their ease of manufacture (Santos *et al*, 2019), but these need more sophisticated supply chains including cold storage.

Is repeated inoculation necessary?

Given that rhizobia are highly competent free-living soil bacteria, is it necessary to inoculate legumes that were grown recently with inoculation in the same field? Survival of inoculant strains depends on the hostility of the soil conditions. Rhizobial numbers declined rapidly after inoculation in sandy granitic soils in Zimbabwe, although survival was better in soils with more organic matter or clay (Zengeni *et al*, 2006). If animal manure was added, the rhizobia could survive for several seasons; the extra organic matter was clearly important for the persistence of the inoculant strains in the very coarse sands. Given their relatively low cost, repeating inoculation each time the target crop is grown is advisable to ensure nodulation by effective rhizobia (Zilli *et al*, 2021).

Rhizobial inoculants in Africa

Early research in Africa on soybean focussed on two approaches to ensuring nodulation and N_2-fixation: inoculation with rhizobia or breeding for promiscuous nodulation with native soil rhizobia. In southern Africa, research focussed on rhizobial inoculants. Field experiments demonstrated strong responses to rhizobia in soybean, and an inoculant factory was established in Zimbabwe in 1961 (Corby, 2011), which continues to produce inoculants to this day. A series of initiatives, notably the UNDP-led African Network of Microbiological Resources Centres (MIRCENs), focussed on building local capacity for microbiological research and inoculation production, with important bases in Nairobi, Kenya and Bambey, Senegal. These MIRCENs facilitated establishment of small-scale rhizobial inoculant production facilities in several countries, including Malawi, Mali, Rwanda, Uganda, Tanzania and Zambia. Many of these facilities were based within universities or research institutes and fell into disuse due to key staff leaving and lack of funding, although some remain active. In two cases at least, the inoculant production was privatised; Biofix was taken over by MEA Ltd in Kenya under licence from the University of Nairobi, and in Malawi Nitrofix is now produced and sold by Agro-Input Suppliers Limited[1]. All of these institutes or companies rely on pasteurisation to sterilise the inoculant carrier. Although the inoculants are effective, they have a relatively short shelf life.

[1] https://www.aisl.mw

By contrast to focussing on inoculation, and aware of the difficulties in delivering rhizobial inoculants to smallholders, the International Institute of Tropical Agriculture (IITA) established a breeding programme to select promiscuously nodulating. soybean varieties that could nodulate with rhizobia that occurred naturally in African soils (Kueneman *et al*, 1984). Varieties of soybean from Asia were naturally more promiscuous than the varieties of soybean from North America, which had been selected in soils with a very narrow diversity of rhizobia (Giller, 2001). The breeding programme focussed on combining advantageous traits of the North American varieties (non-shattering, large seed, high oil content) with those of the Asian varieties (indeterminate growth, promiscuous nodulation) to select 'dual purpose' varieties that yielded well and had prolific biomass (Sanginga *et al*, 2002). The leafy biomass contributed N to the soil, boosting yields of subsequent cereal crops and helping control the parasitic weed *Striga hermonthica* (Sanginga *et al*, 1999). Although the promiscuous varieties that emerged from this breeding programme (denoted TGx – tropical Glycine cross) could nodulate with rhizobia indigenous to African soils, they still responded well to inoculation as it seemed the inoculant strains were more effective in N_2-fixation (Osunde *et al*, 2003).

As discussed above, common bean often does not grow well in infertile soils and is sparsely nodulated; therefore, substantial research has focussed on assessing its need for inoculation. Common bean was introduced to Africa in the 16th century, yet it nodulates with bacteria that naturally occur in African soils (Giller *et al*, 1994), although the nodules formed are often poorly effective in N_2-fixation (Giller, 2001). Multi-locational need-to-inoculate trials conducted with common bean in northern Tanzania showed consistent, although often small, increases in grain yields with inoculation, particularly when applied together with phosphorus fertiliser (Amijee & Giller, 1998; Giller *et al*, 1998; Ndakidemi *et al*, 2006).

The N2Africa project

I had the privilege to co-lead a large-scale project 'Putting Nitrogen Fixation to Work for Smallholder Farmers in Africa' (N2Africa – n2africa.org) that focussed on increasing the production of grain legumes and the inputs from N_2-fixation. The project worked for over a decade from 2009 to 2019 with many partners in 11 countries: the Democratic Republic of the Congo, Ethiopia, Ghana, Kenya, Malawi, Mozambique, Nigeria, Rwanda, Uganda, Tanzania and Zimbabwe. N2Africa was designed around a central hypothesis that N_2-fixation by legumes, grain and biomass yield depend on:

$$(G_L \times G_R) \times E \times M$$

where G_L = the legume genotype, G_R = the genotype(s) of rhizobia nodulating the legume, E = the environment, M = management (Giller *et al*, 2013). Essentially, the genetic potential of the symbiosis depends on the interaction of the legume and rhizobial genotypes ($G_L \times G_R$). These need to be selected to be well adapted to the local environment (E), which includes the climate (temperatures, rainfall, day length, *etc*, to encompass the length of the growing season) and soils (acidity, aluminium toxicity, limiting nutrients, *etc*). Agronomic management (M), including sowing dates, plant density, weeding, rhizobial inoculation and use of mineral fertilisers, control of pests and diseases, determines to what extent the genetic potential of the symbiosis can be achieved.

The project used a 'development-to-research' approach centred around large numbers of simple farmer 'try-outs', which had a dual purpose of testing out the 'best bet' technologies available, as well as demonstrations of the technology that could be used for farmer learning and discussions. A common design was to have 10 × 10 m plots of four treatments: no amendments, only inoculation, only P fertiliser, and both inoculation and P fertiliser. A well-adapted legume variety and good agronomic management were used in all cases. These experiments did not follow the standard design of need-to-inoculate experiments; the N fertiliser treatment was omitted to avoid the appearance that this was being recommended for legumes.

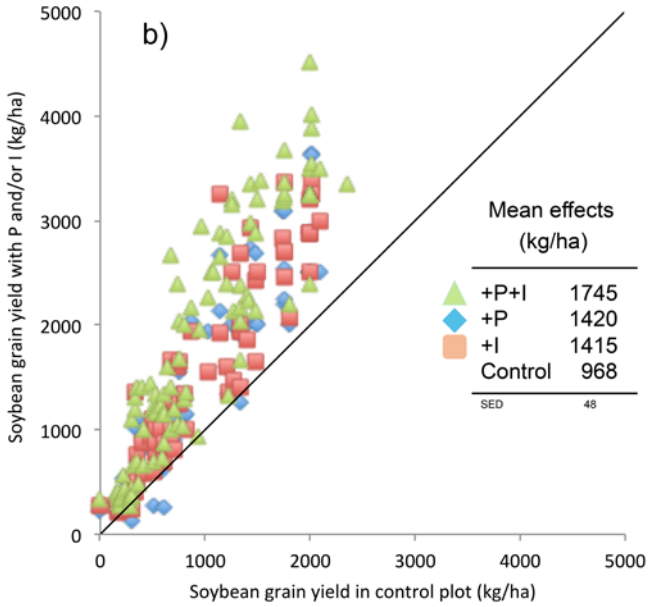
An example of one season of such farmer try-outs with soybean in northern Nigeria (Figure 1, Ronner *et al*, 2016) showed strong responses to both inoculation and P fertiliser, and an additive response when applied together. Given the relatively small cost of rhizobial inoculant compared with P fertiliser, the combined effect of the two inputs together makes the use of P fertiliser economic. In this example, the high-quality inoculant, Legumefix, was used[2]. A combined analysis of data on soybean response to inoculation from 1960 farmer try-outs and 122 replicated on-farm trials across 10 countries revealed wide variability in yields (van Heerwaarden *et al*, 2018). Overall, both specific and promiscuous soybean varieties responded significantly to inoculation, with a stronger yield response in the specific varieties. Local inoculants were used in the majority of these trials, which explains part of the variability in crop response. An inoculant company, NoduMax[3], was established by IITA through N2Africa that produces high-quality inoculants using gamma-irradiated peat as a carrier, which should give more consistent crop response.

[2] https://legumetechnology.co.uk

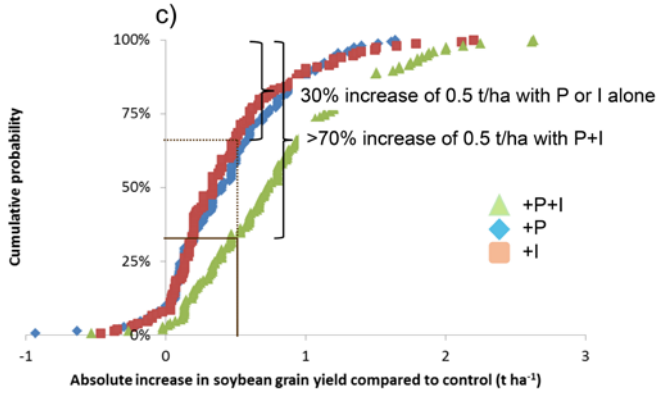
[3] https://propas.iita.org/en/solutions/nodumax-legume-inoculant-for-soybeans/3/details/



Figure 1. a) A farmer 'try-out' testing the effects of rhizobial inoculant and/or P fertiliser on soybean production in northern Nigeria. The unamended control plot is in the foreground.



b) Soybean grain yields in plots amended with rhizobial inoculant (+I), P fertiliser (+P), or both (+P+I) plotted against the yield in the unamended control plot for 163 farms in northern Nigeria (pooled data for 2011 and 2012). Note the huge variability in the unamended plots.



c) Cumulative probability of soybean yield increases compared with the unamended control plot across 163 farms in northern Nigeria (pooled data for 2011 and 2012). Roughly 30 percent of the farm plots amended with either rhizobial inoculant or P fertiliser gave a yield increase of 0.5 t ha^{-1}, compared with 70 percent of the plots amended with both rhizobial inoculant and P fertiliser. After Ronner *et al* (2016)

The numbers of inoculant trials conducted by N2Africa with other legumes was more limited. Chickpea, a cool-season legume, is a major grain legume in the Ethiopian highlands which nodulates and fixes N_2 with a diversity of *Mesorhizobium* species (Gunnabo *et al*, 2020). Inoculation with elite strains of *Mesorhizobium* and P fertiliser gave additive yield responses, similar to those observed in soybean, in 116 farmer try-outs (Wolde-Meskel *et al*, 2018). Yield benefits to application of P fertiliser (+P), rhizobial inoculant (+I) and both (+P+I) were observed on 71 percent, 73 percent and 92 percent of the farmers' fields, with 25 percent of the farmers achieving yield increases of ≥1000 kg/ha with both +P+I. Inoculation responses in common bean were more variable, with fairly strong and consistent responses to inoculation in Ethiopia, Rwanda and Tanzania (Thuijsman & Ronner, 2018). No significant response to inoculation was observed in Zimbabwe, where common bean struggles to grow on the coarse sandy soils (Chekanai *et al*, 2018).

The N2Africa experiments confirmed that large inputs from N_2-fixation in grain legumes are possible only when P deficiencies are corrected (Giller & Cadisch, 1995; van Heerwaarden *et al*, 2023). In addition to strong benefits of rhizobial inoculants and basal P fertiliser on increased yields of soybean and common bean, labour costs for weeding were reduced due to the vigorous crop growth (Kilakila *et al*, 2025). Clear responses of common bean to potassium fertilisers were observed in some of the experiments in Tanzania (Thuijsman & Ronner, 2018), confirming earlier research (Smithson *et al*, 1993). Analysis of trials across the N2Africa countries indicated that soil K deficiencies are indeed localised to specific regions (van Heerwaarden *et al*, 2023).

Intensification through diversification with grain legumes

The huge versatility and diversity of grain legumes, in terms of crops and varieties, offers opportunities to provide options that can match the enormous diversity of agroecologies, farming systems and farms (Vanlauwe *et al*, 2019). A major goal of N2Africa was to increase the area planted to legumes, often less than 10 percent of the farm area in East and Southern Africa, such that a modest increase to 20 percent would immediately double the N input (Giller *et al*, 2013). N2Africa adopted a 'socio-ecological niche' approach to identify legume/rhizobium combinations appropriate for different types of farmers depending on market opportunities (Ojiem *et al*, 2006). For example, 'vertical intensification' using climbing beans suits the very small farms of the Rwandan highlands (Franke *et al*, 2019), chickpeas grow and yield well

on residual moisture, allowing an extension of the cropping season in Ethiopia (Verkaart *et al*, 2018), and legume intercropping, relay crops and rotations can take a myriad of forms (Kermah *et al*, 2017; Kermah *et al*, 2018).

In addition to the production of nutritious grain to diversify diets or for sale, and the use of legume residues as fodder for livestock, grain legumes contribute substantial amounts of N to the soil through fallen leaves and below-ground residues. The residual N benefits to crops in rotation are proportional to the amount of N left in the field, which in turn depends on prolific growth of the legume crop (Ojiem *et al*, 2014; Vanlauwe *et al*, 2019). Grain legumes also boost production of subsequent crops by interrupting pest and disease cycles and suppressing *Striga,* a parasitic weed that can devastate cereal crops (Franke *et al*, 2018).

Future directions for rhizobial inoculants in Africa

Inoculants for promiscuous legumes?

Recent research challenges the received wisdom, based on decades of research across the tropics, that highly promiscuous legumes such as cowpea rarely respond to inoculation with rhizobia (Giller, 2001). Careful attention to strain selection resulted in elite *Bradyrhizobium* strains that increased yields of cowpea when used as inoculum in Ghana and Mozambique (Boddey *et al*, 2017; Osei *et al*, 2020), and in Ethiopia (Ayalew *et al*, 2021; Ayalew *et al*, 2024) and groundnut in Ghana (Osei *et al*, 2020). In such cases, where substantial nodulation is observed on the roots in the absence of inoculation, a high-quality inoculum is essential to ensure that the inoculant strain can displace the native soil rhizobia and form the majority of the nodules.

The need for high-quality inoculants

All the evidence indicates the need to prioritise high-quality inoculants, particularly for smallholder supply chains (Vanlauwe *et al*, 2019). Inoculants must deliver large numbers of effective rhizobium strains to the seed to displace less effective populations in the soil, as in the example of cowpea described above. High-quality inoculants have a long shelf life, which is essential for delivery to smallholder farms due to the long distances and weak supply chains. Although there is ample evidence that lower-quality inoculants can give significant increases in legume grain yields (*eg* Giller *et al*, 2011), they must be used soon after manufacture due to their short shelf life. This creates huge logistical problems due to the short time between manufacture and use, leaving companies only a few months for production ahead of the season and requiring inoculants to be used immediately upon delivery.

Some agronomists suggest that farmers can use soil excavated under a nodulated legume as inoculum, but this runs the risk of introducing soil-borne pests *(eg* nematodes) and pathogens *(eg Pythium, Fusarium*). In Brazil, the loosening of quality control regulations allowed on-farm production of rhizobial inoculants; tests showed that they contained no detectable rhizobia and a myriad of contaminants, including potentially human pathogens with multiple antibiotic resistances (Bocatti *et al*, 2022). In India, independent tests showed that many legume inoculants contained no rhizobia, and some marketed inoculants claim to have an impossibly wide host range, so wide that they even include legumes that cannot form nodules or fix N_2[4]. Although many African countries now have regulations requiring registration of rhizobial inoculants for sale, none have regular testing of the products being sold.

Overcoming barriers to deliver inoculants to smallholders

Despite the clear benefits of rhizobial inoculation for legume production, taking inoculants to scale remains problematic. A clear benefit is that the products are cheap; the estimated cost is less than USD 5 per hectare, which is easily covered by the resulting increases in legume grain yield. However, a cheap product has its drawbacks: a large number of inoculum packets must be sold to make it economically viable for the manufacturer and retailer to deliver and stock the product.

The advent of information and communication technology (ICT) platforms in Africa offers opportunities to overcome transaction costs and facilitate the supply and use of inputs (Ayesiga, 2023). In northern Uganda, farmers' use of inputs and the ensuing grain yields of soybean were enhanced when loyalty incentives were provided through an ICT platform (Ayesiga *et al*, 2026). Financial loyalty incentives were provided in the form of price bonuses for the soybean produced; non-financial incentives were provided as tarpaulins that facilitated threshing and winnowing and enhanced soybean grain quality, resulting in better prices for farmers. Nevertheless, the number of farmers using rhizobial inoculants remained very small due to delays in timely supply to agrodealers.

A promising approach to facilitating the supply and use of inoculants is to bundle them with other

[4] https://www.pioneeragroindustry.com/shop/product/rhizobium-bacteria-nitrogen-fixing-bacteria-1kg/

products and services. In Ethiopia, Abetu *et al* (Abetu, 2022; Abetu *et al*, 2024) investigated the bundling of improved seed of soybean with rhizobium inoculant and phosphorus fertilisers. Farmers were offered a number of bundles through agrodealers in a 'real life' experiment, where they invested using their own resources. Nothing was offered for free. Simply offering the three inputs (seed, rhizobium and P fertiliser) in a bundle resulted in a small increase in the share of farmers purchasing (from 26 percent to 29 percent). Adding a microloan had no effect, but when a market contract from a farmers' union that guaranteed purchase of the soybean grain to be produced at an agreed price was added, 79 percent of the farmers purchased the bundle. The bundling of inputs and services has several advantages: (i) farmers receive all of the inputs they need in a single package; (ii) as all inputs are provided together, the suppliers can adjust the size of the packages to match the needs of average smallholders in the target region; (iii) transport and transaction costs are reduced; (iv) financial and insurance services can easily reach the customers; and (v) inevitably, all actors in the value chain must coordinate their efforts to provide the bundle (Abetu *et al*, 2026).

Conclusions

Symbiotic N_2-fixation by grain legumes has a central role to play in food and nutrition security in Africa. Research across the continent has demonstrated the benefits of rhizobial inoculants alongside well-adapted legume varieties and good agronomic management in ensuring that farmers can reap the benefits of N_2-fixation. When applied together, the additional yield and income from rhizobial inoculants can cover the cost of basal P fertilisers that are essential to alleviate the problems of poor soil fertility. High-quality inoculants are key to ensuring consistent legume yield responses, particularly given the weak distribution networks for agro-inputs in Africa. N2Africa played an important role in boosting the evidence base on grain legume N_2-fixation, raising awareness and delivering appropriate technologies to smallholder farmers (Giller & Ronner, 2019), but much remains to be done. An independent analysis *"... found convincing evidence that N2Africa contributed substantially to a process of technological upgrading of soybean production in northern Ghana, yet the project played a relatively small part in the overall increase in soybean production in that region. In Ethiopia, there was clear evidence that N2Africa had made a decisive contribution to expanding the production and supply of legume inoculants, and had stimulated awareness of and demand for inoculants among small numbers of legume farmers. However, the project has only helped the market for legume inoculants to reach a small fraction of its potential"* (Ton & Glover, 2019).

There is a strong case for further investment to ensure that smallholder farmers in Africa can access rhizobial inoculants and reap the full benefits of symbiotic N_2-fixation by grain legumes.

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Biologicals – commercial reality – current and future potential market

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Having obtained a BSc in Chemical Physics, an MBA and a PhD in Environmental Economics, Dr Shoham worked for Syngenta and legacy companies in a variety of technical and commercial roles for 32 years, latterly as Head of Business Intelligence. For the last 14 years he has consulted for clients in the public, private, academic and NGO sectors on a range of projects spanning the agricultural supply chain. During this time, he has authored over 20 published papers and reports, most recently on the 'hot topics' of biologicals and digital farming. In his current role as Consulting Analyst for S&P Global he has returned to his crop protection and seeds roots, diving ever deeper into both subjects, whilst also diversifying into biological products and remaining at the forefront of developments in agricultural sustainability, thereby closing the loop with his origins as an environmental economist.

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Abstract

Whilst natural products have long been used for control of pests and diseases, so-called biologicals are currently undergoing somewhat of a renaissance. All the major R&D-based crop protection companies have entered the market, often through acquisition, and biologicals are included as a fundamental component of regenerative agriculture, which is also very much in vogue. At the same time there is a lot of hype surrounding the sector, and some of the claims made about its current size and potential growth need to be closely examined. That is the purpose of this paper.

Methodological issues

Until recently several commentators were claiming the market was growing at over 15 percent a year (Impey, 2023). In seeking to validate or otherwise such claims, it is important first to establish what is meant by biologicals. There are two aspects to this. First, which sectors are included? Everyone agrees that biological control agents (BCAs) and biostimulants are within scope. The former control biotic stress, namely insects, diseases and weeds. The latter "*support a plant's natural processes independently of the biostimulant's nutrient content, including by improving nutrient availability, uptake or use efficiency, tolerance to abiotic stress and consequent growth, development, quality or yield*" (Congress, 2022). Beyond that, other sectors which may or may not be included, depending on the assessor, are biofertilisers, fermentation products such as abamectin and the spinosyns, plant growth regulators and multi-site inorganic products such as sulphur and copper. The values of these different sectors are shown in Figure 1.

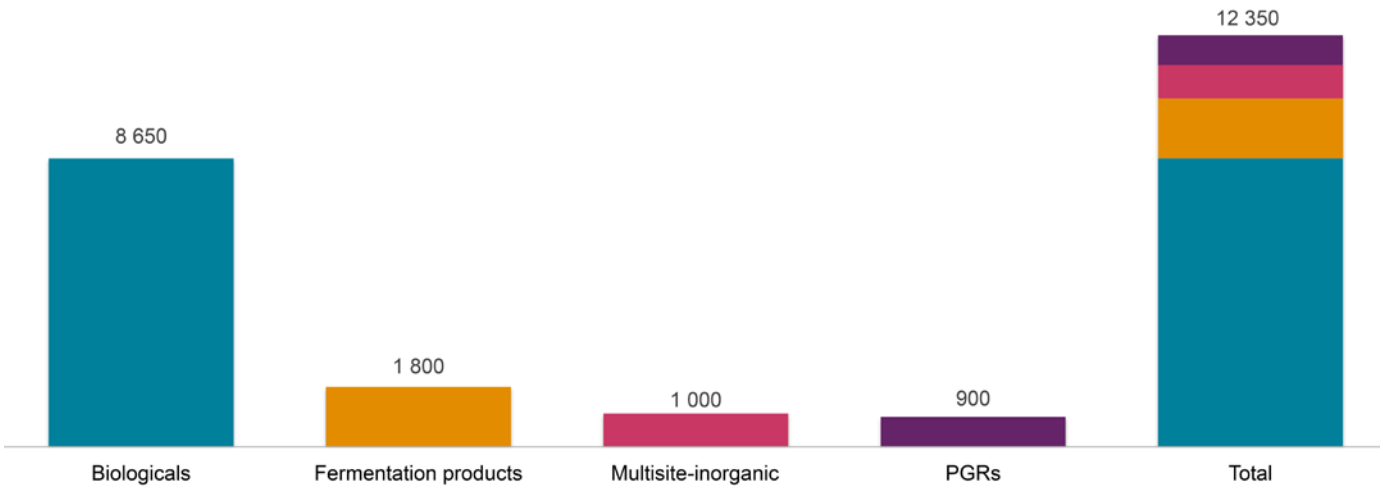


Figure 1. Biologicals and adjacent sectors (Source: S&P Global; PGR: plant growth regulators)

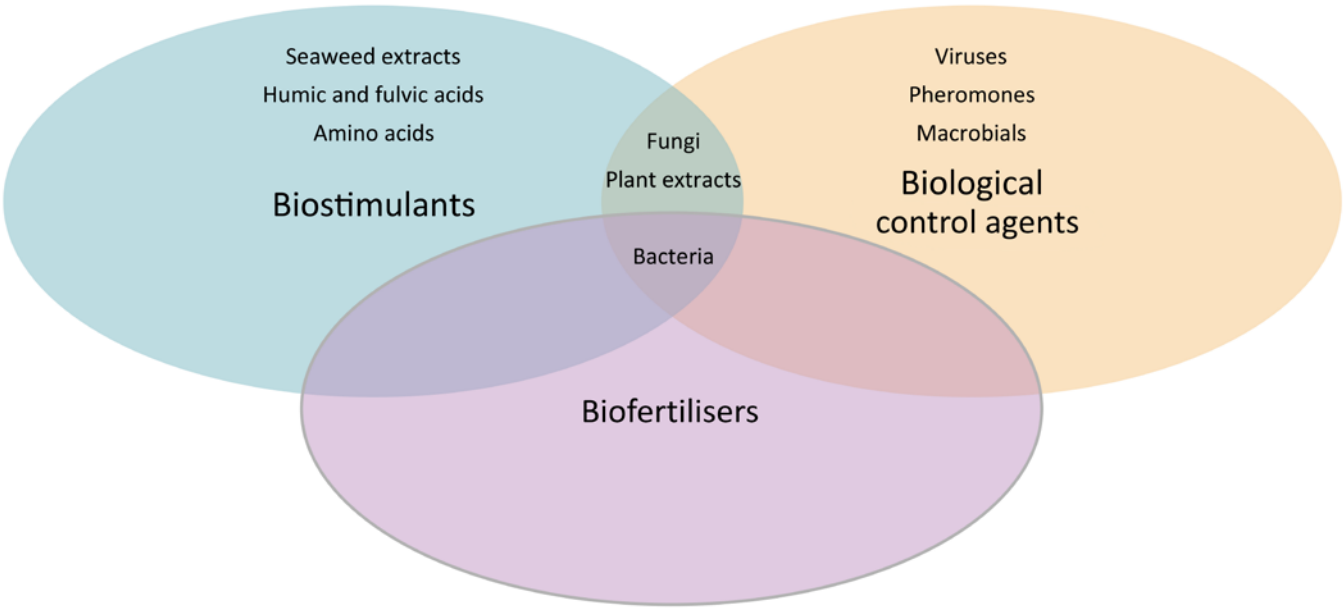


Figure 2. Overlaps across market segments (Source: S&P Global)

Second, having agreed the scope, there may be ambiguity about which products belong to which category (Figure 2). This is particularly the case for certain classes of BCAs and biostimulants. Microbials (bacteria and viruses) and plant extracts, for example, can be classed as BCAs, biostimulants or both, depending on the strategy of the company. These definitional problems can result in delays to the promulgation of fast-track regulatory systems for biologicals, as a prerequisite for any regulation is an agreed definition.

Putting aside the issue of what is included, there remains the problem of obtaining reliable data on biologicals. There are over 2000 biologicals active ingredients (AIs) which make up the market of around USD 9 billion, giving an average product size of USD 4.5 million. This is very small compared to the average size of a conventional crop protection (CP) product, 700 of which make up a market of USD 70 billion (average sales USD 100 million), making it very difficult to pick up sales of biologicals through primary market research. Other market estimation strategies need to be adopted, and crucially a degree of triangulation needs to be employed to increase confidence in any estimates. The market can be viewed from three different perspectives.

Company perspective: Few of the 800 companies participating in the biologicals space will report their sales. These may be large CP multinationals who report biologicals as a product sector *(eg* Syngenta), or the very few specialised biologicals companies which are publicly listed. However, the vast majority of companies do not report biologicals sales, either because they are privately owned, or, if they are public, because biologicals are a relatively small sector which does not merit separate reporting. In the absence of reported sales figures, sales may be estimated using a combination of indicators – manpower, size of product range, facilities, etc.

Product perspective: As mentioned above, the majority of biologicals AIs are relatively small in sales terms. The vast majority have sales well below USD 10 million. This makes it difficult to pick up sales numbers through primary market research. However, various indicators can be used: the spectrum of control; the number of different brands; the number of countries in which the product is registered.

Country perspective: The overall size of a country's CP market provides a benchmark for the biologicals market. Within that, the relative importance of different crops provides clues as to how big the biologicals market might be. Unless there is a row crop which uses a significant amount of biologicals – as in the case of soybean in Brazil and use of inoculants – use of biologicals is likely to be highest in the fruit and vegetables sector. Beyond that, the regulatory regime which is in force has major influence. In countries which have a fast-track system for biologicals compared to conventional CP products, the share of biologicals is likely to be higher. Other factors are the pull from the food chain, which is itself influenced by the strength of the modern retail sector (*ie* supermarkets) and the size of the market for organic food, which provides an indicator of the demand for 'safer' products.

Current and future size

Taking all these factors into account, S&P Global estimates the biologicals market to be around USD 9 billion (Figure 3), split roughly 50/50 between BCAs and biostimulants/biofertilisers.

As far as potential future growth is concerned, there are four principal drivers:

- Regenerative agriculture
- Regulation
- Resistance
- R&D

These can be classed as 'the 4 Rs'.

Regenerative agriculture

Regenerative agriculture combines many different techniques – no-till, cover crops, crop rotations, carbon farming. Use of biologicals also comes within scope. In a recent survey commissioned by Bayer (Bayer, 2024), biologicals featured as 2 of the 17 practices commonly employed by farmers under the regenerative agriculture banner.

Regulation

Regulation is a very complex area which varies by country and product type. BCAs and biostimulants fall under different regulatory regimes. For BCAs, the USA was the first country to introduce a less rigorous process for BCAs which are considered low risk, in 1994. Most recently, Brazil has introduced a more favourable regime, which has greatly increased the numbers of products on the market. At the other extreme, some countries treat BCAs the same as a conventional CP product, which, given the much smaller size of product, represents a considerable barrier to entry. The European Union (EU) is an example of the latter, although there is a concerted effort to accelerate the process for BCAs (IBMA, 2025).

In the case of biostimulants, the EU is leading on the regulatory front, having introduced legislation to treat them under existing fertiliser regulations. The USA, on the other hand, deals with biostimulants on a state-by-state basis, having no federal system, although this is in the process of being addressed under the Plant Biostimulants Act.

The other side of the coin is the continuing loss of major AIs, creating gaps in the market which BCAs can fill (Figure 4 and Figure 5). Recent examples are mancozeb and chlorothalonil, which both lost their registrations in the EU. Both products exhibit multi-site activity, so their loss deprives farmers of valuable tools to manage resistance.

Resistance

Resistance of weeds, insects and diseases to herbicides, insecticides and fungicides, respectively, is a huge and growing problem. A recent analysis by S&P Global showed that 95 percent, 92 percent and 80 percent of the herbicide, insecticide and fungicide markets, respectively, were subject to moderate to high levels of resistance.[1] Biologicals have an important role to play in resistance management as they offer alternative modes of action.

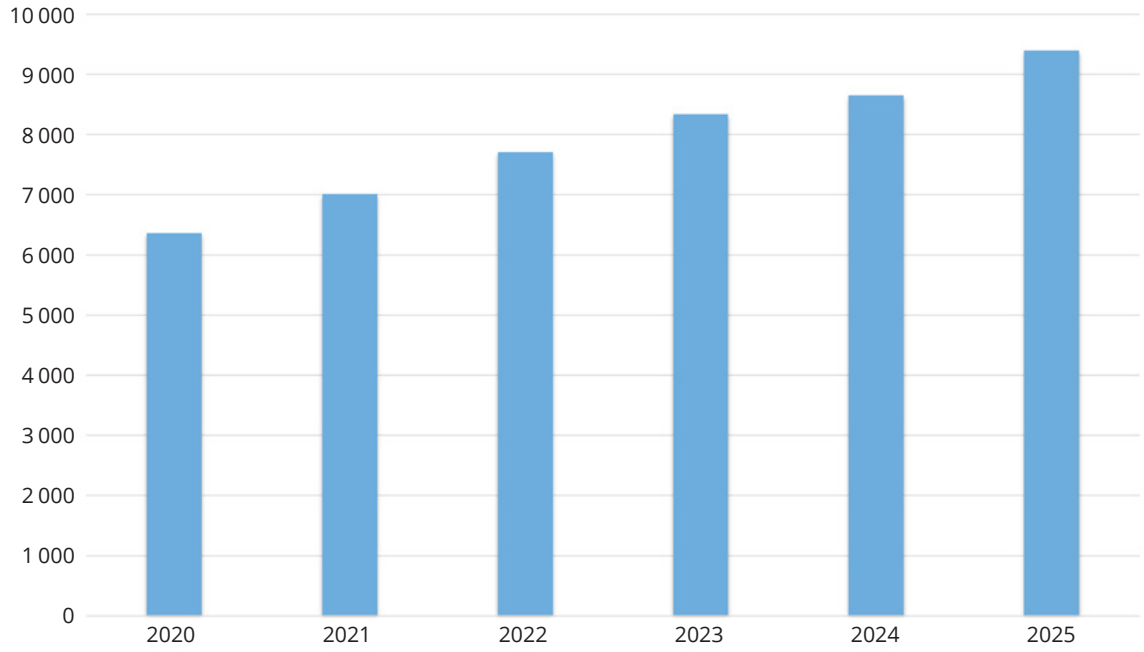


Figure 3. Biologicals market (USD millions) (Source: S&P Global)

[1] Resistance to herbicides, insecticides and fungicides – extent, causes, management and prospects; Featured Insight, November 2025, S&P Global.

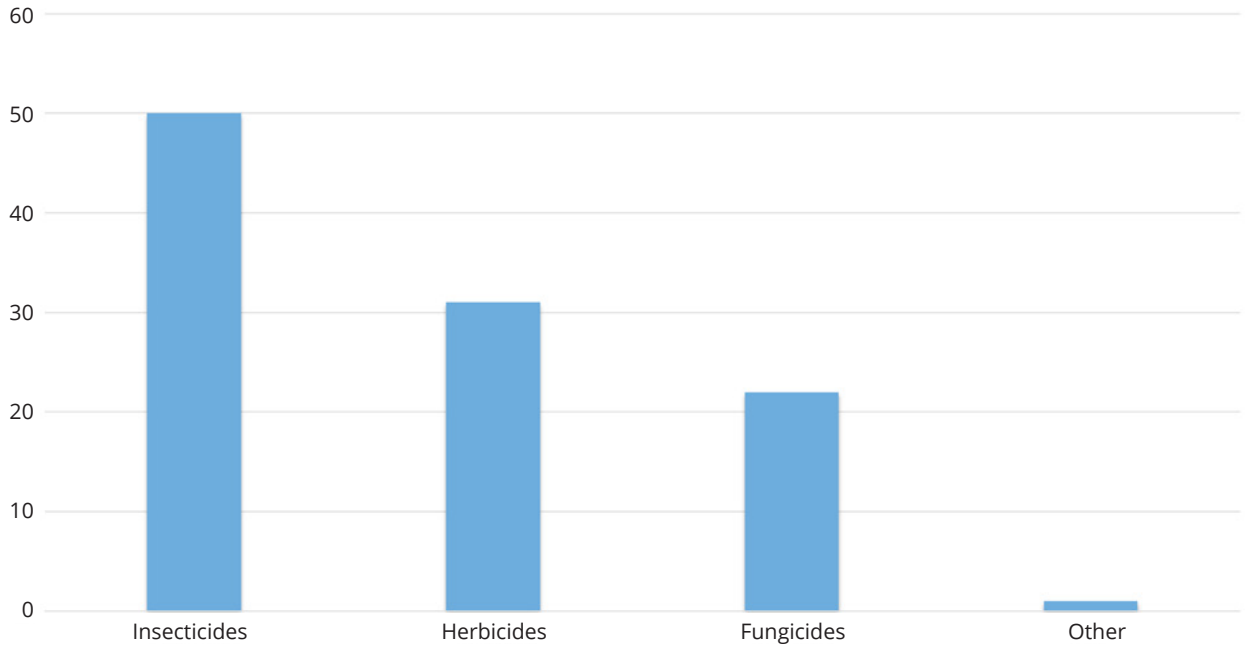


Figure 4. Number of crop protection bans/phaseouts by sector since 2019 (Source: S&P Global)

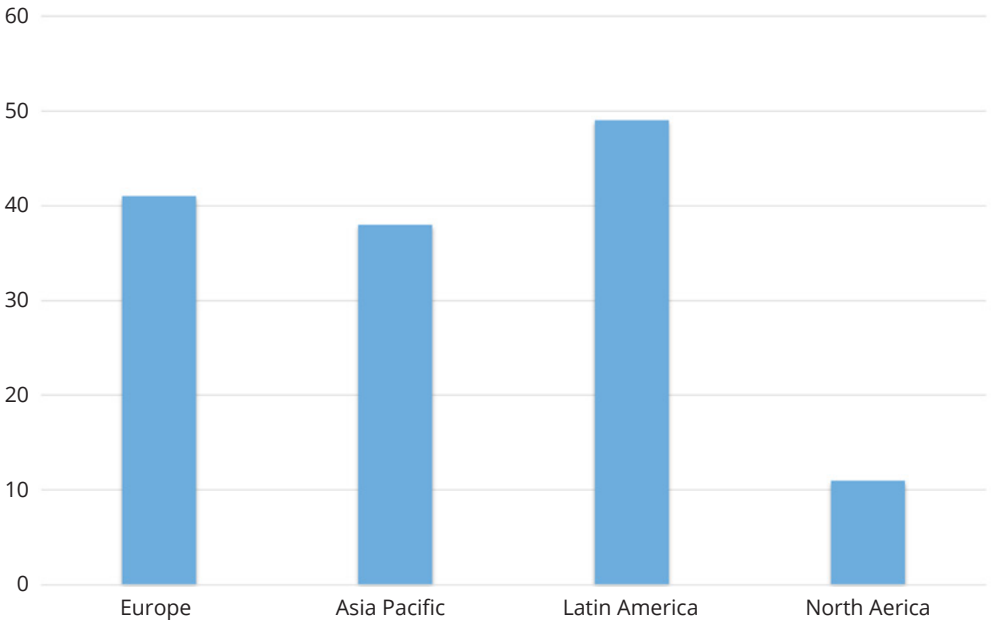


Figure 5. Number of crop protection bans/phaseouts by region since 2019 (Source: S&P Global)

R&D

The current popularity of biologicals has enticed many of the major R&D-based companies into the market. This brings with it a greater level of R&D investment into the sector. The current biologicals industry pipeline is estimated by S&P Global to comprise over 100 AIs. This compares with around 50 in the industry pipeline for conventional CP and continues a long trend of biologicals innovation outpacing that of conventional AI in terms of the number of new products introduced every year (Figure 6).

Consideration of all these drivers leads S&P Global to forecast that the market will grow at a compound annual growth rate (CAGR) of 7.5 percent over the next five years (Figure 7). This is considerably below the level suggested by other commentators, but still above the average CAGR for conventional CP, which is more in the range 2–3 percent, making it an attractive market.

One additional factor which will promote future growth of the biologicals sector is the entry of the major R&D

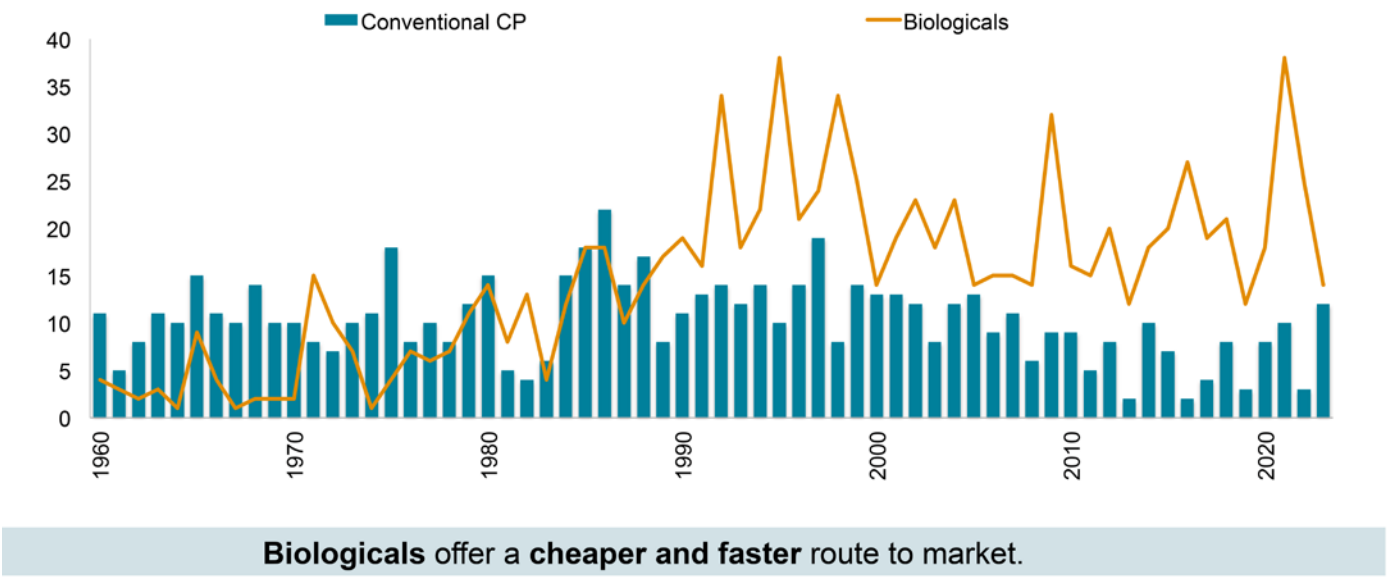


Figure 6. New product introductions per year, 1960–2023 (Source: S&P Global; CP: crop protection)

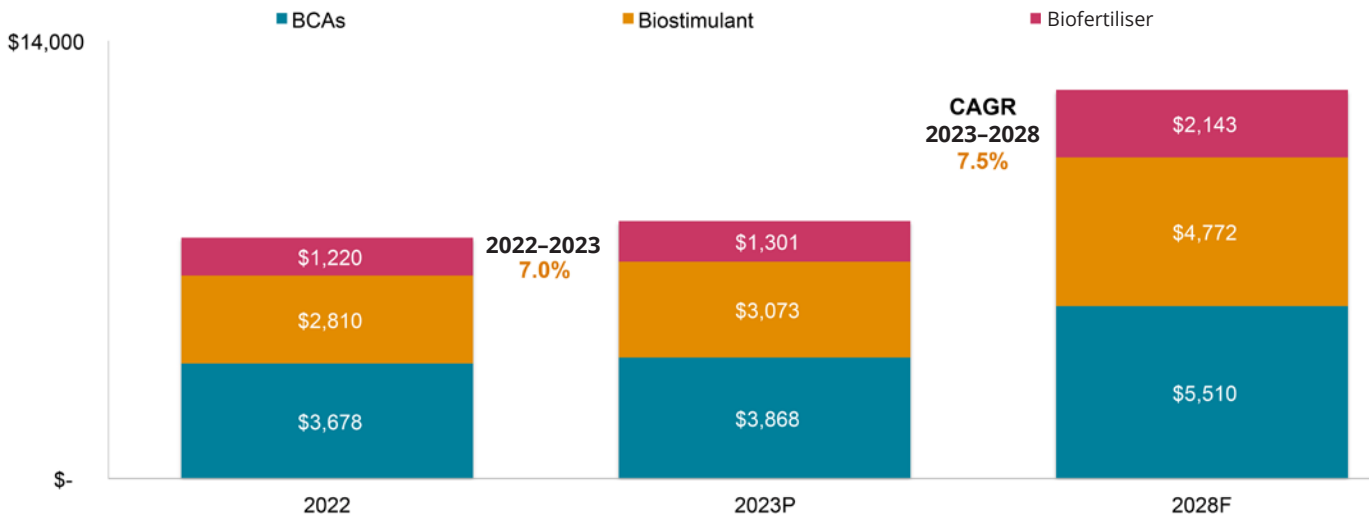


Figure 7. Biologicals market forecast (Source: S&P Global; CAGR: compound annual growth rate, F: forecast, P: preliminary)

companies into the sector. Most of the top 10 crop protection companies have increased their share of the biologicals market through acquisition. A major barrier to entry for smaller biologicals companies is finding a route to market. Distribution is key and distributors wield a lot of power. The major companies already have established channels through which they can sell their biological products, so their increasing participation in the sector will provide more marketing impetus for biologicals and help sustain their growth.

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Endophytic fungi: cryptic biologicals with a high-vis future

Harry Evans



Harry Evans has more than 55 years' experience in plant disease identification and management in tropical agriculture and forestry. He has specialised in the use of fungi for the biological control of invasive alien species, working as a Principal Scientist with CABI and coordinating research projects within the Biological Control of Weeds and Plant Diseases Programme. Currently, he is an Emeritus Fellow with CABI (Ascot, UK), mentoring junior scientists and assisting with projects, including overseas surveys. Prior to CABI he worked for 15 years as a Technical Cooperation Officer for the UK Overseas Development Administration, specialising in plant and forest pathology on cacao projects in Ghana, Ecuador and Brazil, as well as on pine diseases in Central America. Harry has published more than 250 peer-reviewed papers, for which he received a DSc from the University of London in 1999, and is a co-author of the standard reference book Atlas of Entomopathogenic Fungi.

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Abstract

Fungal endophytes are defined as asymptomatic colonisers of plants for all, or a part, of their life cycles. There is increasing evidence that coevolved species can form mutually beneficial and highly specialised associations with their host, providing the plant with an additional armoury to combat abiotic and biotic stresses. The author's research on plants of economic importance – including commodity crops (cacao, coffee), as well as invasive alien weeds – in their centres of origin provides evidence of the importance and uniqueness of coevolved endophytic fungi in plant population dynamics in natural ecosystems. It is posited that these fungi can and will play an equally pivotal role in agricultural ecosystems in the future.

Introduction

Fungal endophytes occur within the living tissues of healthy plants without producing any apparent symptoms, and their presence may confer certain advantages to the host plant and vice versa. Mutualistic and, typically, coevolved endophytic fungi offer a variety of potential benefits to their host plants: induced resistance; growth enhancement; tolerance to abiotic factors – including drought, heat and heavy metals – increased resistance to biotic constraints, such as pests and pathogens (Schulz & Boyle, 2005). As the latter authors conclude, endophytic fungi occupy a continuum, from beneficial (mutualists) to aggressive (amensalists) colonisers of plants. The emphasis here will be on the mutualists: coevolved species that form intimate associations with their plant hosts – typically, growing systemically and intercellularly, without provoking a host response (Figure 1) – in an association that is beneficial to both organisms: the fungus affords increased resistance or tolerance to both abiotic and biotic stresses, in effect acting as bodyguards; the plant provides nutrients, as well as offering protection from environmental stresses and microbial competition.

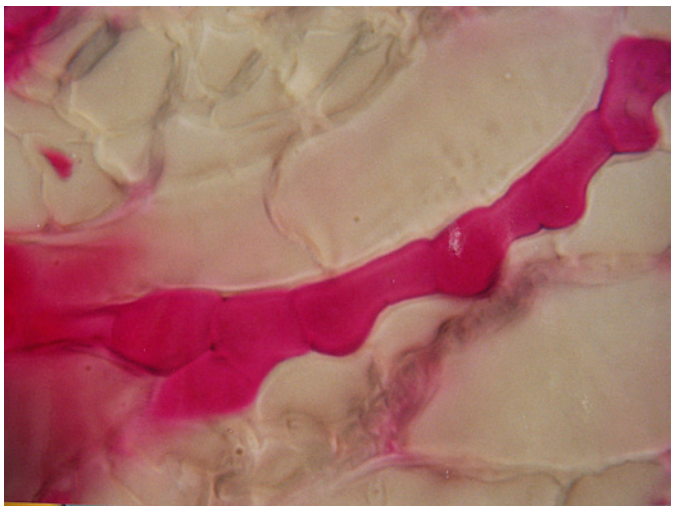


Figure 1. Specialised mycelium of an endophytic fungus growing systemically and intercellularly within the stem tissues of a healthy plant without eliciting a host-defence response (Photo: H Evans)

The conception

It was during research on the biological control of invasive alien species (IAS) that the significance of centres of origin of organisms and the relevance of globalisation, with the subsequent 'McDonaldisation' of the world's flora and fauna (Ritzer, 2015), struck a chord with me. This global movement of exotic species has been happening for centuries – exemplified by the movement of human diseases from Africa to the Americas, such as yellow fever, during the slave-trade era (Evans *et al*, 2018) – but has speeded up

dramatically over the past 20–30 years. Specifically, these IAS projects involved alien weeds and the use of the classical biological control (CBC) approach for their management, whereby searches for potential CBC agents are carried out in the centre or region of origin of the weed target; the premise being that alien plants (neophytes) arrive without, or are depauperate in their coevolved natural enemies (Evans & Ellison, 1990; Evans *et al*, 2001). Thus, such plants have a fitness or competitive advantage over the indigenous flora and, under certain circumstances, can become invasive and problematic, posing a threat to natural and/or agricultural ecosystems, as first posited in the enemy release hypothesis (ERH) of Keane & Crawley (2002). However, it was felt that this did not wholly explain the 'silver bullet' phenomenon, whereby the introduction and release of a single CBC agent has an immediate, profound and sustainable impact on an otherwise seemingly intractable weed problem, such as rubber-vine weed (*Cryptostegia grandiflora*) in northern Queensland, Australia, where it posed an actual and potential threat to natural and agricultural ecosystems over an estimated 40 000 km^2 until the release of a coevolved rust species from Madagascar (Figure 2; Tomley & Evans, 2004; Evans, 2013).



Figure 2. Shrubs of the highly invasive alien rubber-vine weed (*Cryptostegia grandiflora*) in northern Queensland, heavily infected with and defoliated by *Uredo cryptostegiae* from Madagascar – a species closely related to coffee leaf rust (*Hemileia vastatrix*) – three months after its release as a classical biological control agent. The rust reduced or eliminated flowering and seed set, stopping spread of the weed into the Northern Territory and allowing recovery of grazing land and restoration of native Eucalyptus forest. (Photo: H Evans)

The birth of an idea

The germ of the idea was that not only neophytes arrive without their coevolved natural enemies and, thus, are fitter and more competitive than indigenous plants, but also that these natural enemies are also subject to natural-enemy pressure ('little fleas have lesser fleas') in their centres of origin. As a consequence, should they ever catch up with their host plants – after arriving accidentally or being introduced deliberately as CBC agents – they would be fitter and more damaging. This natural-enemy pressure had been highlighted during 'conventional' plant pathology projects searching for potential CBC agents of crop diseases.

The evidence from tropical tree crops

Theobroma spp

This centred on a USDA-funded project on *Theobroma cacao* as a replacement crop for coca (*Erythroxylum coca* var. *coca*) in north-west South America. The major constraints to cacao cultivation in this region are two 'mushroom' species (*Agaricales*), *Moniliophthora roreri* and *M. perniciosa*, the causal agents of frosty pod rot and witches' broom disease, respectively. The hypothesis was field-tested on an endemic wild relative of cacao, *Theobroma gileri*, in sub-montane rainforest in north-west Ecuador, where *M. roreri* was suspected to have evolved. A plethora of natural enemies – including highly adapted and seemingly coevolved, fungal-feeding insects, as well as mycoparasites – was encountered on pods infected by the pathogen, severely restricting spore production and, seemingly, limiting the impact of the pathogen since estimated pod losses were low (Evans *et al*, 2003). In sharp contrast, barely 300–400 km away in commercial cacao plantations on the coastal plain of western Ecuador, pods attacked by *M. roreri* showed dense sporulation – often resulting in 80–100 percent crop loss – with no evidence of specialist fungal or insect colonisers; in effect, the pathogen had arrived in the region free of its coevolved natural enemies and these had never emerged from their forest refuges. In addition, a search for endophytic fungi in the healthy stems and pods of the wild *T. gileri* trees was included, using a novel, *in situ* isolation protocol (Evans *et al*, 2003; see Figure 3). These samples yielded a highly diverse mycobiota, unexpectedly rich in species of *Trichoderma*, a well-documented genus with high biocontrol potential (Figure 4), leading the foremost expert on this fungal group (Gary Samuels at USDA-Beltsville) to state that *"Trichoderma is usually considered a genus of free-living soil fungi… and this is a new niche. This discovery suggests a potential for protecting crop plants against attack by plant pathogens through induced resistance or antibiosis*" (Samuels, 2006). Subsequent analysis of these *Trichoderma* isolates at USDA-Beltsville revealed numerous new species, with a proven endophytic ability in the annual crop plants tested and tangible host benefits, including increased growth and drought tolerance. When these surveys were extended to include cacao (*Theobroma*

cacao) in its native range in the Amazonian region of Ecuador and Peru, similar novel guilds of endophytic fungi were encountered, contrasting with the situation in cultivated cacao where significantly less endophytic diversity was present (Thomas *et al*, 2008).



Figure 3. Ethiopian scientist training how to take samples for isolation of endophytic fungi from the sapwood of semi-wild *Coffea arabica* near Bonga, Kaffa Region, south-west Ethiopia, watched by the farmer. The collaboration of local scientists and stakeholders is essential in classical biological control projects in line with the Nagoya Protocol (Photo: H Evans)

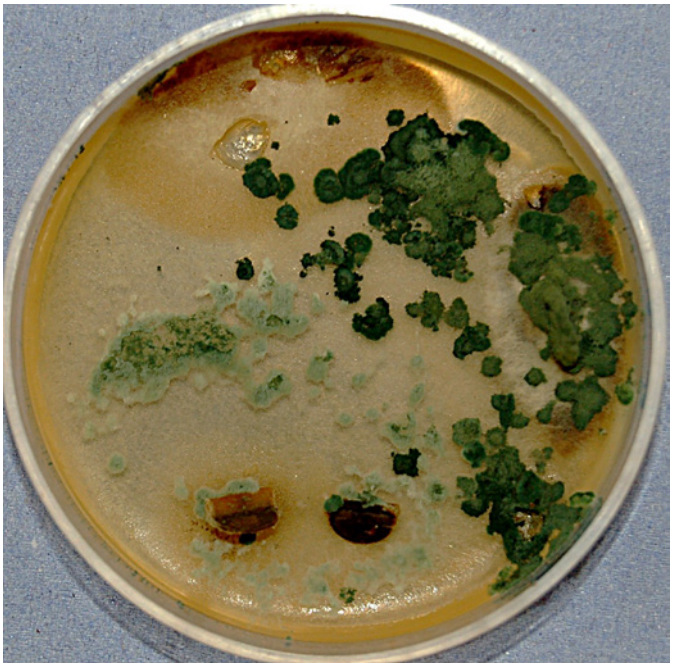


Figure 4. Typical green *Trichoderma* colonies (two distinct species: one pale green; the other darker) emerging from sapwood samples from stem of wild *Coffea arabica*, Ethiopia (Photo: H Evans)

Coffea spp

Based on this evidence, World Coffee Research funded surveys in Africa to look for coevolved mycoparasites of coffee leaf rust (CLR) caused by *Hemileia vastatrix* on wild species of *Coffea*, as well as to explore the guilds of endophytic fungi in these populations, with the aim of assessing their potential as CBC agents in the Americas. Surveys were concentrated in Cameroon and Ethiopia (see Figure 3) and yielded almost 80 isolates of the genus *Trichoderma* – 16 species in total, 4 of them new taxa – reflecting the richness reported previously in wild *Theobroma* (Evans *et al*, 2003). Equivalent surveys in semi-naturalised *Coffea arabica* in Brazil failed to locate any *Trichoderma*, either as mycoparasites on the rust or as endophytes within the plant (Rodríguez *et al*, 2021). Subsequent papers on other mycoparasitic genera – *Cladosporium*, *Clonostachys*, *Digitopodium* – have followed, culminating in the most recent, on *Lecanicillium*-like isolates, in which seven new species and two new genera are described (Colmán *et al*, 2025). In short, there is a bewildering array of potential and novel CBC agents associated with CLR and *Coffea* spp in their African centre of origin, compared to their exotic range in the Americas.

The evidence from CBC invasive alien weed projects

During the selection and subsequent intensive host-range screening of fungal pathogens for the CBC of invasive alien weeds, the initial emphasis is on eliminating natural enemies, especially mycoparasites. Thus, on its introduction in the target country, the selected agent is free of natural-enemy pressure, increasing its fitness as a pathogen. As we saw from the results of the above studies from tropical tree crops, fungal plant pathogens harbour a wealth of mycoparasites that would reduce their impact in natural situations, which would be eroded further by the actions of antagonistic endophytes. This potential endophyte interaction was also investigated during some CABI weed biocontrol projects, most notably on Japanese knotweed (*Reynoutria japonica*): a highly problematic IAS in the UK, particularly in urban situations. For example, knotweed growing through the tarmac of a car park in Camberley (Surrey) was found to be devoid of endophytes, whilst the plant in its natural habitat in Japan – such as on volcanoes – had a rich and diverse endophytic mycobiota, including a novel and still-to-be-described family of Ascomycetes. Some of these endophytes were later shown to inhibit the development of a coevolved rust fungus on Japanese knotweed (Kurose *et al*, 2012).

The endophyte-enemy release hypothesis

Based on this evidence, Evans (2008) conceived the endophyte-enemy release hypothesis (EERH), which posits that, in addition to neophytes arriving without

their coevolved natural enemies, a more cryptic but still significant factor could also be involved: mutualistic fungal endophytes. Thus, alien or exotic plants in the absence of their coevolved endophytic fungi and natural enemies would have a double competitive advantage because they would have more resources to allocate to growth and reproduction with 'no bodyguards to pay' for their protection and no coevolved natural enemies: thus, exotic crops thrive; alien weeds invade. However, this increased fitness comes with a price since neophytes in the absence of their bodyguards are extremely vulnerable to attack by coevolved natural enemies lacking their own natural enemies. Plant pathology is littered with examples: potato blight (*Phytophthora infestans*) arriving in Europe in the 1840s, more than 200 years after the introduction of its coevolved host from the Americas, and *Hemileia vastatrix* catching up with its *Coffea arabica* host in Ceylon in the 1860s, both history-changing events (Evans & Waller, 2010). And, of course, this would be an additional factor to further explain the 'silver bullet' event in the CBC of invasive alien weeds.

The future

Can these mutualistic fungal endophytes, or fungal endosymbionts, be exploited to benefit agriculture since, undoubtedly, all agricultural crops are lacking them following domestication and intense plant breeding over centuries?

In perennial woody crops, such as cacao and coffee, this would be challenging because of plant architecture. And, although endophytes have been successfully inoculated into seedlings of both crops and re-isolated after several months (Figure 5; Evans *et al*, 2003; Rodríguez *et al*, 2021), there is no long-term evidence of how long these will grow with and remain in the plant. In contrast, in annual monocot crops with a simple architecture – such as cereals – fungal endophytes grow readily through the tissues intercellularly, and colonise the inflorescences systemically: thus, horizontal transmission through seeds is common, although not in dicots, where vertical transmission appears to be the rule.



Figure 5. *Trichoderma* emerging from healthy stem of cacao seedling, six months after inoculation of germinating beans with a new species originally isolated from *Theobroma gileri* in Ecuador (Photo: H Evans)

However, thus far, there have been no studies to use this approach in food crops but there is compelling evidence of the potential benefits from *ad hoc* surveys of wheat and its relatives in their natural range in the Middle East. Marshall *et al* (1999) isolated a diverse range of endophytes from wild *Triticum* spp, which led them to conclude that: "*Fungal endophytes of the genera Neotyphodium inhabit wild wheat species grown indigenously on the Anatolian Plateau of Turkey. These endophytes may influence the ecology of Triticum species, and may also serve as a source of biological control agents of pests and abiotic stress factors in wheat.*" In addition, they speculated that: "*the evolution of Triticum species and the domestication of wheat may have been influenced by Neotyphodium endophytes.*" Despite these promising findings, there appears to be no follow-up study to extend the work to an agricultural scenario. A similar, more recent endophyte survey of wheat ancestors in Israel, using both isolation and DNA sequencing, found that "*wild grass relatives of wheat contain a wealth of taxonomically diverse fungal endophytes that are not found in modern wheat, some of which belong to taxa with known beneficial effects*" (Ofek-Lalzar *et al*, 2016). Included among these were species of *Ophiocordyceps*, *Lecanicillium* and *Engyodontium*: well-documented fungal pathogens of arthropods, especially *Ophiocordyceps*, an obligate parasite of insects. Moreover, a recent study of the endophytic fungi of a wild relative of barley has yielded a similar eclectic mix of species, rich in mycoparasites with proven biocontrol potential against some of the major diseases of barley (Høyer *et al*, 2022).

This begs the question: what are such disparate fungi doing in these wild hosts and why are they not being exploited for agriculture?

Evidence for the first question, as well as a pragmatic example of the second, comes from work with turf grasses where the aforementioned genus *Neotyphodium*, an obligate endophyte of grasses, has been the subject of intensive research. Some years ago, I attended a USDA meeting at Rutgers University, New York and saw varietal trials of tall fescue lawn grass, *Festuca arundinacea*, where plants inoculated with *Neotyphodium* far outperformed those without, showing resistance to pests and diseases, as well as drought tolerance. The *Neotyphodium* had been isolated from plants from northern Europe – the

centre of origin of tall fescue – imported as seed for the turf-grass breeding programme. My CBC background kicked in and I explained that they had actually brought the coevolved *Neotyphodium* in the seed from Europe, which had been lost in the commercial varieties being used as turf grass in the USA. The fungus is now incorporated in all turf-grass products based on tall fescue, marketed as endophyte-enriched seed and promoted with multiple benefits by a wide range of companies: "*Finelawn Elite is an endophyte-enhanced tall fescue with >70 percent Neotyphodium endophyte which provides resistance to pests and diseases; including brown patch caused by Rhizoctonia solani and also improves abiotic stress tolerance – especially, to drought – and faster seedling establishment*." Rutgers University is now reaping the benefits with annual royalties in the millions of dollars (Funk & White, 1997; Meyer *et al*, 2012): a beautiful example of serendipity in science, as well as showcasing the potential of CBC.

From these few examples, the answer to the above question is obvious: mutualistic endophytic fungi are present in all wild relatives of crop plants – whilst totally absent from the crops grown for agriculture – and confer significant benefits to the host plant. Based on the turf-grass experience, it is recommended that coevolved fungal endophytes should be sourced from the centres of origin of the major crops and the most promising ones should routinely be incorporated into crop varieties of the future.

Conclusion

The world's population is predicted to rise from the present 8 billion to 10–11 billion by 2050. Food production will need to keep pace, with increasing pressure to access marginal land. In addition, global warming is predicted to rise dramatically over this period, with increased risk of drought, as well as extending the geographic range of pests and diseases. All these factors will increase the need for higher yielding, pest/disease-resistant and drought-tolerant crops. There is burgeoning and compelling evidence that mutualistic fungal endophytes can act as bodyguards, not only providing additional resistance to pests and diseases but also tolerance to abiotic factors, such as drought, as well as boosting growth (Figure 6). A recent study has re-emphasised their potential as growth promoters or biostimulants when endophytes from wild grapevine were found to increase the growth and seed production in the test plant *Arabidopsis*; seemingly, following changes in the plant's hormone biosynthetic pathways (Aleynova *et al*, 2026). The fact that fungal endophytes can readily be incorporated into the seeds of cereal crops will be of particular benefit to low-income farmers since there will be little or no additional costs incurred for pest and



Figure 6. Tomato plant four months after inoculation with the above *Trichoderma* isolate, showing significantly increased growth compared with the un-inoculated control plant in the background. In addition, the *Trichoderma*-inoculated plants exhibited drought tolerance during an earlier growth stage when the irrigation system failed over a long weekend, whilst the control plants wilted and some died. (Photo: H Evans)

disease management, crop irrigation and, potentially, with reduced fertiliser inputs in endophytes functioning as biostimulants. To undertake the type of projects listed above will, of course, require international cooperation with the common goal of improving food production, especially for farmers in developing countries. Unfortunately, convincing donor agencies of the long-term and environmental value of this novel approach has, thus far, been a frustrating experience.

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Isolation and characterisation of plant growth-promoting bacteria in Guatemala



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Introduction

Agricultural systems based on maize, beans, cacao and cardamom are essential for Guatemala's food security and rural economy. However, these agricultural systems face multiple challenges, including soil degradation, intensive use of agrochemicals and low resilience to climate change. Such pressures have led to declining productivity and loss of soil biodiversity. In this context, an emerging alternative is biofertiliser derived from native soil microorganisms that enhance agricultural productivity, reduce dependence on external inputs and conserve local microbial biodiversity. More specifically, studies have shown that plant growth-promoting (PGP) bacteria enhance nutrient availability, stimulate root development and improve plant tolerance to stress. By using native soil bacteria, it is possible to strengthen crop productivity while maintaining ecological balance and reducing agrochemical inputs. In order to contribute to agroecological innovation and to the resilience of smallholder farming systems in the country, this study aimed to identify native soil bacteria with the potential to promote plant growth in strategic crops in northern and western Guatemala.

The research aimed to isolate native bacterial strains from soil supporting cardamom, cacao, maize, bush bean and the milpa system (association between maize and climbing bean) in Guatemala. Sampling covered 27 municipalities across seven departments: Alta Verapaz, Quiché, Huehuetenango, Quetzaltenango, Totonicapán, Sololá and Chimaltenango. The bacterial isolates identified were screened for PGP traits: nitrogen fixation, indole–3-acetic acid (IAA) production, phosphate, potassium and calcium solubilisation.

Methodology

Soil, root and/or nodule segments were processed to obtain pure cultures through serial dilutions. Dilutions 10^{-3} and 10^{-4} were plated in duplicate on Nutrient Agar (NA) and incubated at 28°C for 24 hours. Subsequently, morphologically distinct colonies were re-isolated. Pure isolates were characterised by colony morphology, Gram staining and catalase test, and were also plated on YEMA medium for the detection of potential *Rhizobium*. PGP capacity was assessed using specific selective media: for nitrogen fixation (Nfb), nutrient solubilisation (phosphate, potassium and calcium in NBRIP, PKV-Mod1 and PKV-Mod2 media, respectively), and the ability to produce the phytohormone IAA.

From the isolate collection, bacteria were selected for identification, prioritising those with rapid growth (<24 hours) and the presence of at least three or four PGP properties. For species-level identification, DNA was extracted from the selected bacteria and the full 16S region (V1–V9) was sequenced. Products were analysed with BLAST NCBI® for high-resolution taxonomic identification.

Results and discussion

A total of 143 soil samples were collected from maize, bean, cacao and cardamom cropping systems, yielding 1201 bacterial isolates. The microbial composition was found to differ across the various crop types and systems.

The most prevalent ability was nitrogen fixation, found in 28 percent of the isolates. Potassium and phosphate solubilisation abilities were detected in 22 percent and 23 percent of the isolates, respectively. IAA production was the least frequent property, detected in only 6 percent of the total collection.

Of the 1201 total bacterial isolates, 40 percent demonstrated at least one PGP trait. Only a few exhibited all five PGP properties, positioning these candidates for multifunctional biofertiliser development. This highly multifunctional group was primarily concentrated in maize and the milpa system, while cacao showed the lowest number.

The 127 bacterial isolates prioritised for genus identification were distributed across the different crops and system (soil/root). The majority of the

prioritised isolates originated from maize soil and milpa system soil, representing the main focus of subsequent taxonomic analysis.

The identification analysis revealed *Pseudomonas* as the most frequently detected genus across all crops. This genus is associated with nitrogen fixation, siderophores, phytohormones, solubilisation of phosphorus, potassium and zinc, and other related properties. Also, *Acinetobacter* showed high prevalence, being found in all except the milpa root system, and is known for producing IAA, siderophore, gibberellin, antibiotic and biosurfactants/ bioemulsifiers, and for solubilising phosphate, potassium and zinc. A variety of unique genera were identified per crop, with cardamom exhibiting the highest richness (11 genera). Conversely, the crop with the lowest diversity was the milpa root system, where 92.31 percent corresponded to *Pseudomonas* and 7.69 percent to *Raoultella*.

Acknowledgements

This research work was supported by the CRIA programme, funded by the United States Department of Agriculture (USDA) and implemented by the Ministry of Agriculture, Livestock and Food (MAGA) of Guatemala and the Inter-American Institute for Cooperation on Agriculture (IICA). The authors want to express sincere gratitude to the team of the Center for Agricultural and Food Studies of the Universidad del Valle de Guatemala for their technical assistance and help in the collection and processing of the samples.

The Aflasafe story: from aflatoxin challenge to safer food and trade

Alejandro Ortega-Beltran, IITA



Alejandro Ortega-Beltran is a Senior Plant Pathologist and Head of the Pathology and Mycotoxin/Aflasafe Unit at the International Institute of Tropical Agriculture (IITA; HQ in Nigeria). He earned his BSc in Biotechnological Engineering from the Instituto Tecnológico de Sonora (Mexico) and a PhD in Plant Pathology from the University of Arizona (USA). He was a postdoctoral scientist at the University of California, Davis. His current work focusses on developing, testing, registering and scaling aflatoxin biocontrol technologies across Africa, helping farmers produce safer crops, improving food safety, health and trade outcomes. He also collaborates with maize, cowpea, soybean and banana breeders to develop disease-resistant cultivars and promotes capacity-building by training technicians, scientists, students and regulators across Africa, the Americas, Europe and Asia.

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Abstract

An international team led by the International Institute for Tropical Agriculture has been investigating the management of aflatoxin. Highly carcinogenic in nature, aflatoxins impact the quality and quantity of harvest, causing health and economic impact. This research has investigated the use of fungal species which do not create aflatoxins to replace those that do. When a suitable species was identified, production and registration challenges had to be overcome to make a product of known efficacy available to farmers at scale.

Introduction

Aflatoxin is a major public health, trade and nutrition security issue, particularly in Africa. Aflatoxins are produced by certain moulds of the genus *Aspergillus*, particularly *Aspergillus flavus*. The fungi can grow on multiple crops but are of particular concern on maize and groundnut. The fungi can infect in the field but more usually are a bigger problem with stored grains. Aflatoxins are among the most carcinogenic substances known and are described as the most potent carcinogen found in nature.

Exposure to aflatoxin is generally through ingestion of contaminated foods, and is associated with immune suppression, stunted growth (Khlangwiset *et al*, 2011), delayed development (Abbas, 2005), aflatoxicosis (Queensland, 2014) and liver cancer. It is associated with about 30 percent of liver cancer cases in Africa. Children are particularly susceptible although links between childhood stunting and aflatoxin exposure have not been consistently detected in all studies (Turner *et al*, 2007). No animal species is known to be immune.

The United States Food and Drug Administration (FDA) action levels for aflatoxin present in food or feed are 20–300 ppb (FDA, 2000). Aflatoxin levels have been recorded in Africa at over 48 000 ppb. In Africa, around 40 percent of commodities in local markets exceed allowable levels in food. Figure 1 demonstrates how the presence of aflatoxin makes for a significant barrier to trade, in this example to the European Union (EU). Africa is estimated to lose up to USD 670 million a year in rejected exports because of the presence of aflatoxin (it should also be noted that food produced in developed countries is sometimes also rejected in organised markets due to the presence of aflatoxins, although such contaminated commodities may still reach consumers through unmonitored, informal markets).

Aflasafe

Not all genotypes of *A. flavus* produce aflatoxin. Such genotypes are commonly referred to as atoxigenic and can be used as biocontrol agents. Aflasafe is a biocontrol product containing atoxigenic genotypes of *A. flavus* as active ingredients that outcompete aflatoxin-producing species in the field. When searching for atoxigenic genotypes, large-scale screening using microbiological, chemical and molecular methods allows for identifying those that do not produce aflatoxins but also those that can outcompete aflatoxin-producing genotypes. Several Aflasafe products have been formulated and tested in farmer-led field trials. Results from over 12 000 fields (trials and commercial usage) in 10 countries show that use of Aflasafe products allows producing safe crops, with, in general, 80–100 percent less aflatoxin than untreated neighbouring crops. This work is summarised in Figure 2.

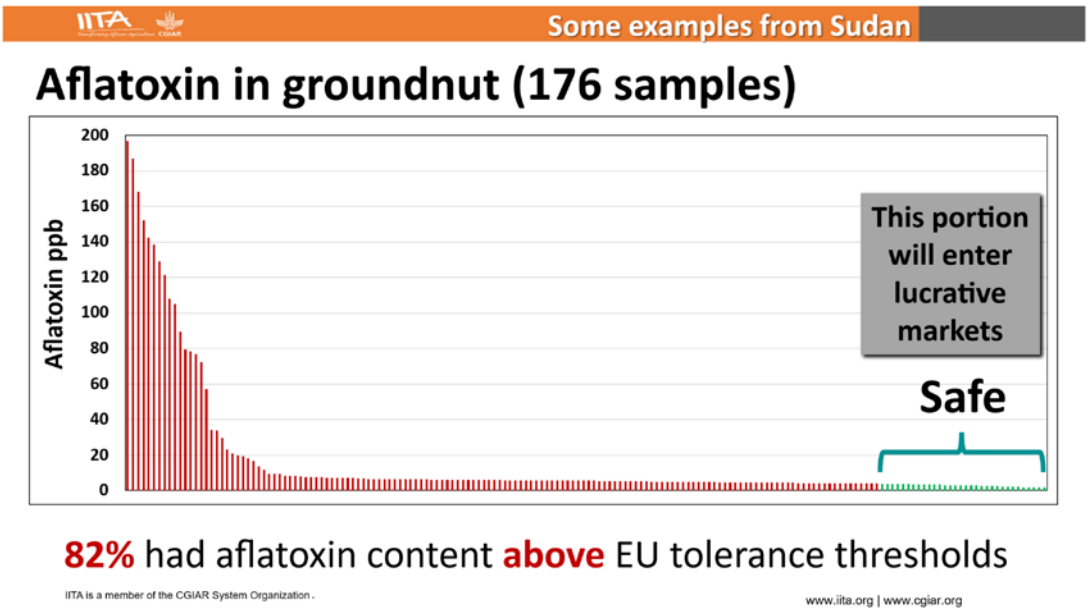


Figure 1. Aflatoxin contamination in groundnuts sampled in Sudan (Source: Author's field data)

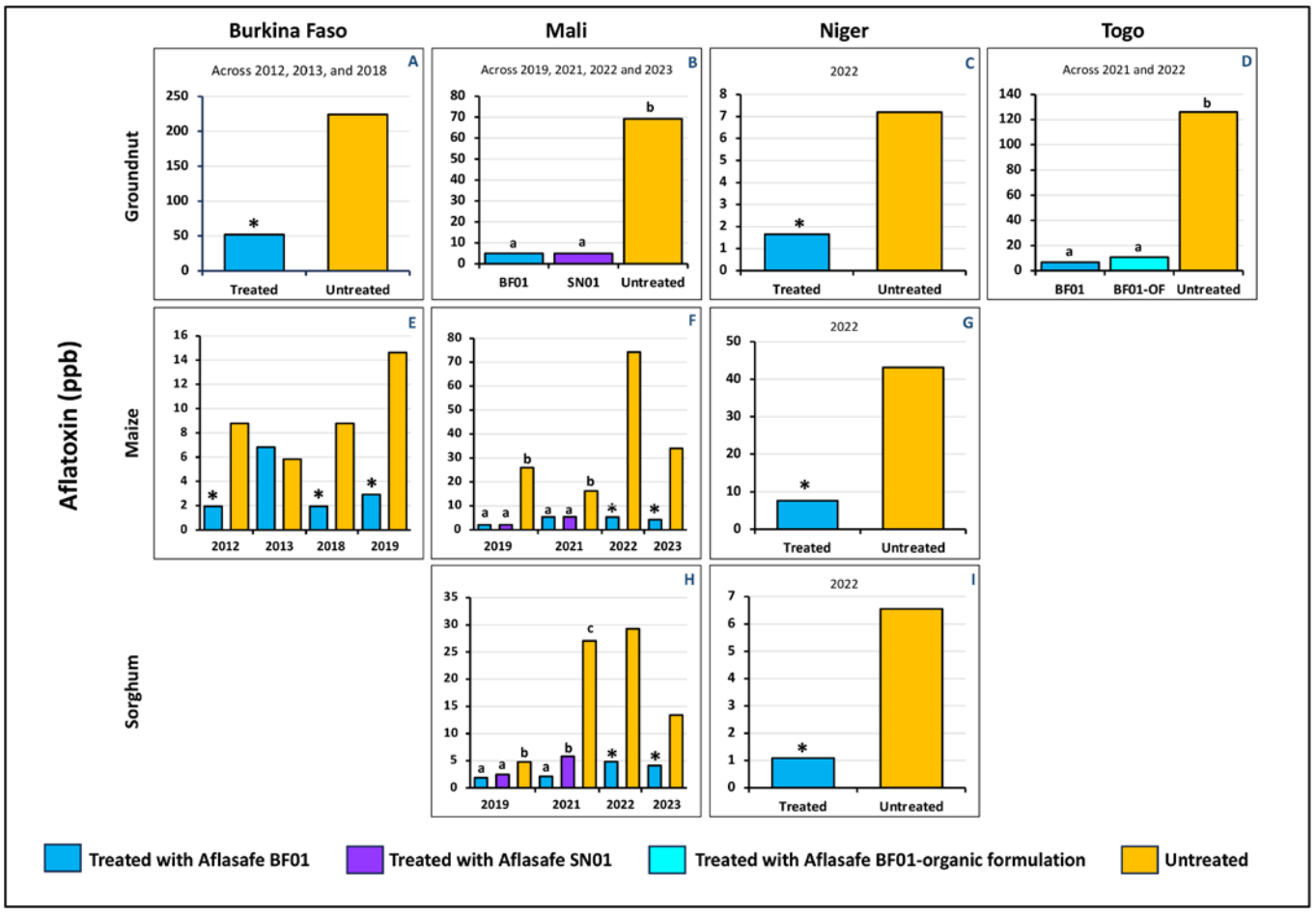


Figure 2. The impact of different Aflasafe treatments on different crops in different countries (Source: Bonkoungou *et al* 2024)

Road to large-scale usage

Even with tested and registered Aflasafe products containing effective atoxigenic genotypes, the path to commercial use is long and sometimes difficult. Challenges include the registration of this unique product, industrial production of the agent and how to stimulate demand for a product which addresses a poorly acknowledged problem (Bandyopadhyay *et al*, 2022).

Registration of Aflasafe

Registration of aflatoxin biocontrol products with the regulatory authorities is a significant challenge. Procedures followed for registration of two aflatoxin biocontrol products in the United States by the Environmental Protection Agency assisted in the interactions with regulators. Biopesticide registration training workshops were conducted in Ethiopia, Kenya, Nigeria, Malawi, Senegal, Tanzania and Sudan. Through these workshops and other interactions regulators became familiar with efficacy and risk assessment procedures for the registration of aflatoxin biocontrol products. These agencies were considered as partners and were kept informed of key R&D developments and understood that native atoxigenic genotypes are already present in target areas, *ie* the registrations do not concern bringing new material into the target environments. To date, 17 commercial products have been registered in 13 countries (14 of the 17 commercial aflatoxin products were developed by IITA and partners).

Aflasafe production

In addition to stimulating demand, there was also a need to stimulate supply. The challenge was how to make Aflasafe production more simple and more scalable, how to increase production capacity from ~300 kg/week to 5 tons/hr (Kaptoge *et al*, 2024). Scaling was dependent on industrial manufacturing and effective partnerships with the private sector. Donor support enabled the refining of manufacturing processes, developing fit-to-scale production models and strengthening commercialisation strategies. IITA has facilitated the production of thousands of tons of biocontrol products – leading to over a million tons of aflatoxin-safe crops.

The key lesson learned was that innovation alone is insufficient for scaling solutions like Aflasafe. It is necessary to develop industrial processes, strategic partnerships, effective commercialisation strategies, key awareness and sensitisation campaigns and sustained investment.

Even though the use of the product has expanded significantly, the uptake is still limited in aflatoxin-conscious core market segments dominated by large processors, exporters and government procurement. The challenges in scaling out this technology are summarised in Figure 3.

Aflasafe impact case study in Nigeria

Extract from Gates Notes (2023):

"Nigeria is home to some of the most interesting work being done in agriculture, and I had the opportunity to check out a few of the most promising innovations in the pipeline. I was especially excited to hear more about Aflasafe, a product that protects crops from a deadly compound called aflatoxin that is created by a fungal infection. (It's estimated that nearly a third of all liver cancer cases in Africa are due to aflatoxin exposure.) They have a novel approach to scaling up and supporting farmers, and I'm optimistic their product will save many lives."

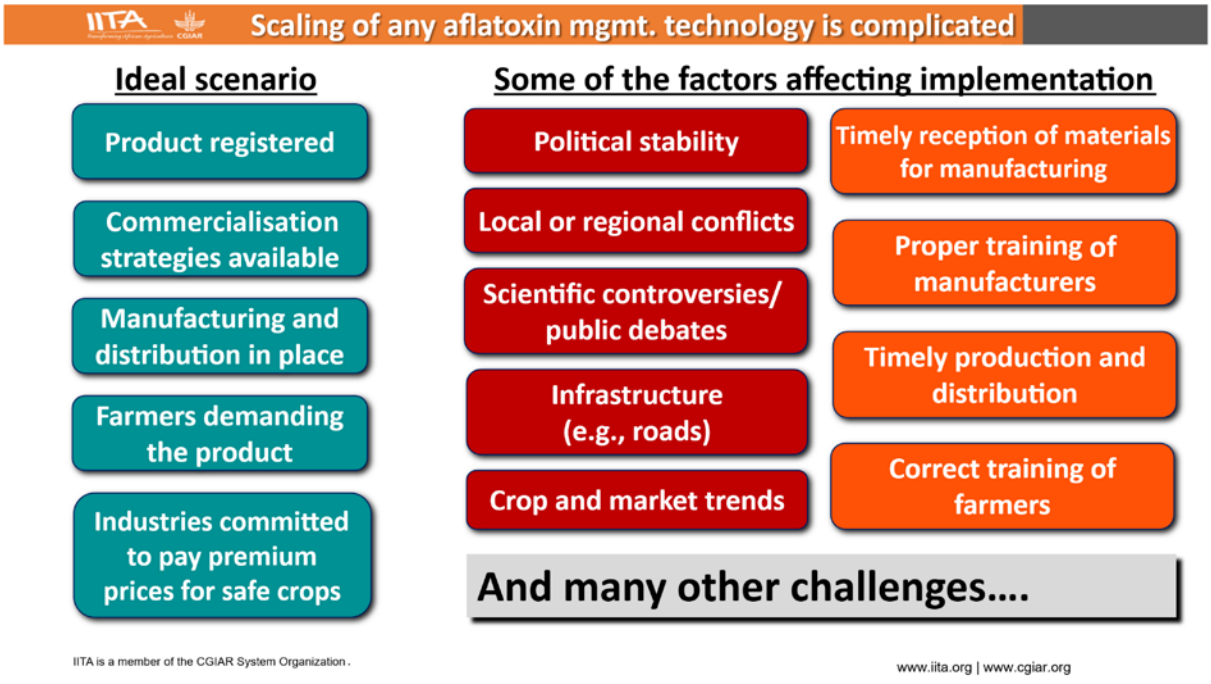


Figure 3. Factors affecting uptake and adoption of Aflasafe

In six years, 32 agri-businesses worked with 75 786 smallholder farmers who applied Aflasafe on 99 500 hectares of maize in Nigeria. The result of this was that most of the grain was of a quality that could be exported: >95 percent grain lots with <20 ppb (US-FDA action level); >90 percent with <4 ppb (EU), which increased income by an average of 16 percent per smallholder farmer. Smallholder consumption of Aflasafe-treated maize increased.

Additional impacts

Export income in The Gambia: For years farmers in The Gambia have been unable to export groundnuts to Europe because of aflatoxin rates. However, the treatment with Aflasafe has changed this for about 7000 farmers who treated approximately 5000 hectares. They obtained 15 percent more for their product because it can be exported to the EU market, and the premium could reach 30 percent more over the long term.

Food security in Kenya: The Galana-Kulalu irrigation scheme is in an aflatoxin-prone area. Nearly all (99 percent) of the scheme's maize was aflatoxin-safe by Kenya's standards, while 96 percent met the EU standard. Nearly half a million of the region's most vulnerable people benefitted from aflatoxin-safe maize for one month.

Conclusions: lessons learned in the promotion of Aflasafe

Aflasafe has achieved significant impact in terms of human health and increasing income from crops, particularly maize and groundnuts. However, it is not a magic bullet. Its successful adoption is the result of overcoming significant challenges. Overcoming these challenges has been achieved through, amongst other activities:

- Creation of awareness about aflatoxin and its management
- Use of biocontrol as a key component of an aflatoxin control system
- Creation and promotion of testing facilities
- Premium from an aflatoxin-conscious market for start-up
- Public sector support such as input supply schemes
- Partnerships with Government institutions and industry trade bodies
- Monitoring and implementation of standards in the marketplace
- Development of a system to converge technical, policy and institutional innovations.

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The Green Muscle experience: beyond biopesticide identification

Belinda Luke, CABI



Dr Belinda Luke is the Global Team Leader for PlantwisePlus, where she leads the programme's work on augmentative biocontrol. With a background spanning biological control, agricultural development and capacity-strengthening, she works closely with global partners to embed science-based, climate-resilient solutions into national plant health strategies.

She has extensive technical expertise in mycoinsecticide research and development, including mass production, quality control, formulation, field evaluation and the scaling of fungal-based biological control products. Dr Luke was also a member of the pioneering LUBILOSA programme (Biological Control of Locusts and Grasshoppers), contributing to the development and deployment of environmentally sustainable alternatives for acridid management.

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Abstract

Throughout history, locust swarms have caused devastation to crops and livelihoods. There are a number of synthetic pesticides approved for use against locusts and grasshoppers, but these also come with disadvantages such as environmental and human health issues. The LUBILOSA programme identified an isolate of the fungus *Metarhizium acridum*, which efficiently killed locusts and grasshoppers. This was developed into an oil-based formulation registered as Green Muscle. Although the research programme ended in 2002, this was not the end of the story as Green Muscle needed to be manufactured and made available in a financially viable manner.

Introduction

The *Lutte Biologique contre les Locustes et Sauteriaux* (LUBILOSA) programme was established to develop biological alternatives to synthetic pesticides for the control of locusts and grasshoppers. This programme lasted for 13 years from 1989 until 2002. LUBILOSA was conceived and led by CABI working in partnership with Département de Formation en Protection des Végétaux (DFPV: Department of Crop Protection Training) of the AGRHYMET Regional Centre (ARC) in Niamey, Niger, the Comité permanent Inter-États de Lutte contre la Sécheresse dans le Sahel (CILSS: Permanent Interstate Committee for Drought Control in the Sahel), Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) and crop protection agencies of Niger, Benin, Burkina Faso, Chad, Mali, Senegal and The Gambia.

The first step was to identify the best possible candidate isolate, from a fungal species, for the management of locusts and grasshoppers, with a strong focus on the desert locust, *Schistocerca gregaria*. Within fungal species there can be significant variation in virulence against a target pest. This required screening fungal conidia. It soon became clear that the hydrophobic conidia would need to be applied within an oil-based formulation as water was scarce in these areas. Ultra low volume (ULV) spraying (which is also used for synthetic pesticides) was the ideal solution as it meant low volumes of liquid were required and the oil-based formulations protected the fungal conidia from desiccation. Likely candidate fungi had to maintain their virulence within an oil-based formulation and had to be able to be grown on artificial substrates – which would be required at the later mass production stage of the programme.

The LUBILOSA team settled on an isolate of the entomopathogenic fungus *Metarhizium acridum.* It can infect locusts and grasshoppers through contact and is highly virulent (Lomer *et al*, 2001). The commercial biopesticide developed from conidia of this isolate was named Green Muscle®. Green Muscle is effective against all instars and adults of grasshoppers and locusts. It is sprayed onto locusts/grasshoppers and the conidia grow into the locust, causing death between 7 and 20 days depending on environmental conditions and the life stage of the locust (Figure 1).

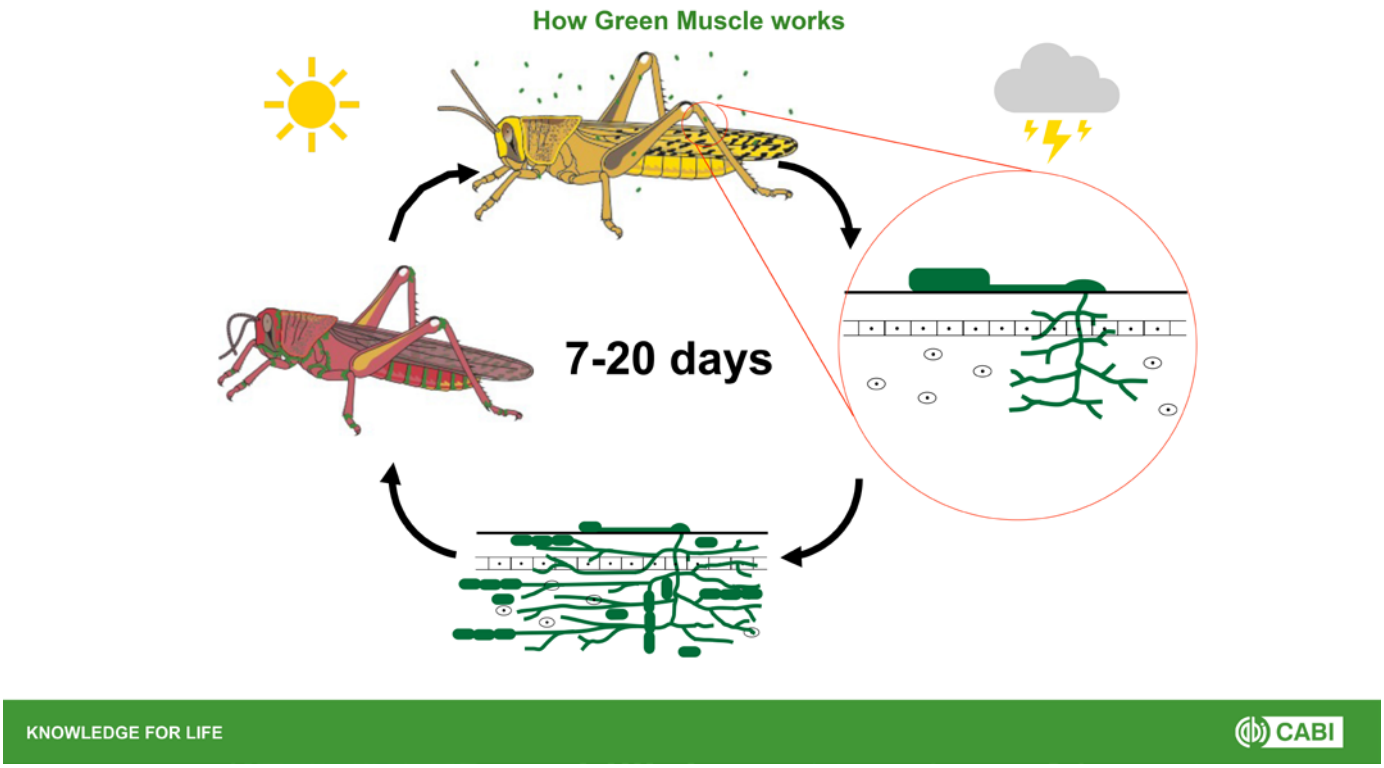


Figure 1. The infection process for Green Muscle (based on the fungus *Metarhizium acridum*). The variation in days to kill depends on environmental parameters.

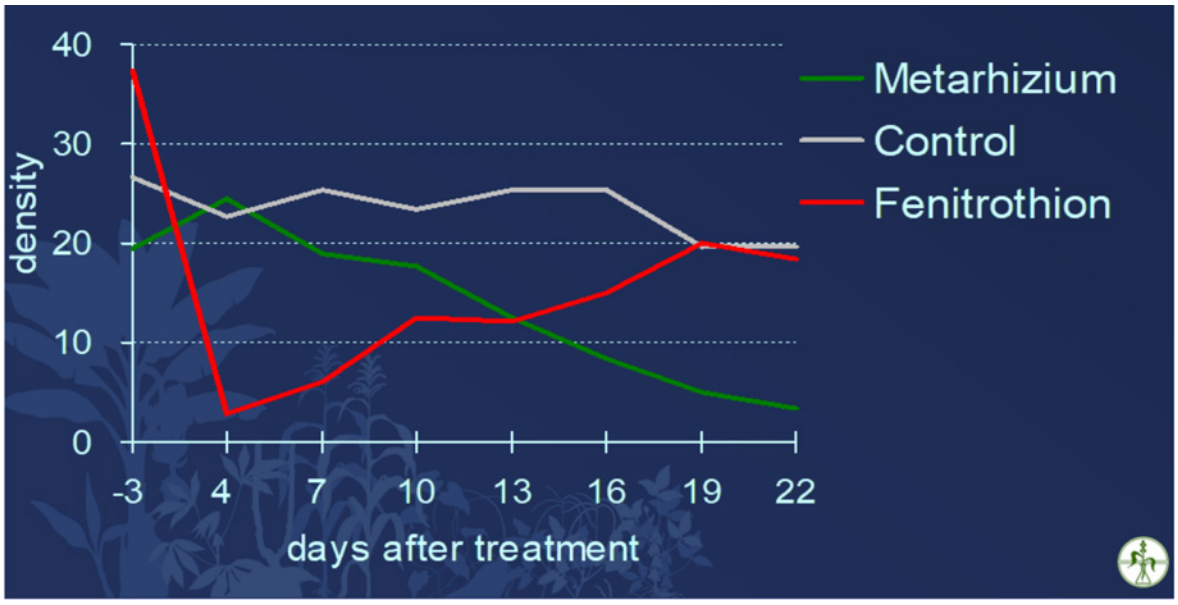


Figure 2. Mean grasshopper population density after application of *Metarhizium acridum* at 100 g/ha and Fenitrothion (a synthetic pesticide) at 250 g/ha on 50 ha plots in 1996

The effectiveness of Green Muscle was compared with Fenitrothion, a synthetic pesticide commonly used for grasshopper and locust management (Figure 2). The synthetic pesticide had a very significant immediate knockdown effect (not shown on the graph). However, grasshopper populations swiftly rebounded to the control level by new grasshoppers immigrating into the area. Although Green Muscle is slower acting, once it does start to cause mortality, it brings the density of the grasshopper population down to levels similar to that seen on day 4 of the synthetic control treatment. Additionally, infected grasshoppers stop eating 3–4 days after infection, greatly reducing the damage caused. Grasshoppers infected with *Metarhizium* will release fungal conidia which can lead to further infections within the grasshopper population, a process called secondary recycling. A combination of the viable sprayed conidia and secondary recycling means that new grasshoppers

entering the sprayed area will pick up fungal conidia and die, hence keeping the population under control for a longer time, resulting in fewer biopesticide applications compared to synthetic pesticides.

Table 1 highlights some of the similarities (in white) and differences (in green) between the biological mycoinsecticide and a standard synthetic pesticide. As the speed of kill is slower with the biological, they are better used in a preventative manner to control the juvenile grasshoppers. In emergency times, Green Muscle can be applied as part of an IPM programme with synthetic pesticides.

Table 1. Characteristics of mycoinsecticide (biological pesticide) and a synthetic pesticide

Mycoinsecticide	Synthetic pesticide
Contact required	Contact required
Apply using conventional sprayers	Apply using conventional sprayers
Good IPM tool	Good IPM tool
Slower speed of kill	Faster speed of kill
Living organism	Synthetic
Low toxicity	High toxicity
Organic	Non-organic
Particulate	Solution
Preventative	Curative
No evidence of resistance	Evidence of resistance
No cost of disposal of containers	Cost of disposal of containers

Commercialising Green Muscle

Although small-scale, local biopesticide production was considered, it was quickly realised that contamination was a major blocker for this industry. Instead, the LUBILOSA team saw that the only way to produce sufficient Green Muscle for the management of locusts and grasshoppers was for private sector companies to be awarded a licence for its manufacture. Initially, two companies were identified and given support in the production of *Metarhizium*.

Biological Control Products SA (Pty) Ltd (BCP) in South Africa was the leading producer of biologicals in South Africa. It was also registered in Namibia, Zambia, Tanzania, Ethiopia, Sudan and Egypt, and it manufactured Green Muscle for some of the trials. However, in 2018, following two sets of acquisitions (by Becker Underwood and then BASF), the Green Muscle licence was terminated as BASF did not see Green Muscle fitting in with their future direction, and their Green Muscle licence reverted to CABI.

Natural Plant Protection (NPP) in France was able to achieve temporary sales in CILSS countries in West Africa; however, NPP was unable to produce *Metarhizium* using its own production process. In 2007, a Green Muscle licence was awarded to SenBio Tech, Senegal (to replace NPP). However, SenBio Tech closed in 2012.

Éléphant Vert (EV), set up in 2012, developed a new product called Novacrid® to control locusts and grasshoppers (at this time the Green Muscle product was held by BASF). In 2018, EV took over the Green Muscle licence with the idea to phase out Novacrid and promote Green Muscle. CABI is still engaging with EV, where various staff changes have made progress relatively slow.

It should be noted that locust/grasshopper control markets are often difficult to break into. The small companies producing *Metarhizium* are in competition with large synthetic companies with extensive marketing departments and historical links.

Making Green Muscle available for use

The desert locust, being a transboundary pest, is usually controlled by government agencies supported by donors and intergovernmental agencies such as the FAO. Therefore, the marketing of Green Muscle was aimed at governments rather than individual farmers. The marketing itself encompassed multiple challenges.

Locust outbreaks occur when climatic and vegetation factors are suitable. Desert locust outbreaks are not constant, occurring approximately every seven years and not necessarily in the same locations. Desert locust populations are monitored and rises in population can be managed to prevent swarms of locusts from occurring. However, not all locust/grasshopper populations are monitored. In the 2019–2021 desert locust upsurge, the locusts multiplied in Yemen, where a civil war was taking place. Early treatment could not take place due to human safety in a war-torn country.

During desert locust outbreaks, FAO tends to coordinate the management of the swarms. Pesticides (synthetic or biological) are often procured through a FAO tendering process. However, the tendering and due diligence processes delay the procurement process.

Green Muscle contains a living organism, which affects its rates of production. To manufacture Green Muscle requires the *Metarhizium* to be grown in a two-phase system and for it to produce conidia without cross-contamination with other microorganisms. This is a six- to eight-week process. Producing quantities of

formulated Green Muscle at scale requires either a labour-intensive scale-up of small-scale production processes or the procurement of expensive industrial machinery. Once produced, for best results, Green Muscle should be stored at a cool temperature, ideally around 5°C.

In comparison, synthetic pesticides can be manufactured relatively quickly and stored at ambient temperatures until they are needed. Therefore, there is often more of a lag in getting sufficient quantities of Green Muscle compared to its synthetic alternatives. Once Green Muscle has been produced, it needs to be managed carefully and requires reliable transport, as is usual when moving living organisms.

However, in the 2019–2021 desert locust upsurge, these problems (despite additional challenges due to the COVID-19 pandemic) were overcome and Green Muscle and an insect growth regulator were successfully used in Somalia, with efficacy of over 90 percent consistently achieved (Owuor & McRae, 2022). Green Muscle samples have also been sent to Pakistan, India, Uganda and Iran, and this expansion of markets beyond Africa (grasshoppers and locusts are also present in the Americas) would help the viability of this venture. It could be further supported by marketing Green Muscle as a tool for managing other locust and grasshopper species, which, although occurring in smaller numbers, occur on a regular annual basis.

Conclusions

The LUBILOSA programme successfully developed a biopesticide for locust and grasshopper management. The programme implemented a multi-partner approach and addressed all aspects of getting a biocontrol agent into use; achieving this at a cost of GBP 10.2 million is remarkable, considering that developing and registering a synthetic pesticide generally takes at least 10 times this amount.

The implementation team identified an isolate of *Metarhizium acridum* that was formulated into a product called Green Muscle. It has been shown that Green Muscle, over a longer time period, provided better levels of locust control compared to a synthetic pesticide registered for use against locusts.

The scientific challenges were addressed, but there has been an ongoing challenge in terms of how to make sufficient quantities of Green Muscle fast enough to respond to irregular outbreaks of locusts. In addition to working with the private sector to meet Green Muscle demands, often at short notice, the team also conducted advocacy activities to facilitate Green Muscle supply. This included raising interest among governments in the use of a biocontrol product for locust control, working with donors for funding and seeking alternative markets for grasshopper control other than just for desert locusts.

Acknowledgements

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The *Metarhizium* story (or the *Metarhizium* safari in Africa)

Henry Wainwright



Henry studied at Nottingham and Bath Universities and lectured at Writtle College and Bath University. He also worked at ODNRI (now NRI) for seven years. In the 1990s, his wife Louise ran an integrated pest management consultancy business in Kent, working on pests such as mites, thrips and vine weevil, and diseases including mildew, botrytis and fusarium. In 2000, Henry and Louise moved to Kenya, initially working for a production and export horticultural company before establishing their own biological control business, Real IPM, from scratch in 2003. Real IPM collaborated with organisations such as ICIPE, Syngenta Bioline and CABI. The support of donors such as DFID, USAID and the EU was critical in promoting IPM/biocontrol in the smallholder sector. The collaboration with ICIPE and CABI enabled the commercialisation of various strains of Metarhizium anisopliae – now important and widely used biocontrol agents in the horticulture sector in Africa.

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Abstract

Research into biologicals is critical, but the value of the research findings only becomes clear when the research is made available to a significant number of people. Real IPM worked with researchers at ICIPE to produce commercial biopesticides for the management of thrips based on an isolate of *Metarhizium anisopliae.* Donor support enabled Real IPM to develop new products and new markets. Success is not always guaranteed, but with significant challenges faced by traditional pesticides there would appear to be opportunities for further growth in both developing and developed markets.

Introduction

Multinational agrochemical companies have dominated the global market for crop protection agents since the dawning of the 'green revolution' in the 1940s. The agrochemical market has seen exponential annual growth, from a few billion dollars in the 1960s to over USD 80 billion today.

However, those attributes which heralded pesticides as the foundations of food security, namely broad-spectrum activity and persistence, turned out to be their Achilles heel. Resistance and harmful chemical residues have undermined their relentless market growth and created a market for alternative technologies without these associated risks.

The small, but agile, biopesticide industry is developing alternatives to conventional chemistry. Real IPM Kenya Ltd is playing a part in developing innovative programmes for the use of biopesticides produced in Kenya at an affordable cost. Affordability enabled these biopesticides to be used in prophylactic preventative programmes despite their narrow target spectrum and their short persistence in the environment. Integrated pest management (IPM) using affordable biopesticides as a mainstay is now challenging the unrivalled dominance of the agrochemicals. The potential is significant, as biopesticides are now used to protect crops as diverse as rice and roses grown on the Equator, where year-round growing conditions favour rapid pest and disease development.

Biopesticides are now recognised as a credible alternative to chemical pesticides, as regulators around the world are realising the need to genuinely fast-track biopesticides into the market place to give food producers a real choice.

In the following account, I report on the commercial uptake of *Metarhizium* in East and Southern Africa and explore some of the drivers that enabled Real IPM to thrive.

Research and development

Key to the commercialisation of a biopesticide such as *Metarhizium* was collaboration with researchers, donors, the private sector and growers. At Real IPM, we were fortunate that ICIPE had already been working on selecting strains of *Metarhizium anisopliae* against a variety of pests. Similarly, CABI had been developing the technology of Green Muscle for use against locusts. After the turn of the century, donors realised that to achieve their development goals, the private sector, in particular start-up companies like Real IPM Kenya Ltd, needed support in translating their research investment into commercialised products. At this time, Real IPM had a substantial predatory mite production and sales business and was keen to expand its portfolio of biological crop protection agents.

Selection of the isolate

Under a Memorandum of Understanding with ICIPE in 2009, Real IPM had access to numerous strains of *Metarhizium anisopliae* with potential against a range of targets (pests). A key decision was which strain(s) to commercialise? The factors to consider in commercialising a biopesticide are extensive and are summarised in Table 1. Choice was not always dependent on the 'best' isolate in laboratory experiments.

Table 1. Factors to consider when deciding which biopesticide isolate from a research institute's portfolio to commercialise

Factor	Comment
Mass production	Can the product be easily and economically mass-produced?
Storage	Can the isolate be formulated to provide shelf life for the distribution chain and on-farm storage?
Compatibility	Can the biopesticide be tank-mixed with chemical pesticides (including fungicides)? Does it harm relevant macro-biologicals which are strategically important to IPM in this crop?
Ease of application	Can conventional spray equipment or drip irrigation equipment be used to distribute the biopesticide?
Importance of target pest	Is it a seasonal or all-year-round pest? – affects cash flow
Importance of the crop	Area and extent of the crop – affects overall sales value
Current cost of control	What is the crop protection budget in each target market?
Competitors in each crop	What are the alternatives and the costs of other chemical and biological crop protection agents?
Single isolate/ multiple targets	Can the same isolate control multiple target pests to offset registration costs?
Customer type	Customers range from small-scale subsistence to large-scale farmers, which influences buying power, pack sizes and storage life.
Life cycle infection stage	The ability to target various life stages of the pest enhances overall effectiveness.
Formulation	*Metarhiziums* are hydrophobic, which can present formulation challenges.
Non-target organisms	Ensure safety and IPM compatibility
Field persistence	Longevity after application

Real IPM decided to commercialise four *M. anisopliae* isolates (Table 2).

Table 2. The isolates of *M. anisopliae* that were commercialised and their targets

Isolate	Targets
ICIPE 69	Thrips, mealybug, whitefly, snout beetle (vine weevil), fruit fly, caterpillars
ICIPE 78	Mites
ICIPE 62	Aphids in EU
ICIPE 7	Ticks

Case study: Met 69

M. anisopliae 69 (Met 69) makes an interesting case study against thrips. Met 69 was isolated in 1990 in Kinshasa, Democratic Republic of the Congo, but it was over 20 years until a company tried to commercialise the isolate. Though shown as an effective control agent of a range of thrips in a controlled environment, the challenge was to develop an effective field control. Thrips has become an increasingly important pest of horticultural crops worldwide. Thrips is such a successful pest due to a plethora of reasons, including a fast life cycle, high mobility (wind), cryptic and thigmotactic behaviour, wide host range, complex life cycle (crop and soil phase), a reduced number of pesticides available, *eg* neonicotinoids withdrawal, and high risk of pesticide resistance. Yet targeting thrips with a biopesticide presents many of the same problems encountered when applying a conventional pesticide. Therefore, there was a need for innovative development in targeting thrips at all stages of its life cycle. With partners, Real IPM was successful in developing application of Met 69 as foliar sprays and soil drenches, in combination with exciters and lures, auto-dissemination devices and bio-mulches. How the product was used was found to significantly vary depending on the type of crop and grower; therefore, formulation and pack size had to be refined for the end users. The grower now has a varied toolbox of Met 69 products to tackle thrips.

Impact

As of 2025, the isolate *M. anisopliae* 69 was registered for sale in numerous countries (see Figure 1). A biopesticide might take 2–4 years for registration in African countries. Real IPM and now its parent company (Biobest) have been registering various strains of *Metarhizium* in Europe. Though the dossier preparation was initiated in 2016, EU Annex I registration is expected in 2026 and EU Annex III in 2028 (when sales would be permitted). Therefore, despite headlines over the past 15 years claiming that the EU will move to fast-track biopesticide access, this has not yet happened



Figure 1. The countries where *M. anisopliae* 69 has been registered and is used against a range of pests (Source: Wainwright, 2026)

The take-home messages from Africa with regard to the successful adoption of biopesticides have been threefold. There have been significant (i) innovations on formulation and delivery to meet the different user needs, (ii) researcher/donor/private sector collaboration to enable the introduction of new technologies and (iii) knowledge transfer with regard to how to use biopesticides, which has been a critical component to enable grower uptake and adoption.

For any commercial development to be successful, the environment must be receptive. For biopesticide and biological control agents to be adopted, there must be drivers. These include:

- Pesticide resistance: As a result, many standard active ingredients have stopped working as control agents.
- European customer pressure on residues: There is intense pressure by customers on growers to reduce the level of chemical pesticide residues on horticultural crops being exported to Europe. This does not mean an increase in organic product, just a reduction in the number and levels of residues found in conventionally grown crops.
- Competitive pricing of biologicals: A local production base for biological control agents has meant that they have become competitively priced and affordable.

Combine this with other factors such as: an enabling registration/legislation environment in many African countries, an educated and motivated workforce (as was found in Kenya), a business-friendly environment (as was found in Kenya), a good local transport hub (*eg* Nairobi airport) and strong technical support (engineers, couriers, materials) available within the country. Through these factors a sustainable biological control industry has developed in Southern and Eastern Africa.

Conclusion

Despite the very positive progress in the development of biopesticides in Africa, there are always challenges, especially at the smallholder level. These include low-cost generic pesticides, the lack of knockdown effect of biopesticides, the imitators/fake products, the need for rigorous quality control and arrival of invasive pests. Even so, the story in Africa is very positive. Biologicals including *Metarhizium* have and continue to successfully impact African agriculture and biocontrol has become a sustainable technology. Finally, one of the key reasons why this has been a success story is the collaboration between researchers, growers, regulators, donors and the private sector in getting biopesticides into widespread use in Africa.

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Development and registration of bioprotectant Biophyt 1.0 for sustainable agriculture

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Abstract

Bioprotectants are pest management products derived from naturally occurring organisms such as bacteria, fungi, viruses, insects and plants, or from their bioactive metabolites including plant extracts, lytic enzymes and antibiotics. The authors have assessed various strains of *Bacillus* obtained from diverse ecological sites throughout Trinidad and Tobago against various pathogens of lettuce. Through a series of laboratory, glasshouse and field studies, a liquid biological formulation was developed as a potential alternative to synthetic chemical pesticides. This paper outlines the systematic process undertaken for the isolation, efficacy testing, formulation development and regulatory registration of the product, designated Biophyt 1.0.

Introduction

Synthetic chemical pesticides have contributed significantly to crop protection, higher yields and global food security. However, their extensive and prolonged use has raised serious concerns regarding adverse impacts on the environment and human health. These concerns include soil and water contamination, biodiversity loss, disruption of beneficial organisms such as pollinators and natural enemies and the development of pest resistance. Alarmingly, it has been estimated that about 0.1 percent of applied pesticide reaches the intended target, while more than 99 percent affects non-target organisms and the environment (Pimentel, 1995; Gill & Garg, 2014; Kumar *et al*, 2024). Misuse or overuse further exacerbates these problems, with pesticide residues in food posing risks to consumer health. These challenges have prompted global calls for safer and more sustainable alternatives, with international frameworks such as the United Nations Sustainable Development Goals (SDGs) emphasising reduced reliance on hazardous pesticides and the promotion of biological alternatives to safeguard human, animal and environmental health (SDG 12).

Bioprotectants represent a viable and sustainable alternative within modern crop production systems. Compared to conventional pesticides, they generally offer greater target specificity, lower toxicity to humans and non-target organisms and reduced environmental persistence. Many bioprotectants act through multiple mechanisms, reducing the likelihood of resistance development. Their integration into Integrated Pest Management (IPM) strategies enhances soil and plant health and supports long-term agricultural sustainability. This article details the development and registration process of Biophyt 1.0, a bioprotectant developed at the University of the West Indies (UWI), St Augustine Campus, for the management of fungal and bacterial pathogens, providing an evidence-based model for safe and sustainable bioprotectant production in the Caribbean context.

Identifying the problem

Lettuce is a high-value crop widely consumed raw, making it particularly vulnerable to issues related to pesticide residues. Despite its relatively short growing period (4–6 weeks), it is highly susceptible to bacterial and fungal diseases such as bacterial leaf spot caused by *Xanthomonas hortorum* and *Paracidovorax* species, fungal leaf spot caused by *Cercospora*

lactucae-sativae, and bacterial soft rot caused by *Dickeya chrysanthemi* and *Pectobacterium brasiliense* (Thomas and Saravanakumar, 2019; Thomas *et al*, 2024; Thomas *et al*, 2026). Reports from the Ministry of Agriculture, Land and Fisheries (2013) indicate that in severe outbreaks, up to 100 percent yield loss can occur. Current management practices rely heavily on chemical pesticides, posing significant health and environmental risks. These challenges underscore the need for a safer, more sustainable solution, prompting researchers at UWI to explore bioprotectants as an alternative.

Biological exploration

Recognising the ecological balance that naturally exists between pests and their biological antagonists, researchers conducted extensive bioprospecting across various ecosystems in Trinidad and Tobago. Soil samples were collected and cultured on artificial media to isolate bacteria with potential antagonistic activity. Preliminary *in-vitro* screening was conducted using dual culture techniques against lettuce pathogens: *Xanthomonas hortorum* and *Paracidovorax* spp (causing bacterial leaf spot), *Cercospora lactucae-sativae* (fungal leaf spot) and *Pectobacterium brasiliense* (bacterial soft rot). These preliminary results provided a foundation for subsequent *in-vivo* assessments.

Identification and characterisation of the biological agent

Proper identification and classification of the biocontrol agent are essential for regulatory approval and product development. The isolated bacterial strains were initially characterised based on morphological features and growth characteristics. Further differentiation was achieved through biochemical and physiological assays, including nutrient utilisation, enzyme production (*eg* cellulase, chitinase) and abiotic stress tolerance. Confirmatory identification was performed using molecular techniques such as Polymerase Chain Reaction (PCR) and Whole Genome Sequencing (WGS), providing detailed insights into the organism's genetic makeup, including genes associated with virulence, antimicrobial resistance and disease suppression mechanisms.

Efficacy studies

Efficacy trials were conducted in a phased approach. Initial *in-vitro* assays including dual plate, disc diffusion and broth inhibition techniques demonstrated the antagonistic activity of selected *Bacillus* strains. Promising candidates were subjected to greenhouse and open-field trials, which allowed researchers to evaluate disease suppression under practical conditions. These studies also helped optimise dosage, timing, application methods and formulation consistency across different environments and cropping systems.

Toxicological studies

To ensure the safety of the bioprotectants for human use and non-target organisms, a series of toxicological assessments was conducted in collaboration with the School of Veterinary Medicine at Mt Hope, Trinidad and Tobago. These included acute oral, dermal and inhalation toxicity tests, as well as skin and eye irritation and sensitisation evaluations. All studies were conducted under UWI Ethics Committee approval and demonstrated that the bioprotectant posed negligible health risks when compared to conventional chemical pesticides.

Mass production

Scalability and commercial viability are crucial components of bioprotectant development. The selected *Bacillus* strain was assessed for its ability to grow efficiently in various liquid media. Fermentation conditions, such as temperature, pH and aeration, were optimised for mass production. Stability studies confirmed the effectiveness and viability of the liquid formulation over a 12-month storage period under controlled conditions, indicating its suitability for commercial distribution.

Field application

The formulated product underwent validation field studies, where lettuce plants were treated with the biological agent as a foliar application and as a root drench, and then challenged with the pathogens. All field studies revealed significant reduction in disease incidence and severity when compared to the control. These studies were used to determine optimal application rates, timing and frequency, and assess compatibility with existing IPM programmes.

Labelling

Clear and accurate labelling is essential to promote safe and effective use. The Biophyt 1.0 label was developed in compliance with national pesticide regulations and aligned with FAO/WHO guidelines. It provides comprehensive information, including the product name, active ingredients, formulation type, application rates and methods, pre-harvest intervals, safety precautions, storage instructions and disposal recommendations.

Registration

A comprehensive registration dossier has been prepared for submission to the national pesticide regulatory authority. This dossier includes detailed information on the biological agent's identity, formulation specifications, efficacy and toxicology data, application guidelines, environmental impact assessments and labelling documentation. The regulatory body is tasked with reviewing the submitted data to determine the product's safety, efficacy and compliance with existing legislation before granting registration approval for Biophyt 1.0.

Conclusions

This study demonstrated that the evaluated bioprotectant is an effective crop protection tool for lettuce production, supporting its potential role within integrated pest management systems. However, for growers to realise the practical benefits of these findings, the bioprotectant must be commercially available as a registered product with clearly defined efficacy and safety profiles. The registration process is essential to ensure that the product meets established standards for performance, human health and environmental safety. Through this process, efficacy data, risk assessments and quality parameters are rigorously evaluated, providing assurance to end users regarding product reliability. Additionally, registration enables the development of an approved label outlining proper application rates, timing, handling precautions and risk mitigation measures. Although the registration process can be lengthy and resource-intensive, it plays a critical role in building user confidence. In the case of Biophyt 1.0, successful registration would not only validate its performance but also promote trust and responsible use among producers.

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Streamlining regulatory frameworks for biopesticides in Africa and the Middle East

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Introduction

Today, the Africa–Middle East region stands at a crossroads. It must confront the escalating pressures of climate change, rising pest and disease threats and the demands of a rapidly growing population – all while striving to remain competitive in global export markets that increasingly require food produced with minimal residues. At the same time, farmers across the region face diminishing resources, from shrinking arable land to limited access to safe and effective crop protection tools.

To navigate these realities, policy makers and agricultural stakeholders must prioritise tools that enable farmers to produce more with less while minimising environmental risks. Biopesticides and biocontrol agents (BioPPPs), when effectively integrated into Integrated Pest Management (IPM) programmes, offer exactly this opportunity. These products – derived from natural sources, including beneficial organisms, plant extracts, semiochemicals and nature-identical compounds – provide growers with novel, targeted and environmentally responsible modes of action (FAO, 2017; Jactel, 2019; Mawcha, 2024)

BioPPPs are commonly categorised into four key categories: macrobials (nature's predators), microbials (beneficial fungi, bacteria, viruses and protozoa), semiochemicals (including pheromones), and biochemicals such as botanicals, peptides, proteins and dsRNA-based technologies. Importantly, they complement conventional pesticides by offering new modes of action, enhancing resistance management strategies and helping farmers extend application intervals.

Their benefits are clear: BioPPPs reduce pesticide residues – particularly when applied closer to harvest – improve soil health, present significantly lower risks to non-target organisms and are safer for applicators. These advantages are especially valuable for farmers who supply demanding export markets. Yet despite their potential, Africa and the Middle East remain under-represented in the global BioPPPs market. BioPPPs sales in Africa–Middle East represent approximately 2–4 percent of the global market, a stark contrast to regions such as Asia and North America, where adoption is far higher.

This gap is not due to a lack of agricultural need, but rather the persistent regulatory barriers and demand by farmers.

Access bottlenecks

Across the 72 countries in the Africa–Middle East region, several systemic regulatory and institutional challenges hinder the availability and uptake of BioPPPs.

First, many countries lack dedicated regulatory guidelines for biopesticides, meaning BioPPPs are often assessed using data requirements designed for chemical pesticides. This leads to delays, unnecessary costs and inappropriate testing demands that fail to reflect the low-risk nature of BioPPPs. Clear definitions and tailored data requirements are essential to accelerate market access.

Second, only a small number of countries – including South Africa, Kenya, Zimbabwe, Tanzania, Uganda, Lebanon, Jordan, Morocco and the *Comité permanent Inter-États de Lutte contre la Sécheresse dans le Sahel* – have established frameworks for BioPPPs. The remaining vast majority still rely on conventional pesticide procedures, limiting farmer access and discouraging industry investment.

Third, regional harmonisation remains slow. While the East African Community (EAC) and the Southern

African Development Community (SADC) have developed harmonised guidelines, implementation varies widely. Unlike the centralised expert review processes used by the *Comité Sahélien des Pesticides* (Sahelian Pesticide Committee), many countries must rely solely on limited national capacity, with some applying mutual recognition in isolated cases.

A fourth challenge is the shortage of trained regulatory experts. Evaluating BioPPPs requires specialised scientific understanding, yet regulatory authorities across the region are understaffed and under-resourced. Dedicated expert teams – as recommended in recent policy analyses – would significantly improve review quality and timelines.

Finally, farmers face practical constraints. BioPPPs often require specific storage temperatures, precise application timing or a deeper understanding of biological modes of action. Without sufficient extension services and training, farmers may struggle to achieve optimal results, particularly during severe pest outbreaks.

A window for reform

Despite these challenges, the region is making progress.

In 2019, EAC Ministers for Agriculture and Food Security adopted harmonised guidelines for testing and registering biopesticides and biocontrol agents. Although a 2021 review revealed varied implementation among Partner States, the framework remains a strong foundation for regional alignment.

In the SADC region, draft harmonised guidelines developed through the Standards and Trade Development Facility–International Centre for Genetic Engineering and Biotechnology (STDF–ICGEB) Biopesticides Project have already led to implementation roadmaps in Botswana, Mozambique, Tanzania, Zambia and Zimbabwe. These guidelines, endorsed by the SADC in 2025 for implementation by its Member States, provide a blueprint for establishing dedicated national frameworks and accelerating product registration.

Broader continental progress could be achieved by activating the West African Pesticide Registration Committee and supporting harmonisation efforts in West, Central and North Africa, as well as within the Intergovernmental Authority on Development Member States. Leveraging existing regional tools ensures countries do not need to reinvent the wheel.

In the Africa–Middle East region, adapting established guidelines – combined with investments in technical expertise, regulatory capacity, digitalisation of registration systems and farmer awareness – would significantly enhance access to safe, effective biopesticides.

Across all regions, modernising regulatory systems would reduce administrative burdens, encourage innovation and create greater predictability for industry while enabling farmers to access innovative, low-risk crop protection solutions.

Conclusion

Biopesticides hold tremendous promise for transforming pest management in Africa and the Middle East. They offer low-risk, environmentally friendly solutions that support resilient food systems, safeguard farmer and consumer health and open new economic opportunities – particularly for exporters.

However, without streamlined and science-based regulatory frameworks, farmers will continue to face delays in accessing these tools. The path forward is clear: harmonise regulations, dedicate expert teams, standardise data requirements, strengthen extension services and invest in capacity-building across the agricultural value chain.

With coordinated leadership, collaboration and sustained political commitment, biopesticides can become a cornerstone of sustainable agriculture in the region – empowering farmers, protecting ecosystems and securing the future of food production.

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Brazil biological market

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South America has consolidated its position as one of the most dynamic regions for biological control, having reached approximately 62 million hectares treated in 2024. Within this regional context, Brazil stands out as the main driver of growth. The treated area in the country expanded from 22 million hectares in 2018 to 56 million hectares in 2024, reflecting a rapid and consistent increase in the adoption of biological solutions. This expansion places Brazil not only as the leading market in South America, but also as one of the global references in the large-scale implementation of biological control technologies.

The growth in the use of biologicals in Brazil

This sustained expansion of biologicals reflects a high level of confidence from growers and technical advisors, indicating that biological control has reached a mature stage of adoption within Brazilian agricultural systems. Major crops such as soybean, cotton, corn and sugarcane have played a central role in this process, integrating biological solutions into pest, disease and soil management programmes.

Market consolidation is also evident when turnover is analysed. This is referred to by season as the cropping season stretches over the calendar year. According to unpublished Kynetec data, measured in US dollars, the biological market expanded from USD 461 million in the third season (2022/23) to USD 731 million in the second season (2023/24), representing growth of approximately 59 percent. In the current season (2024/25), turnover reached USD 814 million, adding a further 11 percent increase. This upward trajectory reflects not only greater adoption, but also the expansion of biological programmes across larger areas and a wider range of crops. This growth is presented in Figure 1 and the composition of the growth is presented in Figure 2.

The same trend is observed when turnover is evaluated in Brazilian reals (BRL). In the third season, total turnover reached BRL 2.477 billion, increasing to BRL 3.777 billion in the second season (+53 percent).

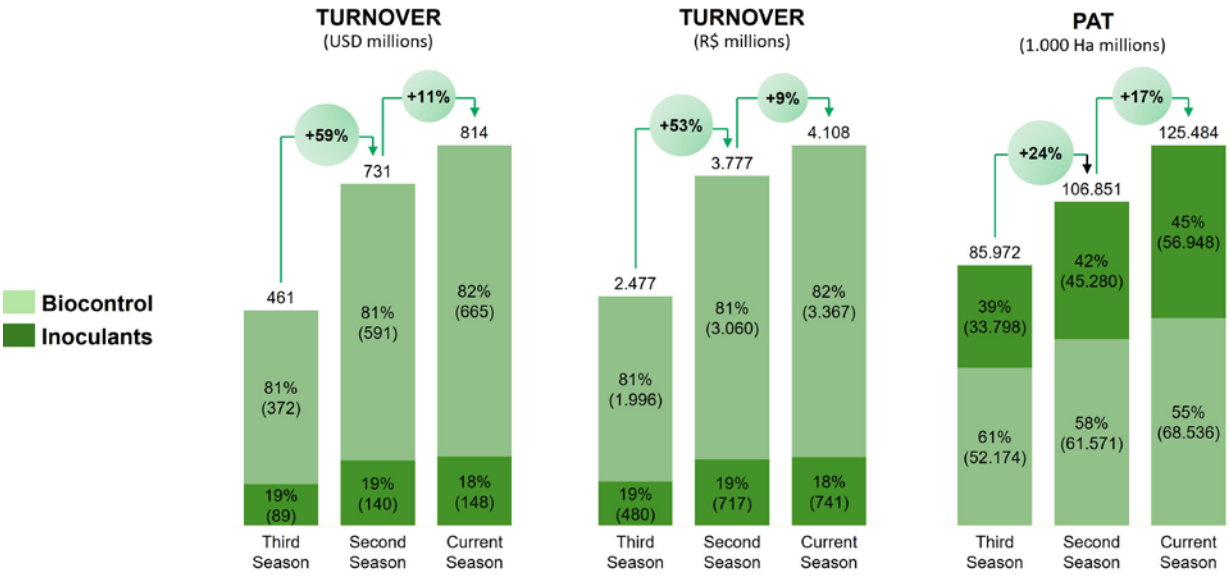


Figure 1. The growth in the biologicals market in Brazil from 2022/23 to 2024/25 (PAT: Planted Areas Treated)

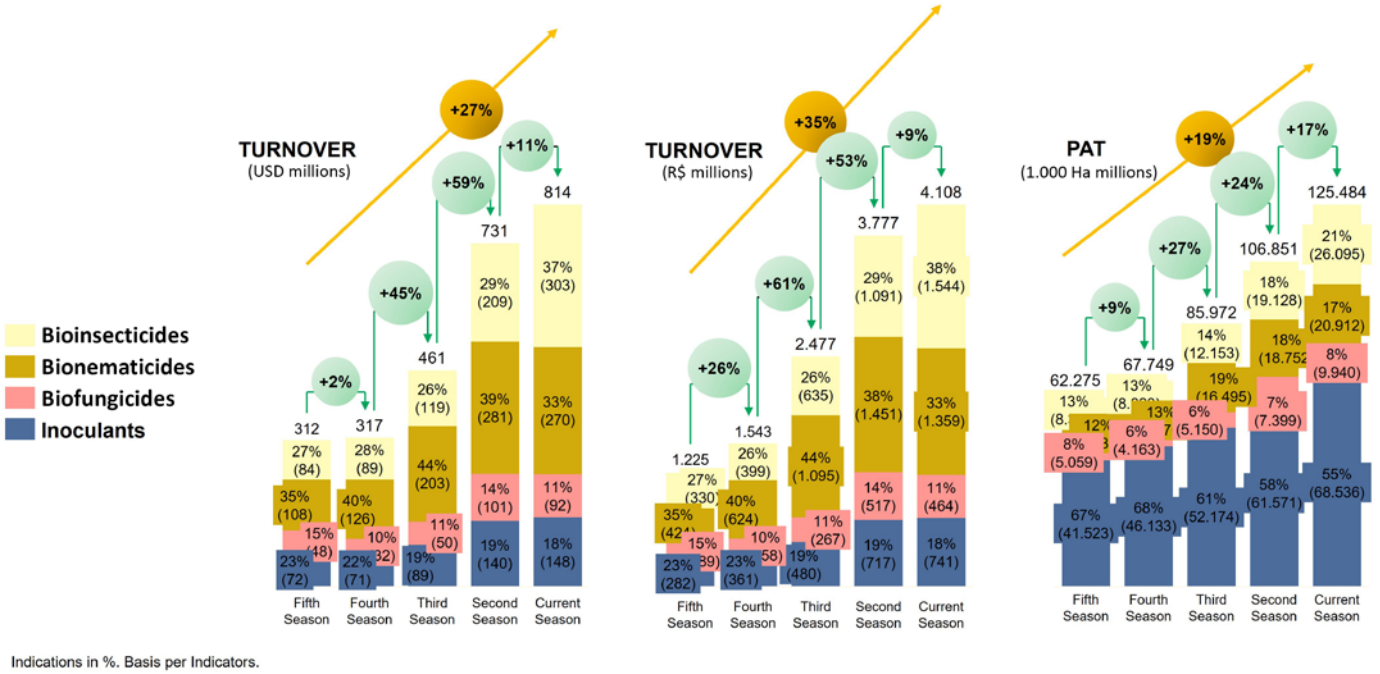


Figure 2. The composition of growth in the biologicals market in Brazil from 2020/21 to 2024/25

In the current season, turnover reached BRL 4.108 billion, with an additional 9 percent growth. The consistency of expansion in both currencies shows that market growth is structural and driven by real demand, rather than by short-term economic or exchange-rate effects.

Another strong indicator of consolidation is the rapid expansion of 'Planted Areas Treated' (PAT) with biological products. In the third season, biological solutions were applied to approximately 85.972 million hectares. This area increased to 106.851 million hectares in the second season (+24 percent) and reached 125.484 million hectares in the current season (+17 percent). These Kynetec data demonstrate that biological control is being adopted at operational scale, transitioning from localised or selective use to standard inclusion in crop management programmes.

Beyond total area growth, the distribution of treated areas among biological segments reveals an important shift in adoption patterns. In earlier seasons, inoculants dominated the treated area, accounting for more than 60 percent of total PAT, indicating a more concentrated use of biological solutions focussed on soil and plant establishment. Over time, this dominance gradually declined, reaching 58 percent in the second season and 55 percent in the current season.

At the same time, bioinsecticides and bionematicides steadily increased their participation, reflecting broader adoption of biological control strategies targeting insect pests and nematodes. This change highlights a transition towards more diversified and integrated biological programmes, in which multiple product categories are combined throughout the crop cycle to manage different biotic challenges.

The sugarcane biologicals success story

Sugarcane production in Brazil represents one of the most successful cases of biological control adoption. The crop has reached an advanced level of maturity in the use of biological solutions, particularly in nematode management, where biological products already dominate control strategies. Beyond microbial inputs, sugarcane systems are also at the forefront of macrobial control adoption, integrating parasitoids such as *Trichogramma galloi* into large-scale management programmes. This progress reflects a combination of operational scale, technical expertise and long-term commitment to Integrated Pest Management, demonstrating that biological control can be effectively implemented across extensive production areas. The sugarcane sector therefore stands as a benchmark for other crops seeking to expand biological solutions within sustainable and economically viable production systems.

When observed across multiple seasons, the data clearly indicate a consistent and sustained growth trajectory. Successive increases in turnover, reaching peaks above 50 percent growth between seasons, combined with continuous expansion of treated area, confirm that the evolution of the biological market is structural rather than cyclical. This growth is supported by proven technical performance, regulatory alignment and increasing awareness of

sustainability requirements in both domestic and international markets.

Biologicals as part of integrated crop management systems

Beyond numerical indicators, the information presented reinforces a broader view of agriculture in which biological solutions play a central role. Biological control, inoculants and soil-related technologies are part of an integrated production system that includes healthy soil life, organic matter, beneficial microorganisms and functional trophic interactions. In this context, crop productivity is increasingly understood as the result of biological processes, not only chemical or physical inputs.

Healthy soils, rich in microbial diversity and organic matter, are fundamental for nutrient cycling, root development and plant resilience. Biological products interact directly with these processes, supporting crop performance while preserving ecological balance. This perspective helps explain why biological solutions are increasingly adopted not only for pest and disease control, but also as tools to improve overall system efficiency and stability.

Factors behind stewardship adoption

The expansion of biological control in Brazil has been driven by a combination of favourable public policies, regulatory incentives and growing global demand for food produced with lower chemical residues. At the same time, important challenges remain, including cultural resistance to adoption, regulatory complexity, limited harmonisation between regions and the lack of standardised metrics to consistently measure performance. In some production systems, particularly direct food crops, adoption levels still remain below their potential.

Discussion on the future for biologicals in Brazil

The Brazilian context highlights the need for continuous innovation in biological product formulations. Tropical conditions, characterised by high temperatures, intense solar radiation and variable humidity, impose significant challenges to the stability and performance of microbial solutions in the field. As a result, the evolution of biological control in Brazil increasingly depends on formulations capable of fitting into standard operational practices, often allowing tank-mix compatibility with chemical products and reliable performance under less favourable environmental conditions. Advances in formulation technology, such as protective carriers, encapsulation and stabilising matrices, play a critical role in safeguarding microorganisms during application and early establishment, ensuring efficacy even when environmental conditions are not optimal. This technological progress is essential to enable the large-scale, operational integration of biological solutions within modern Brazilian agriculture.

Looking ahead, the future of biological control in Brazil is closely linked to greater integration with conventional crop management, especially as a tool for resistance management. Continued advances in infrastructure, technical training, local production capacity and regulatory frameworks are expected to further increase the effectiveness, reliability and acceptance of biological solutions among growers. Ultimately, growers are adopting biological solutions because they see the results in the field. Beyond pest and disease suppression, growers are observing gains in productivity and increased crop longevity, with healthier plants that maintain performance over multiple cycles. This practical validation has been a decisive factor in accelerating adoption, reinforcing biological control not only as a sustainable choice, but as a productive and economically consistent strategy.

The agricultural landscape is therefore increasingly understood as a connected system, in which soil health, crop protection and productivity are inseparable. Biological solutions fit naturally within this model, as they work in harmony with natural processes rather than overriding them. The consistent growth in market value, treated area and diversification of use confirms that biological control is no longer an alternative approach, but a central pillar of modern, sustainable agriculture in Brazil.

Lessons learned from promotion of biologicals in Chiang Rai, Thailand

Dr Atthawit Watcharapongchai and Thanchanok Pongputhinan



Dr Atthawit Watcharapongchai (Bank), as head of field implementation of GIZ Agriculture Thailand, has more than 10 years of experience in promoting sustainable and climate-smart landscape rice farming in Thailand, which includes Integrated Pest Management as one of the key technologies to improve the resilience of farmers under climate change and the current situation. He is leading several climate-smart farming, regenerative farming and landscape management projects, in collaboration with public and private sector organisations.

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Abstract

Challenges to the adoption of biological control agents do not stop with farmer training. A scientific approach needs to be implemented to maximise the effectiveness of the promotion of biologicals. Even with successes from such approaches, further activities are required to achieve adoption of biologicals at scale.

Introduction

The work presented took place in Chiang Rai Province in northern Thailand (Figure 1).

Farming in Chiang Rai Province, Thailand is focussed on rice systems in which potatoes and maize are also grown. Farming systems are dominated by low income, high production costs and indebtedness.



Figure 1. Location of Chiang Rai Province, Thailand

Climate challenges have caused droughts and floods in the last five years. Crop diseases, *eg* late blight and rice blast disease, can devastate crops or increase the cost of production due to the high usage of fungicide.

Climate-smart agriculture and biocontrol

GIZ implements Integrated Crop Management approaches which include climate-smart agriculture (Figure 2), sustainable crop rotation, Integrated Pest Management and augmenting biological controls. The first biological control agent identified for promotion by and with farmers is the fungus of the *Trichoderma* genus.

Trichoderma are found in soils, and several species have been developed as biocontrol agents against fungal diseases of plants (Harman, 2006). They generally grow on the root surface and so affect root diseases in particular but can also be effective against foliar diseases.

A number of agencies have introduced *Trichoderma* as a biocontrol agent in the project area using extension officers and private sector agronomists. However, uptake has been very poor. Therefore, GIZ commenced its work with *Trichoderma* by looking at the farmer decision-making, so as to identify the problem. Farmers admitted that they had heard about *Trichoderma*, but few had used them and didn't know how to obtain them. There was also a rumour that *Trichoderma* block the nozzle of spraying equipment. The GIZ team were emboldened by the fact that no farmer said that *Trichoderma* was not good.

The GIZ team hypothesised that the problem was not with the product/technology, but with its adoption. The general model of adoption has been presented by Rogers (1962) (Figure 3). The responses from the farmer surveys suggested that farmers have gained awareness but few are at the interest or evaluation stages and nobody had got through to trial or adoption yet. The challenge therefore was to move the adoption process forward.

From awareness to adoption

GIZ started with community meetings to refresh the knowledge of *Trichoderma* as a biocontrol agent, to generate interest and confidence in the biocontrol agent. This would reinforce what the farmers already knew. The process was implemented through community meetings with extension officers and community leaders.

This led to the establishment of demonstration plots with *Trichoderma*, as the meetings had identified that 'seeing is believing'. The demo plots were designed and located so that neighbouring farmers could learn

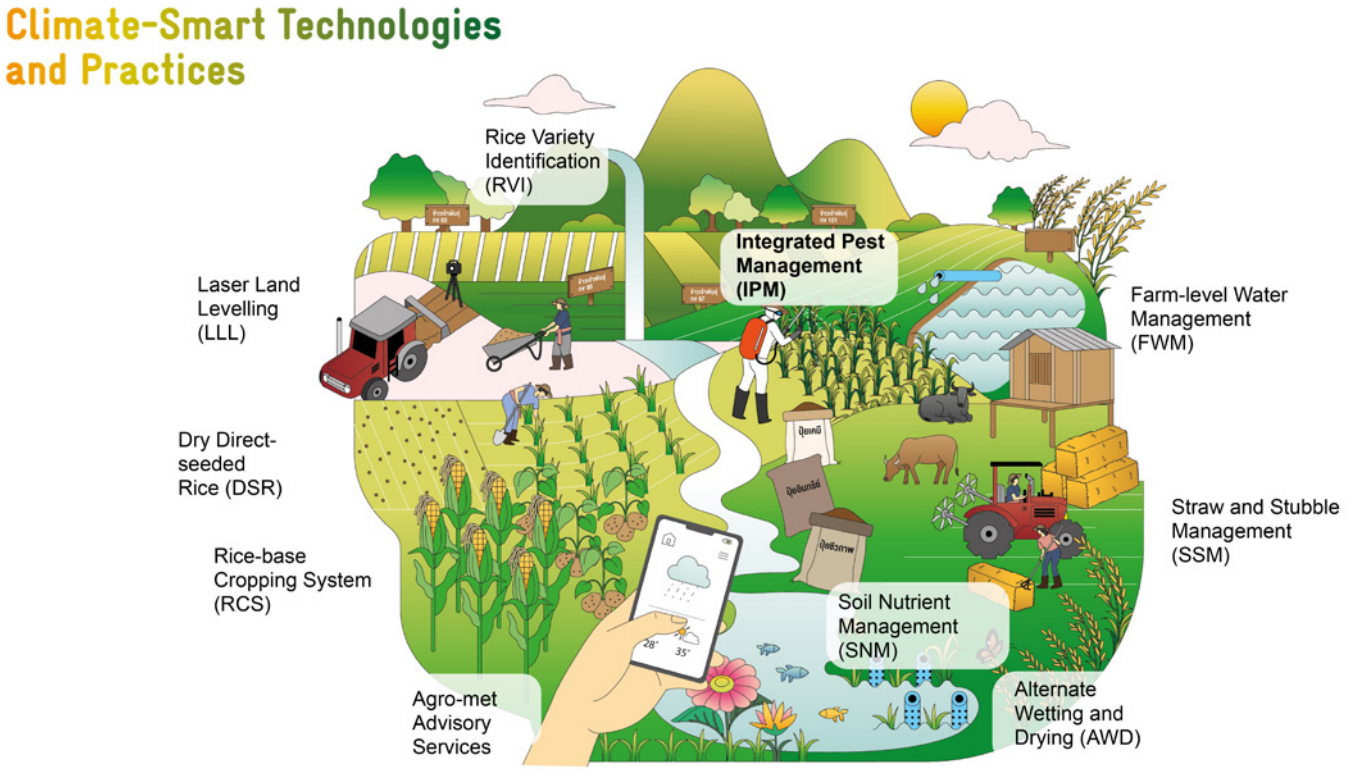


Figure 2. Climate-smart agriculture as implemented by GIZ in Thailand

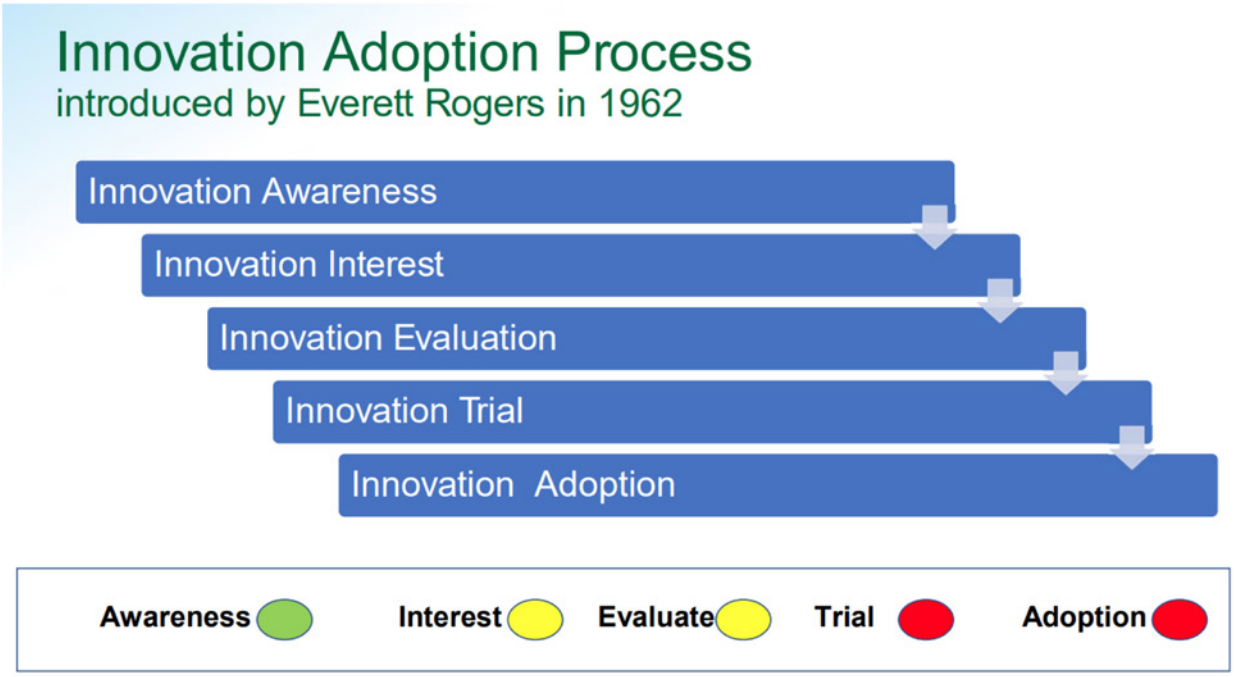


Figure 3. The steps taken to technology adoption (from Rogers, 1962)

together with the host farmer. This provided a day-long learning centre and broadened the exposure to knowledge about *Trichoderma*. Farmers were able to evaluate the efficacy of the *Trichoderma* themselves.

The project collaborated with the Department of Agricultural Extension (DoAE) to stimulate interest and innovation. The DoAE was able to provide starter packs so that farmers were able to produce their own *Trichoderma*. GIZ organised workshops and worked with farmers so that they could incubate and produce their own *Trichoderma* from the 1 kg of *Trichoderma* and other materials provided. This would enable farmers to trial the use of *Trichoderma* on their own farms.

To support adoption, GIZ worked with farmers and spray service providers and drone operators. These individuals had greater spray experience and were able to show farmers how the *Trichoderma* could be applied. This gave the farmers the option of spraying themselves or using these service providers. Farmers identified that the barrier to adoption had come from the application technique, not the technology itself.

In parallel, a monitoring and evaluation exercise was established. In 2022, a survey conducted by Mae Jo University showed that only 5 percent of farmers used biological controls (*Trichoderma*). A year later, a follow-up survey was conducted on farmer records and revealed that 50 percent of farmers had used biological controls, a tenfold increase.

And amongst the adopters, the appetite for additional knowledge continues to grow. After two years of working with the project, one farmer, Ms Wisa, growing potato/rice/corn and vegetable, told me: "*Climate change is getting more severe, so is pest and disease. It's tough, but [I will] not give up. This year is change from El Niño to La Niña, don't know how it's gonna be. The planning of this year must be very careful, need to diversify risk, want to learn more beyond* Trichoderma *Beauveria BS.*"

Scaling up the promotion of biological control

In South-East Asia, GIZ implements a small portfolio of projects and programmes (of varying sizes). These can be used to scale up biological control, for example through the Global Environment Facility-funded Inclusive Sustainable Rice Landscapes (ISRL) project. This project aims to enhance sustainable agriculture through integration with landscape management by significantly reducing environmental impacts to safeguard biodiversity, wildlife habitats, hydrological systems and ecosystems. One of the issues it is looking to address is to reduce the use of illegal pesticides (unregistered or counterfeit), which are often toxic and poorly managed. Part of the strategy to reduce their use is through providing effective alternatives, such as biological control agents. This would then fit into a national roadmap for integrated rice landscape management.

In addition, ISRL will promote knowledge exchange within Thailand and at least two ASEAN countries, encouraging sustainable agriculture to align with national and international standards. Potentially in the

future this could include consideration of biologicals in the Sustainable Rice Production Standard certification programme.

Another project that will promote biological control is the Green Climate Fund (GCF) Thai Rice Project. This is the first GCF project to focus solely on rice, with a EUR 38 million investment. The aim of the project is to transition smallholder rice farming in Thailand to a low-emission and climate-resilient pathway, through the adoption of climate-smart technologies and practices at scale. Within a five-year implementation period, the project is expected to reduce the vulnerability to climate risks and strengthen the climate resilience of 253 400 smallholder rice farmers.

This portfolio of projects will incorporate the promotion of biologicals and the tools that have already proved successful.

Conclusion

GIZ has been able to build on the work of others in the promotion of *Trichoderma* as a biocontrol agent for fungal pathogens of rice and potatoes. By conducting an analysis of adoption from previous efforts and using the understanding of adoption of innovations generated by Rogers (1962), the team was able to successfully bring about farm-level multiplication and application of *Trichoderma*. This approach is now being scaled up through massive projects being implemented by GIZ, which will continue to monitor adoption and use insights gained to strengthen and improve the promotional activities.

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Effective use of biological inputs in regenerative agriculture in Brazil

Aline Vick



Aline Vick is a second-generation Brazilian farmer committed to regenerative agriculture. She holds a degree in Economics, is currently pursuing a postgraduate course in Plant Nutrition and Physiology and is a member of the Global Farmers Network. Managing 1200 hectares at Estância farm in Brazil, Aline integrates regenerative practices and innovative technologies to enhance soil health and efficiency in farming. She is also an advocate for sharing regenerative practices with other farmers, dreaming of a future with a more sustainable agriculture.

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Background

Farming in Brazil has multiple challenges. There is high pest pressure because the tropical conditions favour continuous proliferation of insects and diseases throughout the year. Soil fertility and acidity are challenges to farmers who also need to keep soil covered to prevent denitrification. Climate challenges are increasing due to climate change, with stress from heat, drought and intense rains in particular demanding more resilient systems.

Brazilian farmers are turning to biologicals to provide part of the solution. In a 2023 study conducted by McKinsey, more than 60 percent of surveyed Brazilian producers said that they use biostimulants, biofertilisers and biocontrols in their soil health protocols – more than double the dosage in Europe and the United States. More than half of the cultivated land benefits from these inputs, with 70 percent of farmers saying they intend to maintain or increase spending on biologicals irrespective of input price variations. Usage is especially high on cotton and coffee.

Biologicals on Estância farm

Brazilian farmers committed to regenerative agriculture utilise inoculants: Estância farm has used nitrogen-fixing bacteria for many years with excellent results. There are other biofertilisers derived from algae which improve the crop's ability to absorb nutrients through symbiosis. These can be applied as seed or soil inoculants and foliar applications. In the 2025–2026 season, Estância farm is using seedling inoculants of *Azospirillum* spp (for root development), *Bradyrhizobium* spp (nitrogen fixing), *Bacillus subtilis*, *Bac. amyloliquefaciens*, *Bac. megaterium* and *Bac. licheniformis* (nematode control, growth promoting, soil/fungal disease control, nutrient solubiliser).

The strategic integration of biological inputs allowed Brazilian farmers to significantly reduce their dependence on nitrogen fertilisers. A combination of the biologicals' nitrogen-fixing bacteria, *bradyrhizobium* and *azospirillum*, adds approximately 624 kg of urea per hectare for a fraction of the cost of chemical fertilisers. It is estimated that Brazil saves USD 15.2 billion in fertilisers due to the use of rhizobacteria yearly (data from 2019 to 2020).

Estância farm is able to control the corn flea aphid (*Rhopalosiphum maidis*) with two applications of two fungi, *Isaria* and Beauveria, as well as manage soil-borne diseases through the application of a *Trichoderma* fungus.

Challenges and lessons learned

Adoption of biologicals is not automatic; there needs to be interaction between sales teams, advisory services and farmers. Support is required to address the following issues:

- Product variability and concentration: Farmers need to have trust in the products and manufacturers of the products that they are using. This trust comes from both the product having the stated efficacy and the farmer using the product correctly, *eg* applying the correct concentration.
- Technical training and guidance provision: Training needs to be provided on the use of the products within the local context, *eg* with environmental aspects such as the weather but also agronomic factors such as using biologicals within the same system as chemicals.
- Record-keeping is critical so that slower-acting biologicals can be monitored and productivity can be compared across seasons.

Conclusion

Estância farm has benefitted from the biologicals that it is now using. The biologicals are narrow in their focus and so a number have to be used to bring about positive impacts. With the correct nurturing, the farm management will increase their trust in biologicals and increase their use.

Reference

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Biologicals also need stewardship

Keith A. Jones, Sustainable Agristewardship Pte Ltd



Keith Jones has more than 45 years' experience in sustainable agriculture, Integrated Pest Management (IPM) and biological control, mainly focussed on agriculture in Africa, Asia and Latin America. Keith started his career at what is now the Natural Resources Institute, where he focussed on the development of insect baculoviruses for pest management. This included the formulation and field testing of baculoviruses, as well as the establishment of local production in Egypt, Kenya and Thailand. Keith was seconded to CARE Sri Lanka during the mid-1990s, where he managed an island-wide programme promoting IPM in rice and other food crops through Farmer Field Schools. Later, he was part of a team that advised on the integration of biological and chemical control on cotton in Uzbekistan, including the renovation of units mass producing predators and parasitoids. Following this, he joined CropLife International as Director of Stewardship and Sustainable Agriculture, a major focus of his work being promotion of IPM strategies. This included major collaborations in Vietnam and Thailand on rice IPM and on field crops in India. He is now a consultant with clients including CropLife International, UNEP, IFC, IDH and the Better Cotton Initiative.

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Abstract

The term 'biologicals' refers to a number of classes of quite different farm inputs. Biological pesticides are not without risk to human health and the environment, and risk management precautions need to be taken. Furthermore, particularly with biological products based on living organisms, they need to be well stewarded to ensure that the products maintain their efficacy and are able to fulfil their potential as a pesticide. Biological pesticides are often deployed as part of an integrated pest management system but this deployment needs to be well managed.

Introduction

This paper considers the factors that need to be addressed to promote the effective use of biologicals based on experience gained over the last 50 years. In recent years there has been a growing trend to include various new types of products within the general term 'biologicals'. This means that trying to draw universal recommendations can be complicated – some dealing with living organisms, others with what are basically chemicals derived from or based on products of living organisms (including some that are synthesised). Table 1 shows the types of biologicals that are considered in this paper.

Strengths and weaknesses of biologicals

Biologicals are often promoted as the right choice for pest management because of their inherent safety to humans and the environment – although this safety aspect is not true for all biologicals. In terms of pest management, biologicals have a number of strengths that need to be exploited to the full, if possible. However, they also have several weaknesses, which need to be considered and where possible managed through effective stewardship measures. Some of

Table 1. Types of biologicals (biological control agents)

Group	Type	Main pest target group
Macrobials	Arthropod parasites and predators, irradiated (sterilised) insects	Insects, weeds
Microbials	Bacteria, fungi, viruses, entomopathogenic nematodes, microsporidia	Insects, diseases (incl. plant parasitic nematodes), weeds
Semiochemicals	Insect sex pheromones	Insects
Natural substances	Botanicals, insecticidal soaps, fermentation products	Insects, diseases (incl. plant parasitic nematodes), molluscs

Table 2. Strengths and weaknesses of biologicals

Strengths	Weaknesses
Generally no direct or minimal impact on non-target organisms	Often restricted to a single pest organism
Generally harmless to humans	Risk of allergic reaction with some
Resistance rare or slow to develop	Most are slow acting
Can provide long-term control	Most are highly sensitive to environmental conditions, leading to short persistence and/or specific conditions to work (can be countered by formulation in some cases)
Macrobials can search for pests; semiochemicals do not have to directly come in contact with the pest – in both cases accurate application is not needed	Most require a good understanding of how they work and how to use
Most have no problems with residues (residues can be an issue with some botanicals, insecticidal soaps/oils and fermentation products)	Can be costly and expensive to use
Normally simpler to register compared to synthetic chemical products; some do not require registration	Many need to be stored under special conditions and/or have a short shelf life
	Availability can be limited

Table 3. Stewardship challenges

Group	Main stewardship challenges
Macrobials	• Living organisms with an extremely limited shelf life and period of efficacy in the field – challenges for the producer, the supply chain and the end-user.
Microbials	• Highly sensitive to high temperature and ultraviolet radiation. • May require specific environmental conditions. • Accurate application essential.
Semiochemicals	• Need to be employed on an area-wide basis, rather than just to individual cropping areas. Additionally, work best when pest density is low (early season). Temperature can affect pheromone release rate.
Natural substances	• Botanicals can generally be regarded as low-toxicity chemical pesticides. Inactivated by ultraviolet radiation and high temperatures and action of some microorganisms. • Activity of soaps and oils is usually purely on contact, *ie* there is no residual action – spray coverage is of paramount importance. • Fermentation products generally have low mammalian toxicity, but some, such as abamectin, are classified as highly hazardous. Unformulated products are sensitive to high temperatures and sunlight.

the main strengths and weaknesses of biologicals are summarised in Table 2. A major issue is that use of biologicals is often promoted on the basis of only their strengths, rather than their ability to effectively control target pests, and weaknesses are not considered; inevitably this will lead to failure.

Stewardship challenges and requirements

There are a number of different challenges faced with using different types of biologicals, which reflect their inherent properties. The main stewardship challenges are summarised in Table 3.

Stewardship actions need to be designed to address these challenges (as well as challenges presented by all crop protection products). There are some issues that need to be considered, which are common to all biologicals. These are:

- Use in accordance with an appropriate threshold (taking into account slow action)
- Knowing when and when not to use, *eg* stage of pest – will significant crop damage occur before impact of biologicals?
- Best used as part of an Integrated Pest Management (IPM) strategy

- Appropriate personal protective equipment must be worn (normally minimum required for chemical products)
- Proper disposal of waste.

There are also stewardship requirements that are specific to the different types of biologicals; the most important of these for effective pest management are summarised in Table 4.

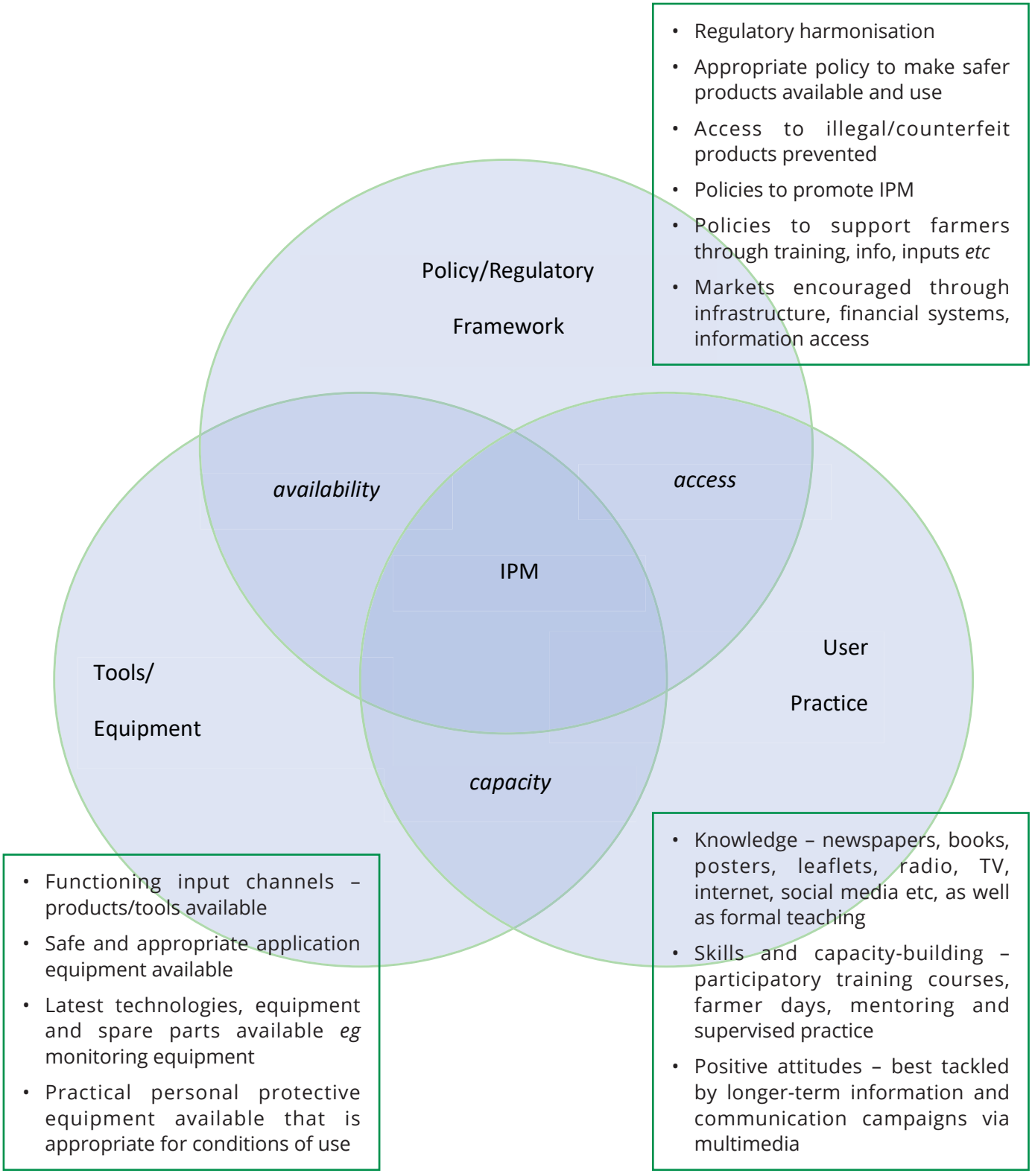


Figure 1. Factors influencing IPM adoption

Table 4. Stewardship requirements for different classes of products

Group	Specific stewardship requirements
Macrobials	Production control (quality) Proper transport and storage Timing of release
Microbials	Production control (quality) Proper transport and storage Timing and placement of application
Semiochemicals	Timing of application Appropriate 'point sources'
Natural substances	Timing and placement of application

Barriers to adoption of biologicals

Even with the adoption of good stewardship practices, there are also other factors that present barriers to adoption and successful use of biologicals, which need to be considered and addressed, if possible. These include:

- Inappropriate choice – not based on 'right tool for the job' but on other factors, *eg* 'natural' vs 'synthetic'
- Lack of understanding by growers, *eg* when to use, slow action *etc* – requires training and extension
- Poor availability – pest management options have to be based on availability and affordability.

Integrated Pest Management

IPM provides a framework where all available management tools are considered – biological, cultural and chemical (if prevention has failed). Biologicals should be one of the preferences for consideration in such a system – often used in combination with other techniques and tools that are available. IPM itself needs supportive policies, approaches and actions if it is to be adopted and to make economic sense (which it normally does, but often requires time). Some actors promoting the adoption of IPM are shown in Figure 1. If biologicals are to be successful with an IPM strategy, appropriate stewardship is essential.

Further practical information on adoption of IPM can be found at g-fras.org/en/knowledge/new-extensionist-learning-kit-nelk.html#technical-2-integrated-pest-management

Conclusion

Biologicals have been shown to be effective tools for cost-effective pest management. However, their uptake can be hindered if recommended and used inappropriately. This requires a proper knowledge of when, where and how they can be used, including good stewardship practices. Despite being of varying properties, there are common stewardship practices that should be adopted, as well as ones specific to the different types of biologicals. None are too arduous.

Biologicals are generally best employed as part of an IPM system, which itself can be promoted through appropriate policies, approaches and actions as an essential part of stewardship of crop protection products. The take-home message is 'Biologicals need stewardship too!'

Further information and detail on Biologicals and stewardship can be found at:

croplife.org/wp-content/uploads/2024/12/CLI-Stewardship-IPM-Guideline-2024.pdf?v=1734354405

Biofertilisers and biostimulants: is the bubble about to burst?

Ken Giller



Ken Giller was recognised as the TAAI 'Development Agriculturalist of the Year' in 2024. He has conducted research on nitrogen fixation in the tropics for over 40 years and is author of the book Nitrogen Fixation in Tropical Cropping Systems *published by CABI in second edition in 2001. He has led a number of initiatives such as the Bill & Melinda Gates Foundation-funded 'N2Africa – Putting Nitrogen Fixation to Work for Smallholder Farmers in Africa, (n2africa.org), which worked in 11 countries over 10 years from 2009 to 2019. Ken has over 500 peer-reviewed papers and has been on the Web of Science list of Highly Cited Researchers (top 1 percent) since 2016. He has supervised over 100 PhDs successfully – more than half from African countries. Ken joined Wageningen University as Chair of Plant Production Systems in 2001 after holding professorships at Wye College, University of London, and the University of Zimbabwe.*

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Abstract

Inoculants of bacteria that fix nitrogen with cereals and other non-legume crops have developed into a multi-million-dollar industry. The rise of these microbial inoculants has been driven by exaggerated claims by scientists and vast amounts of venture capital. An increasing number of scientific reports indicate no response in crop growth or yield to inoculation with these products in the field. A review of the scientific literature indicates that, when observed, crop responses are due to the effects of plant hormones produced by the bacteria and not N_2-fixation. As increasing numbers of farmers and scientists become disillusioned with the false promise of microbial N_2-fixation in non-legumes, is the bubble about to burst?

Introduction

One of the dangers of having been around for a long time is that you get a feeling you've seen it all before. That's certainly the case with the promise of microbial nitrogen fixation with cereals. My first job after completing my PhD in 1982 was to measure nitrogen fixation in the rhizospheres of sorghum and millet. I was employed at Rothamsted Experimental Station, working in collaboration with the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Hyderabad, India. The research was funded by a grant from the UK Overseas Development Administration, and the aim was to gather sufficient scientific evidence to determine whether inoculants of free-living nitrogen-fixing bacteria warranted promotion and commercialisation.

The background to the project was a long-standing collaboration between John Day at Rothamsted and Peter Dart at ICRISAT. They were both authors of a seminal paper which showed high rates of nitrogen fixation associated with the roots of tropical grasses in Brazil using the acetylene reduction assay (Döbereiner *et al*, 1972). Dinitrogen gas, N_2, which comprises almost 80 percent of the atmosphere, is a triple-bonded molecule that is reduced to ammonia by the enzyme nitrogenase. Acetylene is also a triple-bonded molecule which is reduced to ethylene by nitrogenase, so the rate of N_2-fixation could be measured by incubating roots of tropical grasses in chambers enriched with acetylene and measuring the accumulation of ethylene. The publication of their paper aroused a lot of interest and, when coupled with reports of responses of crop growth to inoculation with N_2-fixing bacteria (Smith *et al*, 1976), the prospect of N_2-fixing cereals seemed a reality. Although a paper published in 1979 showed that these microbial inoculants stimulated root branching and root hair growth through the production of plant hormones (Tien *et al*, 1979), the enthusiasm for nitrogen fixation in cereals was not quelled.

Peter Dart was leading a team at ICRISAT investigating nitrogen fixation associated with the roots of millet and sorghum. Much of the work involved use of the acetylene reduction assay to measure nitrogen fixation. Observations of different rates of N_2-fixation associated with different genotypes of millet and sorghum led to crossing experiments to see if this was a heritable trait (Figure 1). Many glasshouse and field experiments to test the growth and yield response of millet and sorghum to inoculation with N_2-fixing bacteria were also being conducted.

My research involved the use of the stable isotope of nitrogen, ^{15}N, to trace microbial N_2-fixation. I conducted experiments in which intact roots of



Figure 1. Paper bags being placed over the flowering spikes of millet plants grown in the glasshouse at ICRISAT to allow specific crosses to be made. The plants are growing in large pots that can be sealed to allow injection of acetylene to assess rates of N_2-fixation. (Photo: K Giller)

small sorghum plants were exposed to $^{15}N_2$ gas (Figure 2). Using this very sensitive method, we could demonstrate that N_2 was fixed in association with the roots and taken up by the sorghum plants (Giller *et al*, 1984). But the amounts of N^2 fixed were very small and only detectable when we added farmyard manure to the growing medium. I also conducted studies using isotope dilution and nitrogen balance methods which indicated no significant amounts of N_2-fixation in millet and sorghum. As time went on, I became more suspicious of the results being reported. Crop response to inoculation in field experiments was very erratic, but there seemed to be selective reporting of the positive responses. Further, although the acetylene reduction assay is highly sensitive, it is subject to a number of problems. Long incubation times were used, which gave inflated N_2-fixation rates. Notably, acetylene blocks the normal oxidation of ethylene in the soil, so ethylene accumulates during incubations that has nothing to do with N_2-fixation. This problem was already highlighted in 1976, yet the acetylene reduction assay was still routinely employed (Giller, 1987). Based on my experiences in India and on an extensive literature review, I concluded that the amounts of N^2 fixed by bacteria associated with the roots of cereals were of little significance in agriculture (Giller & Day, 1985). To my surprise, a year later, ICRISAT produced a workshop proceedings entitled 'Cereal nitrogen





Fig. 2. Experiments conducted in the glasshouse exposing the roots of sorghum plants to $^{15}N_2$ gas at ICRISAT, India. a) The plumbing to allow the growth chambers to be flushed and $^{15}N_2$ gas introduced. b) Young sorghum plants sealed to all exposure of the root systems to $^{15}N_2$ gas. See Giller *et al.* (1984) for details of the method. (Photos: Ken Giller)

fixation' (Wani, 1986), which concluded the opposite, as did another review article (Dart, 1986). This was my first experience that scientists furnished with the same information could reach diametrically opposite conclusions.

Microbial inoculants offering the promise of N_2-fixation with cereals and other non-legume crops had been around for a long time: Azotobacterin was already used on 10 Mha in Russia in the 1930s (Brown, 1974). Researchers had concluded that the (often erratic) responses of cereals and grasses to inoculation with free-living N_2-fixing bacteria were due to hormonal effects and not N_2-fixation (Brown, 1974; Giller & Day, 1985). In 2002, almost 20 years after the publication of our 1985 review, I was invited to give the opening talk at the 9th International Symposium on Nitrogen Fixation with Non-legumes in Leuven. In the intervening period, a number of papers had appeared claiming substantial N_2-fixation and crop growth responses in non-legumes due to the bacterium *Gluconacetobacter diazotrophicus*, but yet again these had been shown to be due to production of plant hormones (Sevilla & Kennedy, 2000). In my talk I referred to three overlapping cycles of discovery and disappointment related to microbial N_2-fixation in non-legumes, where in all cases it had been concluded that crop responses were due to hormonal effects and not N_2-fixation (Giller & Merckx, 2003). This was also the conclusion of the symposium summary (Kennedy, 2003), and other authors in the same year (Dobbelaere *et al*, 2003).

What is happening now?

Fast-forward another 20 years to 2023; I was invited to a convening at the Bill & Melinda Gates Foundation in Seattle to explore the possibilities of microbial N_2-fixation in non-legumes. Having not been directly involved in research on this topic for some time, I was astounded to see how many microbial inoculants were being sold to farmers, particularly in North America, for use on cereals. *Gluconacetobacter diazotrophicus*, the bacterium promoted and sold by Azotic,[1] is actively promoted in Africa by the so-called 'Sustainable Nitrogen Foundation'.[2] Around the same time, I was contacted by a journalist, Joost van Kasteren, who had become aware of reports emerging from American universities that reported no crop response to such products *(eg* Franzen *et al*, 2023). I shared my experiences with Joost, who also interviewed Julie Ardley of Murdoch University, Perth, Australia. She could clearly show that the strain of *Methylobacterium symbioticum* used in the product Blue N, which is marketed as Utrisha N in North America, cannot make nitrogenase – it does not have the HDKENX gene cluster found in all N_2-fixing bacteria (Figure 3). Joost reported these findings in a popular article, in which he talked of the 'fourth wave' of excitement about microbial N_2-fixation with non-legumes (Van Kasteren, 2023). On publication of the article, we were contacted by the manufacturer of Blue N, Corteva Agriscience, and Julie Ardley and I shared our findings with them in detail in August 2023. Together with Euan James, an expert on microbial colonisation of plants, and Murray Unkovich, a leading expert on measurement of N_2-fixation, we published a detailed analysis of the current state of knowledge on microbial N_2-fixation with cereals and other non-legumes (Giller *et al*, 2025). In this review, we call for stringent regulations to

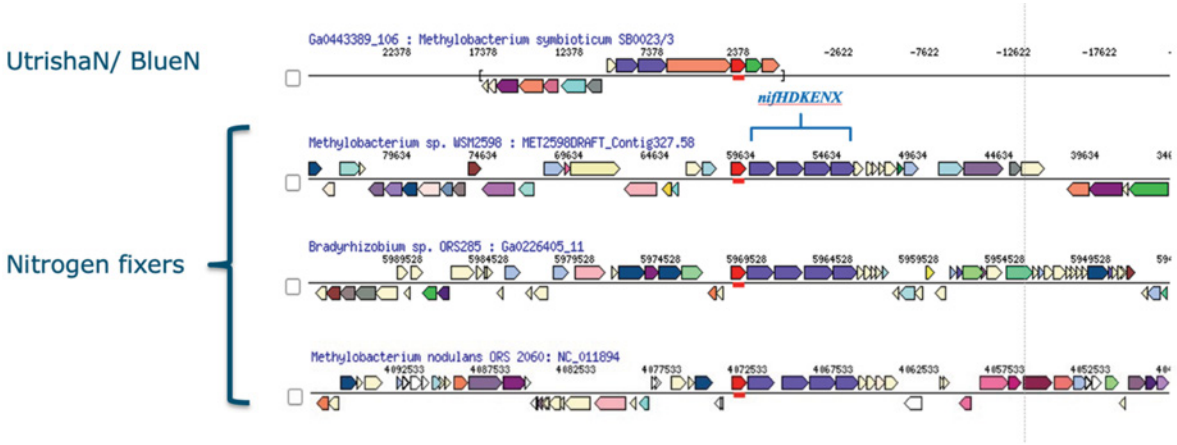


Fig. 3. The bacterium used in UtrishaN/ BlueN (*Methylobacterium symbioticum strain SB0023/3*^{T}) has genes homologous to *nifH*, the gene encoding the Fe protein of nitrogenase, but lacks the genes required for nitrogenase biosynthesis. The two *nifH*-like homologues found in *Methylobacterium symbioticum* strain SB0023/3^T were identified as genes encoding proteins present in two bacteriochlorophyll biosynthesis clusters. By contrast, the N_2-fixing rhizobial strains *Methylobacterium* sp. WSM2598, *Bradyrhizobium* sp. ORS285 and *Methylobacterium nodulans* ORS2060 all possess the conserved nitrogenase biosynthesis *nifHDKENX* cluster. The two *nifH*-like homologues found in *Methylobacterium symbioticum* strain SB0023/3^T were identified as genes encoding proteins present in two bacteriochlorophyll biosynthesis clusters (see Giller *et al.*, 2025 for further explanation). I thank Julie Ardley for preparing the figure and for permission to reproduce it.

[1] https://www.azotic.com/global/
[2] The Sustainable Nitrogen Foundation https://www.tsnf.org.uk

prevent the sale of microbial inoculants with spurious claims of significant N inputs from N_2-fixation with non-legumes. Before products are registered for sale, we argue that independently verified evidence should be provided that the inoculant bacterium can fix N_2 and that significant inputs of N are derived from N_2-fixation by non-legumes in the field, confirmed by more than one method (Giller *et al*, 2025).

What is the theoretical limit for how much N_2 could be fixed with non-legumes?

Andrew Hanson recommends that 'Fermi calculations' – which are basically back-of-the-envelope calculations, or order-of-magnitude estimates (Oliveira-Filho *et al*, 2025) – should be used to scope whether proposed solutions to important problems are realistic. Such calculations, based on the efficiency with which carbon can be used to fix N_2 by bacteria, the ability of N_2-fixing bacteria to compete for carbon released by plants and the amounts of plant carbon available for use by bacteria have been made several times (Table 1). These estimates are fairly similar, suggesting that the maximum rates of N_2-fixation *under ideal conditions* are 4–20 kg N/ha. These amounts are unlikely to be achieved in the field, and are far less than those claimed by the manufacturers of microbial inoculants.

A market out of control?

Despite the overwhelming scientific evidence summarised above, the number of products claiming to fix N_2 with non-legumes increases year by year. Reports suggest that USD 1.5 billion of venture capital has been invested in what are termed 'crop-agnostic nitrogen fixing or availability-enhancing products', which effectively means bacteria that will fix nitrogen with any crop. This is not just money invested in research; it is also building a massive industry in inoculants of N_2-fixing bacteria. For example, Azotic's products were used on 0.8 Mha in North America, and PivotBio's on 1.4 Mha[3]. Shoham (2026) estimates that the market for biological products was growing by 15 percent a year until recently. Although biofertilisers currently comprise only a small proportion of the total, this amounted to USD 1.3 billion in 2023 and is estimated to rise to USD 2.14 billion by 2028 (Shoham, 2026). Among the companies, Corteva Agriscience, the manufacturer of Blue N, is said to be leading the sales with 12.5 percent of the global market[4]. As indicated above, we shared our findings with Corteva in 2023, yet it continues to use the same publicity in which it claims that Blue N fixes N_2 in cereals and a whole range of non-legume crops. This is misleading and surprising for a company that supposedly prides itself on its 'Purpose and Values' on its website.

Accumulating disillusionment in product performance

Since the publication based on 10 universities in the USA, which found no response to microbial inoculants of N_2-fixing bacteria in 59 out of 61 trials (Franzen *et al*, 2023), other reports have also emerged with rare or no response to such microbial inoculants. Independent experiments at eight locations in Canada found no effects of Utrisha N or Envita N on wheat grain yield or protein concentration, nor on N status in canola, despite an expected response to N fertiliser. Experiments in Denmark showed no effect of Vixeran

Table 1. Fermi calculations of the theoretical maximum rates of N^2-fixation that could be supported by a crop of cereals

Cereal	Maximum rates of N_2-fixation that could be supported (kg N/ha)	Reference
Rhizospheres of wheat	15	(Giller & Day, 1985)
General model for cereals	4	(Jones *et al*, 2003)
General model for cereals if the populations of N_2-fixing bacteria could be enhanced	20	(Jones *et al*, 2003)
Aerial roots of maize	15	(Gelder *et al*, 2023)

[3] https://www.pivotbio.com/wp-content/uploads/2025/06/2024-Pivot-Bio-Impact-Report.pdf

[4] https://www.linkedin.com/feed/update/urn:li:activity:7412464359488180224?utm_source=share&utm_medium=member_desktop&rcm=ACoAAC6X56IBb7shRoWAULTylfHEx5hVNFI3cro

(Syngenta) or Blue N on growth or yields of winter wheat[5,6,7]. Six trials across three locations in Sweden over two years testing a range of biostimulants, including Blue N, showed no effect on spring barley yields. These accumulating results demonstrate that stringent regulations are needed to prevent such products from being marketed based on claims they cannot fulfil (Giller *et al*, 2025; Termorshuizen *et al*, 2026).

Conclusion

So what has led to this current popularity of microbial products which appear not to live up to the claims of the manufacturers and the expectations of the farmers? The rise of regenerative agriculture and the pressure to reduce the amounts of mineral N fertilisers used in agriculture no doubt play a major role, as does the profitability of microbial inoculants. Perhaps the blame does not solely lie with companies running ahead of the evidence to market products and profit from their sale. Undoubtedly the exaggerated claims made by scientists to gain attention for their work and garner funding are also to blame.

Are there fairies at the bottom of the garden? Probably not – but we keep telling stories about them generation after generation! That's how I started my talk entitled 'Microbial N_2-fixation in cereals: hype or reality?' at the PlanteKongres in Herning, Denmark in January 2026. It's such a nice idea that cereals and other non-legumes can fix nitrogen through inoculation with bacteria, that we've been telling this story in repeated cycles for almost 100 years – although the evidence points to any increases in crop growth being due to plant hormone effects and not N_2-fixation. My conclusion is that, although there probably are no fairies at the bottom of the garden, the stories will run and run into the future. Unfortunately, the same goes for the fantasy of microbial N_2-fixation with cereals!

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[5] https://iharf.ca/wp-content/uploads/2024/04/Efficacy-of-Foliar-Applied-Nitrogen-Fixing-Bacteria-for-Wheat.pdf

[6] https://iharf.ca/wp-content/uploads/2024/04/Efficacy-of-Foliar-Applied-Nitrogen-Fixing-Bacteria-for-Canola.pdf

[7] https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://cm.projekt.seges.dk/-/media/segesinnovation/planteafgiftsfonden/planteafgiftsfonden-2024/104214/pm_24_104214_ap2_maanedens_forsog_kvaelstoffikserende_bakterier_i_vinterhvede_havde_ingen_effekt.ashx&ved=2ahUKEwiY6e7bhY6SAxWt_7sIHVTiElkQFnoECB0QAQ&usg=AOvVaw2WK_lyJrYvNZrzwejwlozP

The Sri Lanka experience – why a phased transition to biologicals is vital

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Introduction

In May 2021, as the Indian Ocean island of Sri Lanka was experiencing a severe fiscal crisis during the COVID-19 pandemic, the government legislated to stop all imports of conventional fertilisers and pesticides overnight.

Although the adoption of biological and organic solutions had been suggested at various times since 2008, this had previously been considered as a phased rather than an immediate replacement.

The net result was that the experiment was rapidly withdrawn in November 2021, as crop yields of both staples such as rice and key export crops such as tea plummeted.

The Sri Lanka experience demonstrated that a more cautious and gradual approach to biological alternatives is necessary so that agricultural production and farmer livelihoods are not damaged.

Inferior imports

Various problems with the rushed transition were identified in hindsight. Critical amongst these was the significant shortage of domestic supplies of organic and biological fertilisers and pesticides to replace chemical inputs.

This resulted in replacements of variable quality being imported from China, India and Lithuania, among others. Instead of saving the exchequer money, the cost of imported inputs rocketed, while vital rice supplies also had to be shipped to Sri Lanka from neighbouring India.

In defence of biologicals

Despite the botched transition described above, Sri Lanka had a long history of speciality teas and spices grown to organic and biodynamic standards. Furthermore, there had been various attempts to develop domestic alternatives to chemical inputs. Subsidies had meant that smallholders had often over-applied conventional products, particularly in rice fields, leading to farmer illnesses and degradation of soil quality.

Several projects such as the use of municipal solids and tea waste, algae and seaweed, compost and animal manure are all under way in Sri Lanka, but these are still largely at an early stage.

The future

The current President of Sri Lanka, Anura Kumara Dissanayake, comes from a rural background and is keen to explore and encourage alternative forms of cultivation to improve agricultural production, although he was extremely critical of the botched biologicals implementation under the earlier presidency of Gotabaya Rajapakse, who was overthrown after widespread protests during the economic crisis, which resulted from tourist income and garment exports being adversely affected during the COVID pandemic.

These novel projects include the deployment of regenerative agricultural methods in tea production, as well as the development of seaweed and algae and other bacterial-based solutions in Sri Lanka.

Hopefully, however, the lessons of the 2021 experience have now been learned. In the United Kingdom, for example, transition to organics is specified as a strict four-year period by certifiers such as the Soil Association. And neighbouring India has recently tightened up its regulations on biostimulants and biofertilisers, for example.

In the meantime, as Sri Lanka ramps up domestic biological and organic production, the use of hybrid and Integrated Pest Management methods should be adopted. That way, the devastating impacts seen in Sri Lanka in 2021 would in future be averted.

Beyond the hype: an agroecological checklist for the biopesticides sector

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Introduction

The growing biopesticide market represents a pivotal opportunity for sustainable agriculture in the Global South. Rising environmental awareness, regulatory pressures on synthetic pesticides and consumer demand for healthier food systems are driving innovation, investment and regulatory adaptation in the sector. These are significant opportunities, but it is important to also be aware of the risks.

Biovision's experience is that without careful alignment to agroecological principles, the biopesticide industry risks repeating structural and ecological pitfalls seen in the synthetic pesticide sector. These pitfalls include: corporate concentration, input dependency, lack of contextual adaptation, product uniformity and the persistence of pest management systems disconnected from ecosystem-based pest regulation. The concern is that biopesticides are reduced to a 'green substitute' rather than a catalyst for systemic change.

te Wierik *et al* (2025) state that food systems are a critical driver of planetary boundary transgressions, dominating at least four transgressed boundaries (ecosystem function, biosphere function, P and N biogeochemical flows) while strongly contributing to the transgression of two more (pesticides and antimicrobial use). Therefore, in the development of the biocontrol sector, it is important to consider complementary tools within Integrated Pest Management (IPM) and catalysts for locally driven, decentralised and context-specific innovation.

Aligning biopesticide development with agroecological principles

Biovision has developed a checklist to provide key recommendations for aligning biopesticide development with agroecological principles for different actors. The key actors have been identified as:

- **Policy makers and regulators** involved in agricultural inputs and agroecology policies
- **Agroecological advocacy actors** advancing national policies, products and innovations
- **Investors and funders** seeking to support the growth and innovation of the sector

The key recommendations in the checklist are:

1. **Promote national and territorial bioinput strategies.** Build local biopesticide value chains through market incentives, social entrepreneurship and public procurement policies, and link these strategies to broader agroecological transition plans, Nationally Determined Contributions (NDCs) and national sustainability goals.
2. **Design differentiated and progressive regulatory pathways.** Create differentiated registration or approval procedures depending on the risks and complexity of the biopesticide or biocontrol product, and consider the scale of its use.
3. **Develop context-specific transition pathways.** Tailor biopesticide and pest management solutions

to farmers' realities and stages of farm transition. Identify priority regions where replacing highly hazardous pesticides can have the greatest impact.

4. **Invest in local capacity and infrastructure.** Support small and medium-sized enterprises in formulation, biomanufacturing and quality control. Guarantee access to funding and markets for emerging local actors.
5. **Ensure biopesticides are developed and deployed as complementary tools.** Embed biopesticides within IPM and agroecological systems, supporting biodiversity, ecosystem services and soil and water health rather than functioning as standalone substitutes for synthetic pesticides.

QR code to download the full policy brief:

Reference

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One Health, Plant Health and biologicals

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Abstract

Incorporating Plant Health into the established concept of One Health, which to date has focussed on the health of ecosystems, animals and humans and zoonotic risk, is not without its challenges. Yet there are many reasons why Plant Health should be recognised within the One Health approach. This paper sets out the rationale, a call to arms, that supports a fuller integration of Plant Health into One Health and discusses a process of 'qualifying in' what is and is not a Plant Health–One Health factor. The value of Plant Health in One Health is illustrated by examples of (i) first encounter, case zero, pest and disease events; (ii) crop yield and food and feed safety; and (iii) biologicals applied to One Health. The paper concludes with potential high-impact Plant Health actions that place value within a One Health endeavour.

One Health – a complicated conundrum

Critical global issues impacting the economy, environment and technology are increasingly interrelated, creating interconnected risks if action is not taken. Ways to act quickly across geographies, government departments and commercial, public and academic sectors are urgently needed (World Economic Forum, 2020). The One Health (OH) approach offers a way to act.

Building from the high-level overviews of connectivity, a particular perspective relates to climate change, agriculture, biodiversity, health and disease, *ie* where an enhanced understanding is seen to improve health outcomes such as how health-focussed measures affect biodiversity and agriculture, and how conservation measures impact on biodiversity and health. Over a period of time a plethora of buzzwords have evolved to better frame such narratives, including: smart agriculture; regenerative agriculture; sustainable agriculture; sustainable intensification; green economy; planetary health; as well as OH. However, it is also the case that these terms have been used freely by actors without a clear definition or basis of evidence at the risk of misuse and limiting their potential value.

In order to help develop a consensus around OH, the One Health High-Level Expert Panel (OHHLEP) developed the following definition in 2022 (see Box 1).

Box 1: Definition of One Health

"*One Health is an integrated, unifying approach that aims to sustainably balance and optimize the health of humans, animals, plants and wider environment (including ecosystems). The approach mobilizes multiple sectors, disciplines and communities at varying levels of society to work together to foster wellbeing and tackle threats to health and ecosystems, while addressing the collective need for clean water, energy and air, safe and nutritious food, taking action on climate change, and contributing to sustainable development*" (Adisasmito *et al*, 2022).

The length of the definition is indicative that OH remains conceptually complex.

OH requires multisectoral partner collaboration and a transdisciplinary evidence approach to further a holistic and systems-based understanding of 'health domains', namely animal, human and ecosystem. Within and between these domains the OH approach looks at the dependency of relationships, the synergy and trade-offs, taking in working-scales of local, national, regional and global to achieve optimal outcomes. The integrated, multisectoral and transdisciplinary perspective is particularly essential to managing the complexity of the relationships at play between agriculture, biodiversity and ecosystems. The OH approach has already made an impact in responding to infectious diseases, antimicrobial resistance (AMR) and advances in nutrition, but has potential to go much further. For example, the OH approach is appropriate to meet the demands of rapid urbanisation and climate resilience, and reduce the burden of human, animal and plant disease. In addition, it can identify the socio-economic drivers by which the links are influenced, and in so doing determine the appropriate interventions and policies.

A call to action: Plant Health and a place at the One Health table

Zoonosis, animal-to-human disease spread (*eg* Ebola, COVID-19 and AMR), has rightly attracted significant attention under the banner of OH. Indeed, zoonotic events have arguably driven and become synonymous with the OH cause. This in turn has tended towards OH being associated with Animal Health (AH) and Human Health (HH), with limited recognition of Ecological Health (EcoH) and, even less so, Plant Health (PH). Consequently, current OH thinking and resource deployment have most strongly been associated with those governmental structures (*eg* departments, budgets and policy) mandated to AH and HH policy areas. Given the above, it is therefore appropriate to note that a driver of zoonotic first encounter, 'case zero', infection risk is agricultural land-use change, *ie* by smallholder encroachment into forests (deforestation) due to poor and decreasing productivity. Arguably, a further example of the over-dominance of the AH–HH zoonotic axis in OH can be seen in Box 2, which gives a short summary of where current consideration of AMR has undervalued AMR risks associated with plants, *ie* PH.

Accordingly, it is the thesis of this paper that as plants and PH are integral to life on Earth, providing food, materials, medicines, recreation and the air we breathe, there is an unmet need to better qualify PH as part of OH. To this end, there are already signs of change with the Quadripartite (Food and Agriculture Organization (FAO), United Nations Environment Programme (UNEP), World Health Organization (WHO) and World Organisation for Animal Health (WOAH)) now well placed to collaborate on an OH joint plan of action (Danielsen *et al*, 2025).

Box 2. Overuse of antibiotics in humans and animals has been linked to AMR and risk of zoonosis and an OH solution

Here, control or risk-mitigating measures have focussed on surveillance of resistant bacteria and/or genes and antibiotic stewardship. Less recognised is the fact that AMR may also arise in crop cultivation (*ie* PH) through the use of pesticides, particularly the fungicide triazoles and generation of pesticide resistance. The cyclic nature of returning livestock waste back onto pasture, as manure, to enhance growth for future grazing or feed also defines an evolutionary selection loop for AMR organisms and genes. This emphasises the need for coordinated OH approaches to manage antimicrobials across human, animal and plant (including ecosystems and food systems) health domains to guide effective, evidence-based interventions.

Qualifying Plant Health concerns in One Health

In revisiting the OHHLEP definition of OH, a key consideration is the determination, or 'qualification', of a PH factor as part of OH: whilst all things may be 'connected and interdependent', OH factors cannot be all-encompassing. A key question therefore is what PH factors are most applicable to be considered through an OH optic? The following aims to expand on a logic for identifying those PH factors that most strongly align with an OH approach, *ie* as to their qualifying as PH–OH factors.

First encounter, 'case zero', pest and disease events: Deforestation of pristine environments, notably Amazon rainforests, has been associated with opportunistic 'first-encounter' pest and disease reports, including of a zoonotic nature, *eg* the species jump of the Ebola virus from bats to humans. For PH, first-encounter species jumps from native plants onto cultivated crops have also been reported. A significant example is the discovery of *Phytophthora megakarya on Irvingia* in Cameroon as the presumed natural host of cocoa black pod disease (Holmes *et al*, 2003). Similarly, cassava brown streak disease, a viral disease that is geographically limited to Africa, has logically acquired cassava as a host subsequent to its introduction to Africa (Tomlinson *et al*, 2018). In the PH arena there are many examples of new host and

host range expansions that are most likely explained as first-encounter events.

The drivers of deforestation – smallholder encroachment, mining, expansion of oil palm production, road infrastructure, *etc* – are therefore a root cause of emerging pests and diseases impacting across all health domains where, in mitigating these risks, an OH approach could be taken. Many of the features and capabilities for biosecurity, spanning surveillance, detection and response, are common across health domains. This commonality of purpose has recently been advanced as One Biosecurity (Hulme, 2020).

Crop yield and food and feed safety: Access to sufficient, affordable and nutritious food is frequently stated as a PH–OH consideration for the obvious reason that animals and humans need it. Accordingly, crop pests and diseases, pesticide residues and mycotoxins are all major PH factors recognised as impacting on yield and marketability, and attributed as qualifying as PH–OH factors. Interestingly, these concepts of food and feed safety, as driven by HH and AH concerns with mitigation requiring the cooperation of PH, have developed over many decades and pre-date OH thinking.

Whilst attribution of PH to OH in the context of food and feed safety is non-contentious, what is of interest are the disparities between regions and countries and the extent to which food security and safety is effectively managed. The following talks to situations as may characterise developed and low- and middle-income countries (LMICs) and, whilst highly generalised, attempts to put across a key example where the PH–OH opportunity is both met and unmet, respectively.

In a developed world context (*eg* UK, USA, EU countries), food security is spoken more of in terms of supply continuity, operating major and complex national and global market supply chains that ensure safe food is available and at an affordable price. Typically, much of the food and feed is imported, often from LMICs. By these systems the impacts of yield loss, by pests and diseases or by natural events, even when sudden, are dampened by sophisticated supply management, resourcing from different pathways, tapping different global options. Inherent to these systems, food safety concerns – *eg* over mycotoxins and pesticide residues – are extensively managed by governments imposing tight regulations on permissible levels with stringent oversight of the industry by empowering its agencies to undertake risk assessment, surveillance and testing.

By contrast, the situation is very frequently different in LMICs (Subedi *et al*, 2024). Typically, national food security is predominantly met by homeland, often highly localised, production, with less access to international markets. In these situations, shock events that lead to crop failure, such as a new pest or disease outbreak that evades current crop protection practices or an extreme weather event, can rapidly destabilise markets and lead to food insecurity. It is also the case that, whilst food and feed safety regulations are in place and of equivalence to developed nation standards, food and feed safety is not effectively managed and supply chain integrity is far less evident. In brief, supply chains are often informal or otherwise not being systematically tested for pesticide residues and mycotoxins by national authorities.

In these examples, it is suggested that the PH domain of government and industry of LMICs requires more authority to implement food and feed safety systems that parallel the resilience and safety standards successfully deployed by developed nations. It is ironic that the focus of many LMIC national authorities for food and feed safety, often supported by funding agencies, is targeted at exports to the developed world and meeting the standard of these countries.

Biologicals applied to OH

New biologicals, such as pesticides, integrated with pest monitoring and surveillance and plant breeding for nutritional and environmental outcomes, can help deliver a sustainable and economic farming system. Whilst a vast subject, some examples are given below:

Pesticide use: As a result of HH and EcoH concerns, today's farming practices, especially those of the UK and EU, have been pressured through the implementation of new and revised regulations to deliver economic productivity with reduced choice and use of pesticides (Smith *et al*, 2026). These measures, though well-intended in addressing concerns such as neonicotinoids and bee health decline, have often not taken into account the downstream consequences of the imposed changed practices, *ie* the coping strategies deployed by industry and farmers charged with delivering an economic yield. First, there is the recognition that pesticides remain essential for crop protection and regulations that limit the choice of pesticides available to farmers will, through overreliance and overuse of those pesticides – and modes of action – that remain, drive pesticide resistance and thus accelerate ever greater use. And second, in situations where crop protection fails due to the build-up of pesticide resistance within pest or disease populations and a farmer 'switches' to another crop, for which the ecological impact – of that change and at scale if mirrored by many farmers – is unknown. In the UK and EU such a scenario ensued

with oilseed rape and the loss of control over cabbage stem flea beetle populations as an outcome of the neonicotinoid ban (Ortega-Ramos *et al*, 2022).

This approach to looking at the relative power of the health domains may point to an inequality of PH to EcoH. A stronger voice for PH would be to realise greater investment in a next generation of biologicals with very specific modes of action. The possibility of new biologicals is now very real with the use of artificial intelligence to assist with fast-tracking the design of new candidate molecules (Serrano *et al*, 2024).

Breeding for HH and EcoH outcomes: The Green Revolution primarily bred for crop yield under high inputs of nitrogen and pesticides, with national recommended variety listing accordingly aligned as the gateway to market. Consequently, nutritional and environmental outcomes have not been mainstreamed in breeding programmes. Under today's redesign of sustainable 'regenerative' agriculture, researchers, industry and government have the opportunity to work with the PH sector to reprioritise breeder objectives towards EcoH and HH outcomes. Done well, this can be a great example of OH.

Amongst potentially many ways this may be achieved, one area relates to the microbiota of roots. Limited attention has been given to the role of microbials as may be beneficial in providing defence against pests and diseases, making nutrients available to plants and/or improving resilience to extreme weather events. Recent research now suggests that modern and ancient varieties of cereals recruit distinct microbial biota, with evidence that the microbiota associated with ancient varieties is of greater biodiversity and functionality than modern varieties (Reid *et al*, 2024). This could be expected when modern breeding has taken place under high nutrient situations where the advantage of ancient varieties to access nutrition as an outcome of recruiting 'fixing' microbials is negated.

The One Health Nexus Community of Practice

FAO, with the Quadripartite, offers 'Communities of Practice' of governments, academia, non-governmental organisations, international organisations and the private sector to engage in:

- exchange in expertise, practical resources, knowledge and best practices
- research and analysis to inform practice, policy and decision-making
- advocacy for the importance of OH and promoting investment in the field.

The UK Government's support for the One Health Knowledge Nexus is part of its Animal and Plant Health Innovation and Evidence Delivery (APHID) platform for prevention, preparedness and response to emerging animal and plant health threats. This aligns with the UK's approach to biological hazards, which is underpinned by the four foundational pillars of its biological security strategy: understand, prevent, detect and respond (Gupta *et al*, 2025).

Conclusion

Using the analogy of a three-legged stool which is most stable when all legs are of equal length, the OH concept is strongest when HH, AH and EcoH are equally prioritised. Unfortunately, EcoH, particularly PH, is often overlooked, and with a weakened leg, the entire system (like the three-legged stool) can be destabilised, compromising the health of all elements (Lorenzini & Noli, 2025).

For this reason, there needs to be more cross-sectoral collaboration between plant scientists, veterinarians, human health experts and environmental scientists to develop holistic approaches to strengthen agriculture and food supply chains with less impact on the environment and biodiversity, to deliver improved health for humans, animals and plants. In this context, potential actions include: (i) more vigilance of new host and host range expansions through first encounters with a commonality of purpose to advance One Biosecurity; (ii) government and industry consider the PH domain in developing a food safety system commensurate with that of developed nations in all countries; (iii) explore new biologicals (with commensurate risk and safety protocols) for effective PH use with specific modes of action; and (iv) reprioritise plant breeding strategies towards EcoH and HH outcomes.

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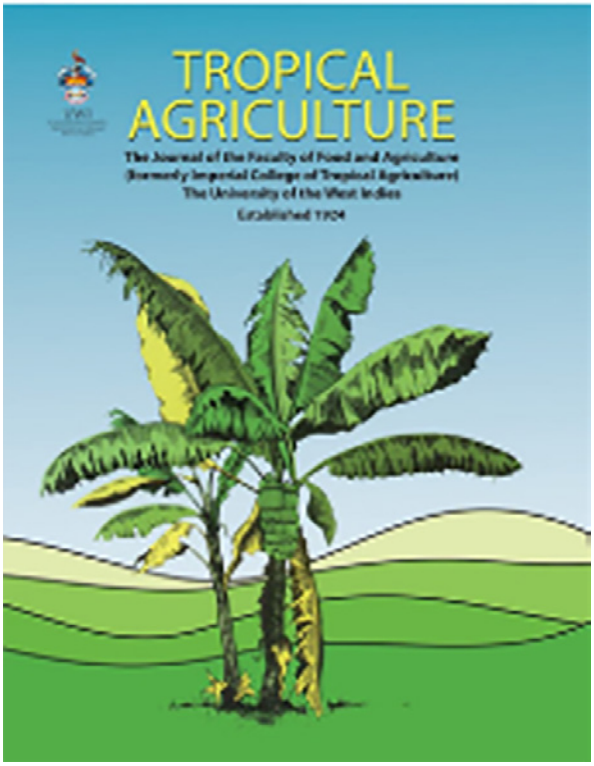
Tropical Agriculture journal

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Volume 103 Number 2 April 2026

Research Papers

Swetha Balakrishnan, Indu Rani Chandrasekaran, Ramalingam Jegadeesan, Kalaiyarasi Ramachandran, Ashok Kumar Govindasamy and Gurusamy Kandasamy 156

Assessment of morphological diversity in chilli (*Capsicum annuum* L.) genotypes using distinctness, uniformity, and stability (DUS) descriptors for improved characterisation and strategic selection

Amarachi Nwokocha, Praise Ajibola, Sani Idris, Olufunso Akinboye, Oluwadara Omopariola and Olajire Fagbola 172

Evaluating mycorrhizal colonisation effects on phosphorus uptake, growth performance and yield of okra *(Abelmoschus esculentus)*

Karamoko Ouattara, Serge Hervé Kimou, Tchoa Kone, André Brahima Soumahoro and Mongomake Kone 189

Greenhouse gas production potential in the rice-growing lowlands of Côte d'Ivoire

Samuel O. Baiyeri, Nnaemeka R. Nwakuba, Adesola A. Satimehin and Chika O. Mmaduakor 200

Physical properties of the seeds of 25 African yam bean (*Sphenostylis stenocarpa*) accessions

Anamika Sharma, L.K. Sharma, Yudhishther Singh Bagal and Tsewang Dolma 216

Performance analysis of cauliflower hybrids under actual field conditions of Jammu Division of Jammu and Kashmir (Union Territory), India

Ferdinand Bizimana, Celestin Munyaneza, Innocent Rwamuhizi, Abdoul-Karim Ndayambaje, Aimable Murera, Felicien Shumbusho, Claire D'André Hirwa, Renée Båge and Martin Ntawubizi 225

Evaluation of artificial insemination success in Ankole and crossbred cows under natural and induced oestrus conditions in Rwanda

A.A. Adeyemo, A.J. Adeyemo, A.V. Adegoke, O.A. Olowu, A.I. Iyanda and D.O. Abidewon 241

Growth response, carcass, meat antioxidant and lipid profile of broiler chickens administered spotted

pumpkin (*lagenaria breviflora*) pulp extract as a phytobiotic

P. Mahesh, B. Mahendran, J. Srikanth, B. Singaravelu, R.T. Maruthi, P. Govindaraj, B. Iswarya and Praveen Kumar 253

Invasive fall armyworm *Spodoptera frugiperda* in sugarcane germplasm: first occurrence in sugarcane in Kerala State, India, and implications for germplasm security

Hong Hieu Tran, Hisashi Datai and Au Ton Nu Hai 269

Comparative economic efficiency of organic and conventional rice production in central Vietnam: Implications for sustainable development

Anuhya Pola, P. Venkatesan, T. Lakshmi, B. Mukunda Rao, P. Lavanya Kumari and G. Krishna Reddy 284

An empirical approach to scale development to measure the effectiveness of Farmer FIRST programme

E.O. Eromedoghene, O.P. Abushe, U.G. Amafade, V.I. Adeoti, J.T. Adeoti and N.E. Omosigho 296

Arable farmers indigenous knowledge and strategies in mitigating climate change effects in Delta State, Nigeria

Review Papers

S. Geethanjali, R. Swarnapriya, V. Rajasree, P. Jeyakumar, S. Maragatham and P. Geetha 308

Sustainable utilisation of banana leaf biomass: a green approach to crop productivity

A. Jason Arockiam, C. Karthikeyan, M. Nirmala Devi, V. Saravanakumar, K.P. Ragunath and R. Suresh 324

Scientometric mapping of policy pathways driving the transformation towards sustainable food systems

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